FINAL REPORT

Technical and economic feasibility of water recycling and energy recovery for red meat processing operations in abattoirs

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NOMENCLATURE

A/O-MBR	Anoxic/Oxic Membrane Bioreactor
ADWG	Australian Drinking Water Guidelines
AGWR	Australian Guidelines for Water Recycling
AQIS	Australian Quarantine and Inspection Service
BOD	Biological Oxygen Demand
CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DALY	Disability-Adjusted Life Year
DO	Dissolved Oxygen
EoP	End-of-Pipe
HACCP	Hazard Analysis and Critical Control Point
HRT	Hydraulic Retention Time
LCA	Lifecycle Assessment
LRV	Log Removal Value
MCA	Multi-criteria Assessment
MS	Milestone
NPV	Net Present Value
O&G	Oil and Grease
OPEX	Operational Expenditure
P&ID	Piping and Instrumentation Diagram
PFD	Process Flow Diagram
QMRA	Quantitative Microbial Risk Assessment
RO	Reverse Osmosis
ROI	Return on Investment
RR	Recycle Ratio
SRT	Solids Retention Time
t.HSCW	Tonnes Hot Standard Carcase Weight
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
UF	Ultrafiltration
WAVE	Water Application Value Engine
WWTP	Wastewater Treatment Plant

1 EXECUTIVE SUMMARY

Project Scope and Objectives	❖ The Australian red meat processing industry uses large quantities of water and energy in order to meet food safety requirements. ❖ Processors in regional areas are often perceived as over users of water, resulting in increases in potential tension between water for red meat production or local community consumption, especially in times of water stress. ❖ This project focused on water recovery to identify viable techno-economic strategies that would significantly reduce potable water consumption that can be implemented by the red meat processing industry.
Milestone 1 Findings: Abattoir Operational Data Collection	❖ Survey responses concluded that processors had concerns regarding the growing uncertainty of the cost of potable water which is exacerbated by risks on water availability due to drought conditions and increasing demand. ❖ The total normalised potable water consumption for red meat processing ranged from 3.10 to 12.18 kL/t.HSCW with sheep/lamb and cattle processors using an average 6.55 and 8.94 kL/t.HSCW respectively. ❖ Cost of potable water and tradewaste disposal were highly variant and dependent on processor's geographical location. Potable water costs ranged from as low as $1.46 to as high as $4.50 AUD/kL. Trade waste disposal costs also fluctuated significantly with prices ranging from $0.25 to $2.54 AUD/kL. ❖ Processors primarily relied on traditional energy sources with some generating biogas from their wastewaters. Feasibility of biogas and alternative energy sources has been well established to yield more significant energy savings than heat recovery from individual "hot" streams given their low volumes. ❖ The current legislation and perceived risks were the barriers that hindered the adoption of direct planned potable recycled water for red meat processing. This limits red meat processors to only specific AQIS-approved reuse options and minimal water savings.
Milestone 2 Findings: Selection of Waste Streams Feasible for Reuse/Recycling	❖ Review and ranking of the waste streams concluded that wastewater from cattleyard wash, boning room, kill floor, side chiller wash, boiler ash wash, and rendering condensates were the most feasible for reuse or recycling. ❖ Direct reuse of wastewater from the boning room, side chiller wash, and boiler ash wash for stockyard wash down will yield water savings of 680 L/t.HSCW (Option 1). This option required minimal treatment of screening and disinfection prior to reuse. ❖ An alternative water recycling option was to produce non-potable class A

	water from treatment of kill floor wastewater, sufficiently meeting an abattoir's non-potable water requirements (Option 2). The non-potable recycling option required biological treatment for nutrient removal and disinfection. ❖ To achieve more significant water savings, red meat processors would need to consider direct planned potable water recycling. Potable water can be produced by treating a combined stream of all six wastewater streams via a biological nutrient removal process followed by a dissolved ion removal process and disinfection (Option 3).
Milestone 3 Findings: Treatment Train Selection and Operating Conditions	❖ The microbial risk associated with the three water reuse/recycling options were quantified through a Quantitative Microbial Risk Assessment (QMRA). ❖ The QRMA determined the required microbial risk of each option and advised on the level of treatment required to ensure that the treated streams were fit-for-purpose and met the required Log Removal Value (LRV) of its end-use. ❖ With the LRVs of each option determined, a Multi-Criteria Assessment (MCA) was used to select the most appropriate treatment train for each option. ❖ Given the low contaminant load in wastewaters selected for direct reuse, minimal treatment of screening followed by chlorination was required to achieve the 2 Log-removal for *Escherichia coli* and maintain a residual chlorine concentration of 0.2 - 2.0 mg/L. ❖ For non-potable Class A water production, a Membrane Bioreactor (MBR) was required for pathogen and nutrient removal. Operating the MBR at a Recycle Ratio (RR) of 450% and a sludge production rate of 25.4 m^3/day, the MBR had a specific energy consumption rate of 0.15 kWh/m^3 and was able to produce 719 m^3/day of non-potable Class A water. ❖ Similar to Option 2, Option 3 also employed a MBR for pathogen and nutrient removal with a Reverse Osmosis (RO) system for further treatment to produce potable water. This treatment train was able to produce 1023 m^3/day of potable water with the MBR and RO having a specific energy consumption of 0.10 and 0.30 kWh/m^3, respectively.
Milestone 4 Findings: Life Cycle and Economic Cost-Benefit Assessment	❖ The environmental impacts and economic cost-benefit of adopting two potable water recycling options, internal and End-of-Pipe (EoP), were evaluated via a Life-Cycle Assessment (LCA) and Net Present Value/Return On Investment (NPV/ROI) calculations. ❖ LCA results suggested that, regardless of recycling configuration, potable water recycling generated an environmental benefit from the reduction in the mineral resource scarcity and freshwater consumption. ❖ Potable water recycling did increase the overall environmental burden given the extra energy and material inputs required with internal recycling

	contributing to a higher environmental burden compared to EoP recycling due to the increased energy consumption associated with the use of the MBR for nutrient removal. ❖ At the current average potable water cost price of \$2.98 AUD/kL, internal recycling was economically more feasible attaining a ROI of 10.2%, a positive NPV of \$2,910,544 AUD after 15 years, and full capital recovery after 8 years. EoP was unable to achieve capital recovery with a low ROI of 0.072% and negative NPV of \$-363,182 AUD after 15 years. ❖ Economic feasibility was dependent on potable water price with both recycling options being not economically feasible at a low cost price of \$1.45 AUD/kL. However, at a higher cost price of \$4.50 AUD/kL, both options were able to recover their initial capital in 5 years.
Recommendations and Future Work	❖ Currently, red meat processors do not segregate their waste streams which reduces opportunities to recycle specific streams and, in turn, makes it difficult to implement proposed water reuse/recycling options. ❖ It is recommended that current abattoirs consider additional investment to retrofit plumbing for waste segregation while greenfield abattoirs should conduct hydraulic planning to allow for access to individual waste streams and minimise cross-contamination between streams. ❖ With food safety and market access legislation being the main barrier to adoption of direct planned potable recycled water, consultation with relevant industry stakeholders and health regulators is critical for validation guidelines to be established. ❖ Pilot testing of the proposed potable water recycling treatment trains is recommended to allow for technical validation of treatment processes and final product water quality compliance monitoring.

2 BACKGROUND

Australian red meat processors use large quantities of water and energy in order to meet food safety requirements, however, given the increasing water scarcity in many parts of Australia, the need for more efficient water use is required. This need is of great concern for abattoirs in rural areas that are often perceived as over users of water, resulting in increases in potential tension between water for red meat production or local community consumption, especially in times of water stress.

According to the 2015 AMPC environmental performance review, the red meat processing industry has achieved clear improvements in energy reduction but only a modest improvement in water use efficiency, further highlights the industry's needs to explore alternative solutions for reuse or recycling of water.

Therefore, Project 2018-1030 aimed to provide engineering solutions and technical recommendations to reduce water and energy consumption of modern abattoirs via a technical and economic feasibility study to identify waste streams paired with technologies capable of water recycling and/or recovering energy from meat processing waste.

3 PROJECT OBJECTIVES

The technical and economic feasibility study was conducted through the following four milestones:

Milestone1 (MS1): The first milestone of the project was to collect abattoir operational data to help identify sources of meat processing wastewaters and their associated water quality and quantity. This was achieved through information collection via a survey sent to the participating abattoirs. The collected data provided advice on the specific processes where significant water and energy savings can be achieved and also allowed for mapping of the current water and energy consumption in Australian red meat abattoirs.

Milestone 2 (MS2): Based on the information collected in MS1, the next step of the project was to pair selected wastewater streams with appropriate treatment technologies to produce treated water that meet water quality standards for identified reuse or recycling applications. Prior to proposing treatment technologies to reduce overall abattoir water consumption, the quantity of wastewater produced by various abattoir processes was also analysed.

Milestone 3 (MS3): This milestone evaluated and optimised the operating conditions of the treatment process trains for the proposed water reuse/recycling options. BioWin and WAVE Reverse Osmosis (RO) modelling tools were used to determine the operating parameters required to meet the recycled water's quality requirements whilst minimising capital and operational expenditure through process design optimisation.

Milestone 4 (MS4): The previous milestones have established that recycling abattoir wastewater to potable standards was the most ideal way for meat processors to achieve significant water savings. There were two ways that potable water could be recovered from abattoir wastewater; 1) Internal recycling utilising a Membrane Bioreactor (MBR) and a Reverse Osmosis (RO) unit to treat six selected waste streams or 2) End-of-Pipe (EoP) recycling which involves using an Ultrafiltration (UF) membrane unit and a RO unit to treat effluent from a conventional water treatment plant. MS4 further evaluated the environmental impacts arising from adoption of these treatment trains, via a Life-Cycle Assessment (LCA), and also assessed its economic feasibility through Net Present Value (NPV) and Return on Investment (ROI) calculations. The two potable water recycling options were compared against the current base case scenario where no water recycling is conducted to contrast the environmental and financial cost-benefits.

4 METHODOLOGY

4.1 Abattoir Operational Data Collection

Abattoir operational data was collected via a detailed survey developed and sent to the participating abattoirs upon agreement of participation. The survey gathered operational information including potable water and energy consumption, wastewater discharge flow rates, and cost of potable water and trade waste discharges. Additional information also helped establish differences in processing practices between participating abattoirs, which accounted for the variations in potable water consumption and the production of wastewater. The survey documented the existing water treatment options utilised by participating processor, their willingness to consider water recycling, and any issues regarding water and energy utilisation. A total of 12 surveys were sent out with eight survey responses received. A general characterisation of the wastewater streams was made from the survey responses, direct interviews, correspondences with abattoir managers, and review of the existing literature. Survey questions can be found in Appendix A.

The operational data collected are detailed as follows:

- Process Flow Diagrams (PFD), Piping and Instrumentation Diagrams (P&ID), water quality and temperatures of monitored wastewater streams.
- Abattoir operational data such as potable water usage, wastewater discharged, and electricity and natural gas consumption.
- Detailed economic information of various operational parameters associated with abattoir processes such as cost of potable water, trade waste disposal, electricity, and natural gas.
- Specific considerations and opinions of the meat processors regarding water reuse and recycling as well as the current technologies implemented for water and energy recovery.

4.2 Selection of Waste Streams and Pairing with Treatment Technologies

4.2.1 Quantification and Identification of Process Water Requirements

The quality and quantities of potable water required for the various abattoir processes were reviewed. Due to the lack of proper water metering for each abattoir process, limited process water consumption information was acquired from the survey, hence, potable water consumption for key abattoir process areas were obtained from published reports and available literature. The abattoir processes water usages were then ranked from highest to lowest in order to identify the processes that utilised high amounts of water. These identified processes would then be considered as potential applications for water reuse or recycling.

4.2.2 Sources, Characteristics, and Volumes of Wastewater Produced

Based on the information obtained from the survey as well as data available in the relevant literature, the characteristics of the various wastewater streams were identified. The report reviewed a wide range of studies to identify volumes and wastewater characterisation data of segregated wastewater streams involved in operation of red meat abattoirs. For each of the stream, the average volume of output was calculated and normalised in unit of litre of wastewater produced to produce one tonne of hot standard carcass weight (L/t.HSCW). The corresponding characterisation data was estimated and reported in unit of mg/L. Weighted selection criteria were utilised to rank the wastewater streams according to their associated strengths and volumes.

The strength of the individual wastewater stream referred to the concentration of wastewater contaminants in the stream which advised on the stream treatability to meet the intended application water quality requirements. Generally, wastewater streams that are low in strength and high in volume are the most suitable candidates for reuse or recycling while segregation of high strength and low volume streams are expected to allow for potential nutrient recovery and subsequent reduction in the contaminant load of the final combined effluent wastewater. Full wastewater characteristics can be found in Appendix B.

4.2.3 Selection of Wastewater Stream for Water Reuse/Recycle

The identified wastewater streams subsequently prioritised the streams for reuse or recycle. Based on each of the contaminant concentration, the characterisation data were classified into four categories: weak, moderate, high, and very high strength. The boundary ranges for each category were determined by calculating lower quartile, median, and upper quartile from the data collected from the survey as well as from available literature.

Therefore, in order to select the most viable wastewater streams for reuse or recycling, a weighted scoring system was utilised to contrast between the wastewater streams according to their associated strengths and volumes. Ranked waste streams based on quality boundary ranges can be found in Appendix C.

4.2.4 Selection of Treatment Technologies for Proposed Water Reduction Options

After the potential wastewater streams are selected, water reuse or recycling options are then chosen. The proposed wastewater streams and reuse/recycling option pairs would then be ranked based on the quantities of wastewater produced and volume of water utilised by the selected end-application.

The wastewater stream characteristics identified the contaminants that require removal prior to discharge, reuse, or recycling. Specific treatment technologies will be selected to meet the water quality requirements of the selected end-application.

4.3 Design Evaluation and Optimisation of Treatment Trains

Proposed options were initially designed based on the water quality of the waste streams with treatment trains selected accordingly, and therefore, prior to the process modelling in MS3, the microbial risk needed to be first assessed to determine the required Log Removal Values (LRV) for each reuse/recycle option before an improved MCA can be conducted to select the most appropriate treatment train. Subsequently, process modelling was performed to determine the optimal operational parameters of the selected treatment trains.

4.3.1 Quantitative Microbial Risk Assessment (QMRA) of Reuse/Recycling Options

A Quantitative Microbial Risk Assessment (QRMA) is a tool that utilises quantitative data to determine the risks of infection and related disease burden to humans from exposure to identified microbial pathogens (Rose and Gerba, 1991). In order to assess the microbial risk with reuse/recycling of abattoir wastewaters, a QRMA with emphasis on microbial pathogens associated with meat processing abattoirs was conducted to ensure that the treated water produced from proposed reuse/recycling options did not pose a health risk to exposed humans.

4.3.1.1 Hazard Identification

Hazards in water recycling systems can be divided into microbial hazards and chemical hazards, both of which pose risks to humans and environmental health, with human health at far greater risk from microbial than from chemical hazards. Given that abattoir wastewaters contain a wide range of microbial pathogens, the first step in the QRMA was to identify the potential microbial hazards present in meat processing abattoirs.

Once the reference pathogens were selected, the next step was to determine the concentration of reference pathogens in the selected wastewater stream. In accordance with the Australian Guidelines for Water Recycling (AGWR), the 95th percentile values was used to statistically estimate the microbial concentration over the assessed time period to reduce effects of external variations arising from unexpected events and incidents (NRMMC, 2006).

4.3.1.2 Dose and Exposure Assessment

The relationship between dose of microbial pathogens and likelihood of illness is obtained from quantification of the concentration of pathogens and the frequencies that they come in contact with humans over a fixed time period. Therefore, the dose and exposure frequencies of each reuse/recycling option's end-use activity was calculated via the equation below.

$$\boldsymbol{Dose} = \boldsymbol{Pathogen\ Concentration} \times \boldsymbol{Exposure\ Volume} \times \boldsymbol{Exposure\ Frequency}$$

For each reference pathogen, the dose associated with its reuse/recycling activity was calculated. For the case of direct water reuse, the dose for direct reuse as stockyard wash was calculated, while for non-potable Class A water, the dose for a range of abattoir activities utilising non-potable Class A water were calculated to establish each activity's pathogen dose. The exposure frequencies for these two options were based on the assumption that an abattoir personnel works on-site for 5 days a week for 48 weeks in a year (240 days).

For the potable water recycling option, the dose response was calculated based on exposure volume and frequency associated with drinking water, which was a more conservative approach that is usually estimated as ingestion of 1 L of water per day per year. This overestimates the actual dose response exposure volume and frequency in abattoirs, which provides a safer estimation, given that under the AQIS Meat Notice 2008/06 abattoirs are not allowed to use recycled potable water for drinking purposes.

4.3.1.3 Microbial Risk and LRV Quantification

The final step of QRMA was to quantify the magnitude of health-based risk for the reference pathogens in the source water and calculate the required LRV to achieve the target DALYs. In accordance with the AGWR (NRMMC, 2006) and the World Health Organisation's Guidelines for Drinking Water Quality (GDWQ) (WHO, 2012), the final target residual risk after treatment is required to be less than 10^{-6} DALYs per person per year. Using a DALYd equal to 10^{-6} DALYs, as well as dose-response models for the selected reference pathogens established in the AGWR, the dose associated with each reuse/recycling option's activities was calculated.

The DALYd for *Escherichia coli* was back-calculated from its dose-response model assuming that the probability of infection ($P_{Infection}$) was 100% and that the DALYs of *Escherichia coli* caused by the infection was 116 DALYs/year (Havelaar and Melse, 2003).

$$P_{Infection} = 1 - e^{-2.18 \times 10^{-4} \times DALYd}$$

Using the reference pathogens' DALYd and the dose of the reuse/recycling option's activities, the required LRV of the proposed treatment train can be calculated using the equation below.

$$Required\ LRV = Log(\frac{Dose}{DALYd})$$

4.3.2 Multi-Criteria Assessment (MCA) of Non-Potable Treatment Trains

In MS2, an initial MCA was conducted to assess and rank the technical feasibility of available treatment options to remove chemical contaminants but it did not account for the microbial risk and the associated LRV requirements. In this milestone, the MCA assessed the treatment trains based on their ability to not only remove chemical contaminants but also microbial pathogens.

The MCA was only conducted to select the best treatment train for non-potable Class A water production because for the direct reuse option, the reuse end-purpose was limited to the stockyard/antemortem area wash, which only required minimal filtration and chlorination, while for the potable water recycling option, the dissolved ions in the wastewater needed to be removed to meet potable drinking water standards. Hence, based on the MCA of MS2, Reverse Osmosis (RO) was the selected treatment process since it is a well-established technology that has been extensively used in directly augmentation of municipal potable drinking water supplies and can effectively remove dissolved ions and pathogens.

4.3.2.1 Criterion Selection and Scoring of MCA

Table 4-1 shows the criteria to assess the technical, financial, and environmental feasibilities of each of the Class A water treatment trains. These criteria, with their definitions and rationales, were determined from the SWOT analysis described in Appendix D.

Table 4-1: MCA Criterion Definition and Rationale

Criterion	Definition	Rationale
Process Complexity	Process complexity considers the number of processes involved in each train, and if any special operation/maintenance is required	Process trains with less process units tend to result in lower start-up/operational failure risks
Process Maturity	Process maturity defines how well-established the proposed treatment train are, especially for abattoir wastewater treatment.	Lower risks are involved with implementation of well-established technology compared to novel/unproven technology
Process Stability	Stability is associated with the likelihood of the process to be affected by unexpected changes in influent wastewater quality	The higher the process stability, the more adaptable the process is to handle unexpected changes during operation
Capital Expenditure (CAPEX)	CAPEX describes the cost involved in purchasing and construction of treatment processes	Lower CAPEX is expected to achieve shorter payback period and reduced capital movement in the early-stages of using the asset
Operational Expenditure (OPEX)	OPEX describes required ongoing expenses including costs for chemicals, energy, labour, and maintenance	Lower operational expenditure ensures good long-term economic sustainability
Process Footprint	Footprint is defined as the land area required by the treatment process	Smaller footprint is expected to minimise cost and environmental impacts
Environmental Impacts	Environmental impacts define the effects of implemented treatment processes on environment including odour, visual impact, and waste production	The lower the environmental impacts of selected treatment trains, the more environmentally sustainable the process would be

Weights were assigned to each criterion through a pair-wise comparison matrix based on the importance of each criterion. After the weight of each criterion was assigned, a scale was developed to systematically score the proposed treatment trains. Combining the weight and the score, the final weighted score of each treatment train was calculated with the most appropriate treatment train achieving the highest MCA score.

4.3.3 Process Modelling of Selected Treatment Trains

4.3.3.1 EnviroSim BioWin Process Modelling

The EnviroSim BioWin software is a modelling tool that simulates biological, chemical, and physical wastewater treatment processes. BioWin has been widely used to select and optimise wastewater treatment processes and to explore CAPEX and OPEX reduction strategies when designing wastewater treatment process trains. The core of BioWin is its proprietary biological model that can accurately model biological nutrient removal processes with the ability to quantify the processes' energy requirements.

The BioWin Anoxic/Oxic Membrane Bioreactor (A/O-MBR) model in this project was initially modelled based on the previously established wastewater MBR with a designed influent capacity of 2500 m^3/day. The treatment process consisted of the anoxic zone, aerobic zone, and membrane zone with volumes of 678 m^3, 1606 m^3, and 357 m^3 respectively. The anoxic zone was not aerated, while Dissolved Oxygen (DO) concentration in the aerobic zone and membrane zone were 3mg/L and 6mg/L respectively. The recycle rate from membrane tank to anoxic zone was 400%, and sludge production rate was 120 m^3/day (**Figure 4-1**).

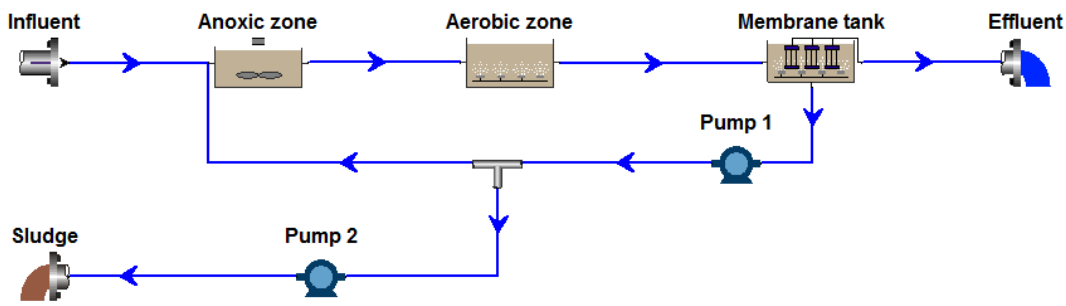

Figure 4-1: Schematic Diagram of A/O-MBR in BioWin

Volume of each zone was scaled according to the volume of influent wastewater for both the non-potable and potable water recycling options and shown in **Table 4-2** below.

Table 4-2: Scaled MBR Volumes Based on Influent Volume

	MBR Influent Volume (m^3/day)	Anoxic Zone Volume (m^3)	Aerobic Zone Volume (m^3)	Membrane Zone Volume (m^3)
Reference MBR	2500	678	1606	357
MBR for Kill Floor Wastewater to Non-potable Class A Water	755	205	485	107
MBR for Combined Wastewater to Potable Water	1208	328	776	172

4.3.3.2 BioWin Model Inputs

Milestone 2 established the concentration of various contaminants in kill floor (WS6) and combined wastewater (WS9) which were based on the average values obtained via data reported in the literature. However, given that wastewater quality data of the specific waste streams were limited, certain parameters were estimated based on conservative assumptions.

Determination Chemical Oxygen Demand Fractions of MBR Influent Wastewaters

The fraction of Chemical Oxygen Demand (COD) in influent wastewater will significantly affect the performance of the biological nutrient removal process. Influent COD can be divided into biomass, readily biodegradable soluble COD (F_{BS}), slowly biodegradable COD (F_{XSP}), unbiodegradable soluble COD (F_{US}), and unbiodegradable particulate COD (F_{UP}) according to the solubility and biodegradability of each fraction. The F_{BS} fraction was reported as 0.1700 for abattoir wastewater (Orhon and Çokgör, 1997) whilst the other COD fractions were calculated using the following equations.

$$Total\ COD = Total\ Biodegradable\ COD + Total\ Unbiodegradable\ COD$$

$$Total\ Biodeg.COD = Readily\ Biodeg.Soluble\ COD\ (\boldsymbol{F_{BS}}) + Slowly\ Biodeg.COD\ (\boldsymbol{F_{XSP}})$$

$$Total\ Unbiodeg.COD\ = Unbiodeg.Soluble\ COD\ (\boldsymbol{F_{US}}) + Unbiodeg.Particulate\ COD\ (\boldsymbol{F_{UP}})$$

$$Fraction\ of\ Unbiodeg.COD\ (\boldsymbol{F_{UB}}) = \frac{Total\ Solids\ (TS) - Volatile\ Solids\ (VS)}{Total\ Solids\ (TS)}$$

$$Fraction\ of\ Unbiodeg.Soluble\ COD\ (\boldsymbol{F_{US}}) = \boldsymbol{F_{UB}} \times \frac{Soluble\ COD}{Total\ COD}$$

$$Fraction\ of\ Unbiodeg.Particulate\ COD\ (\boldsymbol{F_{UP}}) = \boldsymbol{F_{UB}} - \boldsymbol{F_{US}}$$

$$Fraction\ of\ Slowly\ Biodeg.Particulate\ COD\ (\boldsymbol{F_{XSP}}) = 1 - \boldsymbol{F_{BS}} - \boldsymbol{F_{US}} - \boldsymbol{F_{UP}}$$

Due to the low concentration of Total Phosphorous in WS6 and WS9 of 21 mg/L and 17 mg/L respectively, the simulated models experienced a phosphate deficiency which caused deterioration of the nitrification process and subsequently reduced the concentration of nitrate resulting in a high concentration of Ammonia-N and increased Total Nitrogen in final effluent (Nowak et al., 1996). Therefore, for the modelling results to converge, the concentration of Total Phosphorous in WS6 and WS9 were increased to 42 mg/L and 30 mg/L respectively to maintain appropriate concentration ratios of Carbon:Nitrogen:Phosphorous.

4.3.3.3 BioWin Model Outputs

The output parameters of the BioWin model that were monitored were the concentration of BOD, TN, TP, and TSS, as these were the water quality parameters with stipulated limits that needed to be adhered to meet non-potable Class A water requirements. The requirements for BOD, TN, TP, and TSS of a non-potable Class A water were <5.0 mg/L, <5.0 mg/L, <0.5 mg/L, and <1.0 mg/L respectively (EPA, 2003).

4.3.3.4 BioWin Model Optimisation

The optimisation of AO-MBR process in BioWin was performed by monitoring the effluent quality whilst varying Recycle Ratio (RR), Hydraulic Retention Time (HRT) of anoxic and aerobic zones, and the Solid Retention Time (SRT) of the MBR. The HRT of the anoxic and aerobic zones were optimised to identify the minimum volume of corresponding tanks, while the SRT was determined by adjusting the sludge production rate after the optimum RR and HRT values were identified. The specific energy consumption was also monitored to determine the energy reduction of the optimised design.

4.3.4 DuPont WAVE Process Modelling

The DuPont Water Application Value Engine (WAVE) is a software that is capable of modelling RO configurations based on user-specified feed or product water flowrates. The WAVE software utilises a robust calculation engine to accurately simulate complex mass-balance volumes and flows of various RO designs, which in turn can be used to optimise RO design configurations and advise on the system's total energy consumption.

The first step in setting up the model was to define the feed or product water flow rate at an assumed recovery rate of 70%. Subsequently, using the output water quality parameters from the BioWin model, as RO influent feedwater characteristics, the number of passes and stages along with the number of pressure vessels, membrane elements, and membrane type were configured to the desired RO system configurations. Through an iterative process, various parameters were adjusted to yield the optimal RO system design with the aim of recovering the most amount of water whilst maintaining a low overall energy consumption with the minimal amount of RO membranes.

The calculation equations and details for the various parameters are detailed below.

Table 4-3: Definition and Calculation Equations for Various RO System Parameters

RO Parameter	Definition
Salt Rejection (%)	Salt rejection is the measure of how effective the RO membranes are at removing dissolved ions (salt). Well-designed systems are capable of removing 95-99% of salts.
	$\boldsymbol{Salt\ Rejection}\ (\%) = \frac{\boldsymbol{Conc.of\ ion\ feed - Conc.of\ ion\ permeate}}{\boldsymbol{Conc.of\ ion\ in\ feed}} \times \mathbf{100}$
Salt Passage (%)	The inverse of salt rejection expresses the amount of salt passing through the RO system. A higher than expected salt passage would indicate that membranes need to be replaced or cleaned
	$\boldsymbol{Salt\ Passage}\ (\%) = (\mathbf{100}\% - \boldsymbol{Salt\ Rejection}\ (\%))$
RO Recovery	RO recovery is defined as the amount of water recovered as permeate water from

(%)	the feed. For example, at a recovery rate of 70%, 70L of permeate water is recovered from every 100L of feed entering the system. High recoveries (>75%) would mean more water saved, however, results in the system being more prone to scaling and fouling as well as being more CAPEX/OPEX intensive. Therefore, a balance between recovery, concentrate factor, pressure, and temperature needs to be achieved for optimal RO system design and operation.

$$\boldsymbol{Recovery}\ (\%) = \frac{\boldsymbol{Permeate\ Flow\ Rate}}{\boldsymbol{Feed\ Flow\ Rate}} \times \mathbf{100}$$

Concentration Factor	A way to measure the potential of scaling and fouling due to high levels of contaminants and salts in the concentrate stream is to determine the concentration factor. The higher the concentration factor, the higher the likelihood that the solubility limits of each ion may be exceeded resulting in salt precipitation and subsequent scaling/fouling.

$$\boldsymbol{Concentration\ Factor} = \frac{\mathbf{100}\%}{\mathbf{100}\% - \boldsymbol{Recovery}\ (\%)}$$

Membrane Flux (LMH)	Membrane flux is defined as the amount of recovered permeate per unit surface area of membrane per unit time. Given that hydraulic pressure is the driving force for water recovery, selection of the appropriate membrane type would be dependent on the membrane's surface area and rated operating pressure. This would subsequently affect the average flux of the RO system.

$$\boldsymbol{Membrane\ Flux}\ (\boldsymbol{LMH}) = \frac{\boldsymbol{Volume\ of\ Permeate}\ (\boldsymbol{L/hr})}{\boldsymbol{Total\ Membrane\ Surface\ Area}\ (\boldsymbol{m}^{\mathbf{2}})}$$

Membrane Element	Thin-film RO membranes are spiral wound into a membrane element
Pressure Vessel	Pressure vessels are the modules which house the membrane elements. Pressure vessels can hold up to 8 membrane elements with 6-element vessels being the most common.
Stage	A stage defines the number of pressure vessels arranged in series. A one-stage RO system entails feedwater entering the RO system and exiting the system as concentrate and permeates. In a two-stage RO system, the concentrate stream from the first stage becomes the feed to the second stage. This configuration is often used to increase recovery rates.
Pass	A pass is defined as the number of times the permeate is passed through a RO membrane, hence, in a single pass RO system, the permeate is collected after the first membrane stage, while in a double pass RO system, the permeate from the first stage is fed into the second stage resulting in two passes. This configuration is often used to increase permeate quality should a single pass be insufficient.

Results stated herein provide a general guide to the expected optimal design and operating conditions based on normalised water quality data and a model design temperature of 25 °C.

Findings may vary depending on actual abattoir conditions and water quality. It is recommended that site-specific water quality characterisation and operational conditions be conducted prior to implementation of proposed treatment trains.

4.4 Life Cycle Assessment and Economic Feasibility Analysis

The environmental benefits and burdens were evaluated using a comparative Life-Cycle Assessment (LCA) for a base case scenario (no water recycling) and the two potable water recycling options. The economic feasibility of the two options were assessed via a cost-benefit analysis where economic metrics of Net Present Value (NPV) and Return on Investment (ROI) rate were used to ascertain if the options were economically viable for adoption.

Findings from the LCA and economic analysis provided technical and economic viability information that would be beneficial for decision-making and increase the imperative of adopting water recycling in red meat processing abattoirs.

4.4.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool used to systematically evaluate the environmental impacts attributed to a product or service through all stages of its life cycle. LCA solely assesses environmental impacts and is also known as a “cradle to grave” analysis whereby resource usage and emissions of the product are evaluated over its lifespan. Whilst there are other evaluation tools such as Environmental Impact Assessments (EIA), Ecological Footprint, and Environmental Risk Assessment (ERA), only a LCA is capable of providing a comprehensive and quantitative assessment and thus, has been widely applied in the wastewater treatment sector to assess environmental impacts of competing technologies prior to implementation (Foley, 2009, Lane et al., 2012).

LCA is conducted using a standardised method outlined in ISO 14040:2006 (International Organization for Standardization, 2006) and consists of four distinct stages; 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (Figure 4-2).

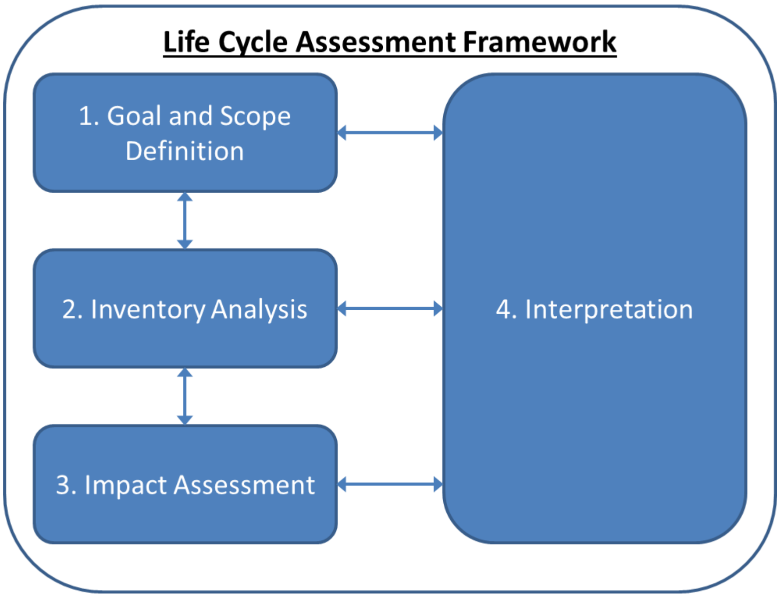

Figure 4-2: Life Cycle Assessment Framework

4.4.1.1 LCA Goal and Scope

The LCA analysed two potable water recycling scenarios; 1) Internal recycling of abattoir wastewater from selected waste streams to produce potable water, and 2) End-of-Pipe (EoP) recycling to produce the same volume of potable water.

Internal recycling involved treating the six selected waste streams (Milestone 3) via a Membrane Bioreactor (MBR) and a Reverse Osmosis (RO) unit to produce 1023 m^3/day of potable water. The EoP scenario recycled non-segregated, combined abattoir wastewater that was first treated via a conventional wastewater treatment plant (WWTP) before undergoing further advanced treatment of Ultrafiltration (UF) and RO to produce high-quality potable water of similar volume.

The goal of the LCA was to quantify and compare the environmental benefits and burdens of Internal and EoP recycling against the base case scenario where no water recycling was considered. The results of the LCA were normalised and compared against the base case scenario for a range of environmental impact factors.

The scope of the LCA is defined by the system boundary for each scenario. In the following comparative LCA studies, only processes within each scenario's boundary were considered with background infrastructure processes associated with tap water production. Likewise, supply (potable town water treatment and supply), electricity generation and supply, and chemical manufacturing were not considered. Construction of conventional wastewater treatment plant construction and the abattoir meat production process were also not included in the LCA boundary as these processes do not contribute to the environmental impact associated with water recycling.

4.4.1.1.1 LCA Functional Unit

The functional unit for this LCA study was defined as 1L of potable tap water used by abattoir processes. The base case scenario only considered potable water sourced from potable town water supply while for the potable water recycling scenarios, both potable water from town water supply and potable water recovered from the abattoir wastewater after the treatment were considered.

4.4.1.1.2 Base Case System Boundary

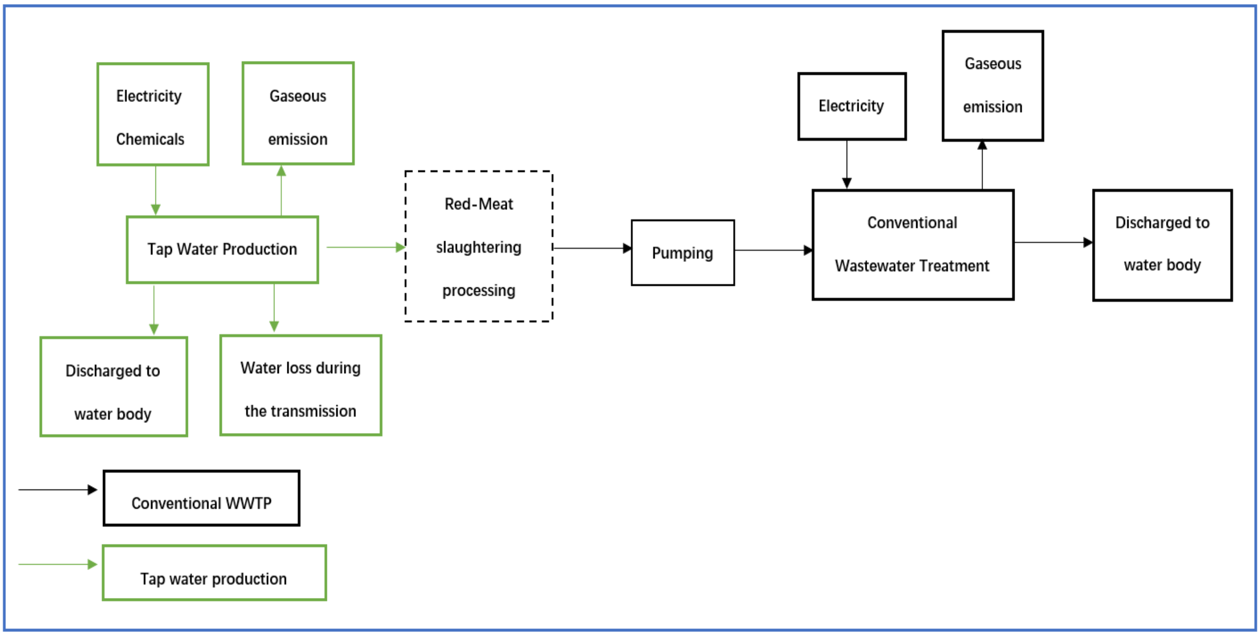

Figure 4-3: System Boundary for Base Case Scenario

Figure 4-3 represents the boundary of a conventional wastewater treatment plant treating abattoir wastewater prior to discharge to designated water body. This is the baseline scenario for this LCA study with 2799 m^3/day of potable town water used by the abattoir and all the produced wastewater treated by the conventional WWTP (2781 m^3/day).

For the base case and water recycling scenarios, the abattoir discharges its untreated or partially treated wastewater for further treatment at an off-site conventional WWTP. A typical conventional WWTP typically consists of primary treatment (settler/clarifier), secondary treatment (activated sludge/biological nutrient removal), and media filtration with disinfection. These treatment processes are external to the abattoir (end-of-pipe) and do not make existing on-site abattoir wastewater treatment processes redundant. However, on-site treatment reduce the cost incurred for wastewater disposal and was factored into the subsequent economic analyses.

4.4.1.1.3 Internal Water Recycling System Boundary

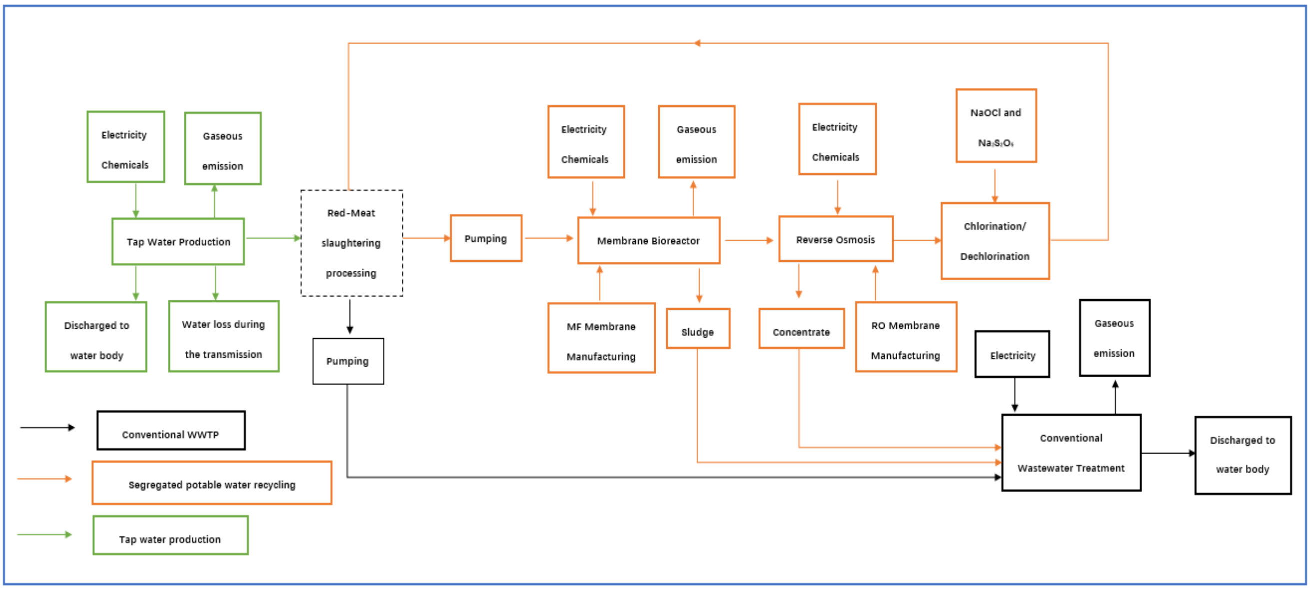

Figure 4-4: System Boundary for Internal Potable Water Recycling Scenario

Figure 4-4 represents the system boundary for internal recycling of the selected segregated waste streams via the proposed MBR, RO, and chlorination system. In this scenario, the volume of potable town tap water, used by the abattoir, is reduced from 2799 m^3/day to 1776 m^3/day with 1023 m^3/day of internally recycled water supplementing the potable town water supply.

The recycled potable water was derived from the six segregated waste streams amounting to a total wastewater volume of 1208 m^3/day producing 1023 m^3/day of potable water at a treatment system recovery of 85%. The waste MBR sludge and RO concentrate were discharged and blended with the remaining abattoir wastewater and treated by the conventional WWTP.

4.4.1.1.4 End-of-Pipe Water Recycling System Boundary

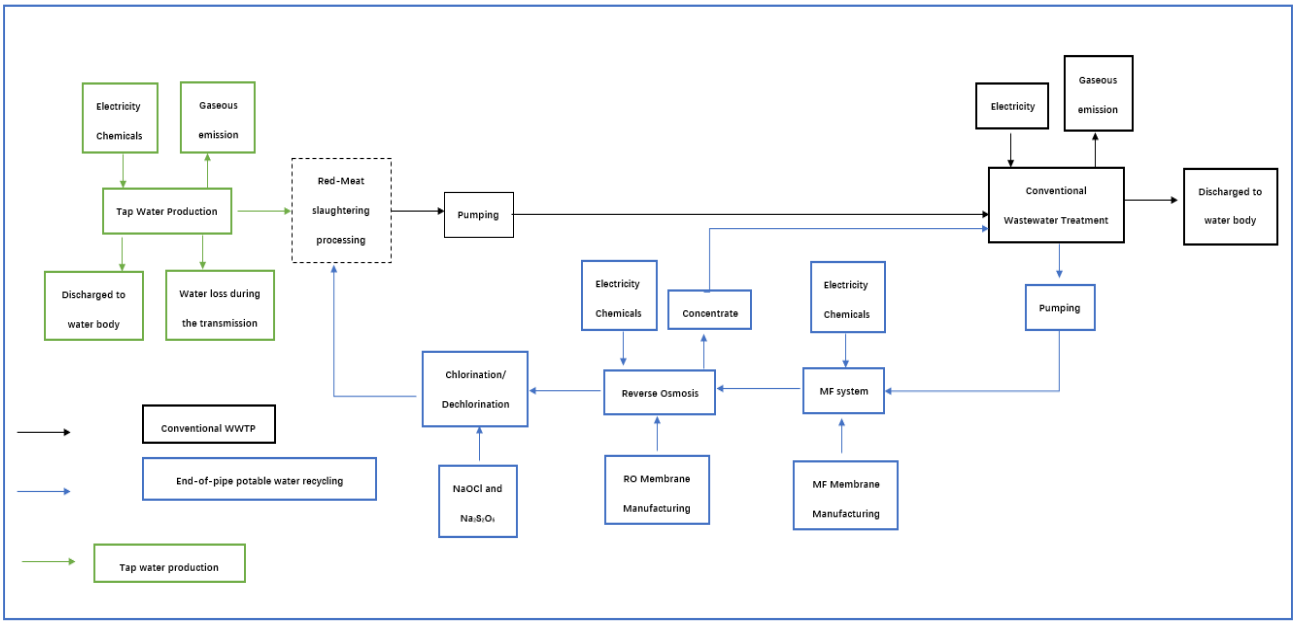

Figure 4-5: System Boundary for End-of-Pipe Potable Water Recycling Scenario

Figure 4-5 represents the boundary of the end-of-pipe potable water recycling scenario. Like the base case, all 2781 m^3/day of abattoir wastewater is comingled and treated via a conventional WWTP. Subsequently, 1440 m^3/day of WWTP effluent is then treated via an advanced water treatment system comprising of UF, RO, and chlorination system to produce 1023 m^3/day of potable water which is then recycled back to supplement potable water consumed by the abattoir process. The waste UF and RO concentrates were discharged and blended with the remaining abattoir wastewater and treated by the conventional WWTP.

4.4.1.2 LCA Impact Indicators

The ReCiPe midpoint hierarchist life cycle assessment method with the Ecoinvent 3 database was chosen for this LCA study as it is a widely used method that is preferred by the wastewater treatment industry. There are a total of 18 midpoint indicators in the ReCiPe method, however, in this LCA, the 11 following impact indicators were selected given their applicability to water recycling (Table 4-4). The definitions and justifications for selecting these 11 environmental impact indicators can be found in Appendix E.

Table 4-4: Environmental Impact Indicators of LCA Study

Impact category	Unit
Global Warming Potential	kg CO2 eq
Stratospheric ozone depletion	kg CFC11 eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO_2 eq
Freshwater eutrophication	kg P eq
Freshwater ecotoxicity	kg 1,4-DCB
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m^3

4.4.1.3 LCA Data Inventory

In this LCA study, Australia-specific LCA Inventory data was sourced from the Ecoinvent 3 database with global data used when specific data was not available for Australia. Inventory data was also supplemented with values obtained from published literature, with the most conservative value being reported in the inventory. The full LCA data inventory can be found in Appendix F.

4.4.2 Economic Cost-Benefit Analysis

An economic cost benefit assessment was undertaken to determine the economic viability of the two water recycling options. Cost-benefit analysis was estimated via discounted cash flow calculations with the economic indicators of Net Present Value (NPV) and Return on Investment (ROI) rate used to evaluate the economic feasibility of each recycling scenario. It should be noted that values presented are indicative and used for the purpose of comparison between the two potable recycling scenarios. A full construction and manufacturing quotation factoring in site-specific information is required for a more accurate economic cost benefit assessment before actual implementation of recommendations.

Capital Expenditure (CAPEX) of water treatment technologies for the two potable water recycling scenarios was estimated using the power law exponent cost correlation (Equation 1). This technique is widely used in engineering process design to calculate an estimated CAPEX, based on plant capacity, from values obtained from existing case studies. Scaled capital costs of various treatment technologies were averaged with the yearly Operational Expenditure (OPEX) estimated to be 15% of the CAPEX. All values were also index-adjusted using the latest available 2019 Chemical Engineering Plant Cost Index of 607.5 (CEPCI) (Equation 2).

$$\boldsymbol{Estimated\ CAPEX = Case\ Study\ CAPEX \times \left(\frac{Estimated\ Capacity}{Case\ Study\ Capacity}\right)^{0.6}}$$

Equation 1

$$2019\ Indexed\ Price = Year\ X\ Price \times \left(\frac{Year\ X\ CEPCI}{2019\ CEPCI}\right) \quad \textbf{Equation 2}$$

Using the estimated CAPEX and OPEX obtained from various case studies and literature, the total CAPEX and OPEX of the water treatment technologies for internal and EoP recycling scenarios were used in the NPV and ROI calculations. Economic analysis assumption and definition of inputs are presented in Table 4-5 .

Table 4-5: Economic Analysis Net Present Value Input Parameters and Assumptions

Input Parameter	Definition and Formula	Assumptions
Capital Movement (CM)	Capital flow for the purpose of investment	Total Fixed Capital (TCI) (Depreciating). Working Capital (15% of TCI) (Non-depreciating).
Depreciation (D)	Reduction in asset's value over time	Asset life assumed to be 15 years. Depreciation rate of 10% used (ATO, 2020). Double depreciation rate (20%) used for first 10 years.
Revenue (R)	Income earned	For this economic analysis, revenue was derived from savings obtained from reduced potable water purchased from local water provider.
Production Costs (Expenditure) (PC(E))	Cost associated with operating treatment technology	Operational expenditure of water treatment technologies was assumed to be 15% of CAPEX. OPEX of all other processes were not considered in this economic cost-benefit analysis.
Gross Profit (GP)	Total profit before tax (R- PC(E))	-
Taxable Profit	Profit after factoring depreciation (GP-D)	-
Profit After Tax (PAT)	Profit factoring tax	Company tax rate of 30% assumed
Operating Cash Flow (OCF)	Operational Cash flow (R- PC(E))	-
Cash Flow (CF)	Operating surplus and capital movement	-
Interest Rate	Proportion of the principal that is charged as interest	Interest rate was assumed to be 0.10% (RBA, 2020)

As part of the economic cost-benefit analysis, a sensitivity analysis was performed to demonstrate the impact of potable water prices on the NPV and ROI rates of the two recycling scenarios. Given that the "revenue" generated was from reduction in costs associated with potable water purchased, a positive NPV and ROI rates would indicate economic feasibility for adoption and implementation of proposed potable water recycling scenarios.

5 PROJECT OUTCOMES AND DISCUSSION

5.1 Milestone 1 Findings and Outcomes

5.1.1 Water Usage in Red Meat Processing

This section reviews the quantity of potable water used by abattoirs during operation as well as the quality and quantity of wastewater produced from their various processes. Due to differences in meat processing practices, size of abattoirs, and meat types being processed, a wide variation in total water consumption was observed. However, in light of the increasing water scarcity and subsequent rise in potable water costs, the previously established requirement of only using potable water in meat processing should be ardently reconsidered to allow for recycled potable water to be used on the abattoir operations and in direct contact with meat products. Changes in the legislation can be achieved through a multiple step validation approach with the first being consultation with the relevant stakeholders and health regulators to identify the areas of concern before risk assessments and validation methods are selected. Validation data collected and analysed would provide evidence-based findings that would be then used to determine the operational monitoring limits of Critical Control Points (CCPs) and subsequent Log Removal Values (LRV) for specific treatment processes.

5.1.1.1 Total Potable Water Consumed

Differences in potable water consumption are to be expected as the participating processors varied in scale (ranging from 1000 to 5000 animals/day), type of meat processed (lamb/beef), and the abattoir's geographical location. These parameters affect the price and availability of potable water which is determined by the local water utility. Variation in potable water prices is further discussed in Section 6.1.4.

Given that the type of meat and the processor scale significantly influence the processor's total water consumed and therefore, total potable water consumption (kL) is not an accurate metric to quantify water efficiency of a processor. Therefore, in order to account for processor scale and meat type processed, potable water consumption was normalised based on tonnes of Hot Standard Carcase Weight (t.HSCW) to provide a better comparison between processors across both meat types.

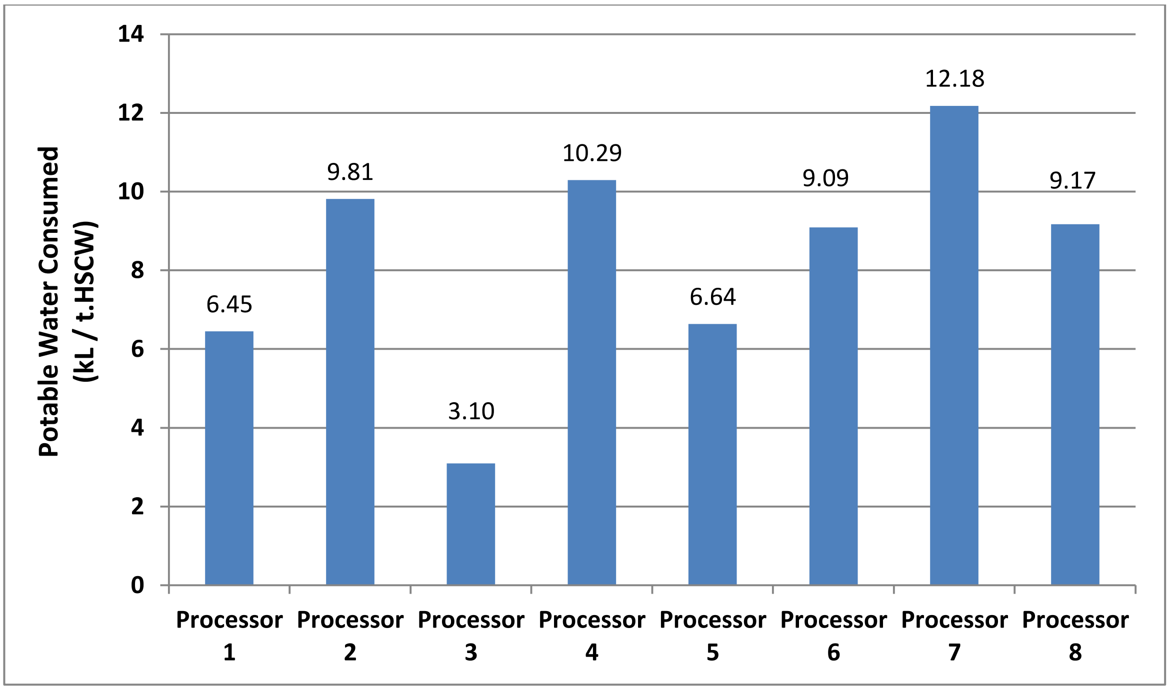

Figure 5-1: Total Potable Water Consumption per tonne HSCW

The total normalised potable water consumption ranged from 3.10 to 12.18 kL/t.HSCW (Figure 5-1). The amount of water consumed was dependent on the type of meat being processed with sheep/lamb processors (Processor 1 and 5) having very similar consumption rates of 6.45 and 6.64 kL/t.HSCW respectively with an average of 6.55 kL/t.HSCW. The cattle processors had relatively similar consumption rates except for Processor 3 which only used 3.10 kL/t.HSCW. The average water consumption of 8.94 kL/t.HSCW for cattle processors is lower than the average potable water usages of 1998, 2003, and 2005 of 11.8, 10.6, and 10.4 kL/t.HSCW respectively (MLA, 2005). This downward trend since 1998 shows that efforts to reduce water usage are having a positive effect in decreasing the industry's potable water consumption.

5.1.1.2 Total Wastewater Discharged

Table 5-1: Total Volume of Wastewater Discharged via Trade Waste or Alternate Options

	Processor 1	Processor 2	Processor 3	Processor 4	Processor 5	Processor 6	Processor 7	Processor 8
Trade Waste Discharges (kL/t.HSCW)	4.53	6.60	N.D.	8.91	N.D.	N.D.	N.D.	8.88
Alternate Discharge Options (kL/t.HSCW)	N/A	N.D.	N/A	6.59	5.12	1.54	N/A	N.D.

N.D. = No Wastewater/Treated Water Discharged
N/A = No Discharge Volume Reported

From the survey data, it was observed that not all the processors had comprehensive water treatment processes on-site with many only having Dissolved Air Flotation (DAF) systems and aerobic ponds. Despite utilising wastewater treatment processes, meat processors were still unable to adequately treat the wastewater on-site and had to dispose the remaining wastewater via the local trade waste system with one processor discharging all wastewaters to trade waste. Four of the eight processors produced wastewaters that could not be sufficiently treated on-site and had to be discharged via trade waste agreements with the local municipal authority (Processors 1, 2, 4,and 8) (Table 5-1).

The volume of wastewater discharged via trade waste disposal ranged from 4.53 to 8.91 kL/t.HSCW with an average of 7.23 kL/t.HSCW. The variance in volume of trade waste discharged was attributed to differences in the treatment processes implemented by each processor. For example, Processor 8 only has a DAF system and hence has to discharge all of its wastewater via local trade waste while Processor 1 utilises a DAF system with aerobic and anaerobic ponds and also held a regulatory license for irrigation discharge to land for crop production resulting in a significantly lower trade waste discharge volume.

Comparison of the total potable water consumed and the total water discharged showed some discrepancies between water usage and discharged. For processor 8, 97% of water mass balance is well accounted where 9.17 kL/t.HSCW was used and 8.88 kL/t.HSCW was discharged, however, Processors 2, 4, and 6 had significant discrepancies in their water mass balance. The trade waste discharge of Processor 2 and 6 only accounted for 67% (6.60 of 9.81 kL/t.HSCW) and 17% (1.54 of 9.09 kL/t.HSCW) respectively. Unlike the other processors, Processor 4 potentially could have double-counted its metered flows resulting in an over-account of the total wastewater produced with a total of 15.5 kL/t.HSCW discharged despite only consuming 10.3 kL/t.HSCW of potable water. Whilst it is not critical to the aims and outcomes of this study, these discrepancies between water consumed and discharged would need to be further analysed to ascertain the source of this imbalance.

The majority of the processors utilised alternative discharge options with only two processors solely disposing wastewater via trade waste discharge. The main alternative discharge options were to use the treated effluent for irrigation of on-site crop production farms or for use as cattle yard wash-down water. Given the differences in discharge volume limits stipulated by water balances calculated in various environmental regulatory licenses (DEC, 2004), six of the eight processors discharged varying volumes of treated wastewater ranging from 1.54 to 6.59 kL/t.HSCW with three processors discharging treated water via alternative options but not reporting discharge volumes (Processors 1, 3, and 7).

5.1.1.3 Wastewater Characterisation

In the attempt to characterise the wastewaters produced by meat processors, the survey requested water quality data of monitored wastewater streams; however, from the correspondences with all meat processors together with observations from a site visit to a beef processor in New South Wales (NSW), it was clear that wastewater streams generated by various processes were not segregated and were only divided into “Red” and “Green” save-all pits.

The only wastewater stream monitored was the final effluent that was discharged directly to either trade waste for trade waste disposal cost calculation or prior to irrigation, after treatment on-site, to ensure adherence to discharge limit licences. Given that none of the wastewater streams could be individually sampled and that all participating meat processors did not monitor the wastewater quality of individual waste streams, a review of the wastewater characteristics available in the literature was conducted to establish the wastewater characteristics of the combined final effluent before treatment as well as that of individual wastewater streams. In this study, the final effluent is defined as the raw combined wastewater prior to any treatment. The table below shows the Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Oil and Grease (O&G), Total Nitrogen (N), and Total Phosphorous (P) of standard meat processors.

Table 5-2: Typical Final Effluent Wastewater Characteristics of Meat Processors

	TCOD (mg/L)	TSS (mg/L)	O&G (mg/L)	N (mg/L)	P (mg/L)	Meat Type	Reference
1	15812	10760	-	288	61	Cattle	(Mutua et al., 2016)
2	10604	5162	1881	295	36	Cattle	(Jensen et al., 2015)
3	12893	8396	2332	245	53	Cattle	(Jensen and Batstone, 2012)
4	9587	4300	783	232	50	Cattle	(Jensen and Batstone, 2012)
5	10800	7530	3350	260	30	Cattle	(Jensen and Batstone, 2012)
6	13126	4412	49	423	396	Sheep	(Muhirwa et al., 2010)

From the literature review, it can be seen that final effluent quality tended to have a COD load of 9587 mg/L to 15812 mg/L, a TSS load of 4300 mg/L to 10760 mg/L, and O&G concentration of 783 mg/L to 5953 mg/L. Total N and P were less variable with an average of 257 mg/L and 46 mg/L respectively (Table 5-2).

Similar to the lack of water quality monitoring of individual wastewater streams, there was a lack of water metering devices to measure the water consumed by each abattoir process. From the literature available, only two case studies were found documenting the water usage of typical abattoirs. Table 5-3 below summarises the breakdown of water consumption by the various abattoir processes for a cattle processor and a sheep processor. As the potable water usage of each processor varied significantly as shown in (Figure 5-1), the associated volume of potable water consumed based on the average consumption of 8.94 kL/t.HSCW and 6.55 kL/t.HSCW, for cattle and sheep processors respectively, are also shown.

Table 5-3: Breakdown of Potable Water Consumption for Typical Meat Processors from Literature

Typical Cattle Processor		
Area of Usage	**Percentage of Potable Water Consumed**	**Volume of Potable Water (kLt.HSCW)**
Stockyards	25%	2.24
Slaughter and Evisceration	10%	0.89
Paunch, Gut, and Offal Washing	20%	1.79
Rendering	2%	0.18
Sterilisers and Wash Stations	10%	0.89
Auxiliary Amenities	7%	0.63
Plant Cleaning	22%	1.97
Plant Services (Cooling/Heating)	4%	0.36
Typical Sheep Processor		
Area of Usage	**Percentage of Potable Water Consumed**	**Volume of Potable Water (kLt.HSCW)**
Slaughter Floor	37%	2.42
Stockyard	0.2%	0.13
Wool Scour	22%	1.44
Wool Tops	12%	0.77
By-products	6%	0.39
Steam	10%	0.66
Condenser	3%	0.20
Amenities	1%	0.07
Unaccounted Uses	8.8%	0.58

From the available literature, for cattle processors, the major consumers of potable water were the stockyards (25%), plant cleaning (22%), paunch, gut, and offal washing (20%), and the slaughter floors (10%). Sheep processors were very different to cattle processors with the slaughter floors having the highest potable water consumption (37%), followed by wool scouring (22%), wool tops (12%), and steam generation (10%). From the breakdown of potable water consumed, it can be seen that there was a wide range of differences in areas of potable water usage across the meat processors, in particular stockyard usage with was 25% in cattle processors and only 0.2% in sheep processors. This could be attributed to differences in processing practices between cattle and sheep.

Findings from both wastewater characterisation and areas of water usage indicate that recommended technologies for recycling/reusing wastewaters would need to be tailored to the meat type of the processor to maximise volume of water recovered from waste streams that are deemed suitable for recycling/reuse.

5.1.1.4 Costs of Potable Water and Trade Waste Discharge

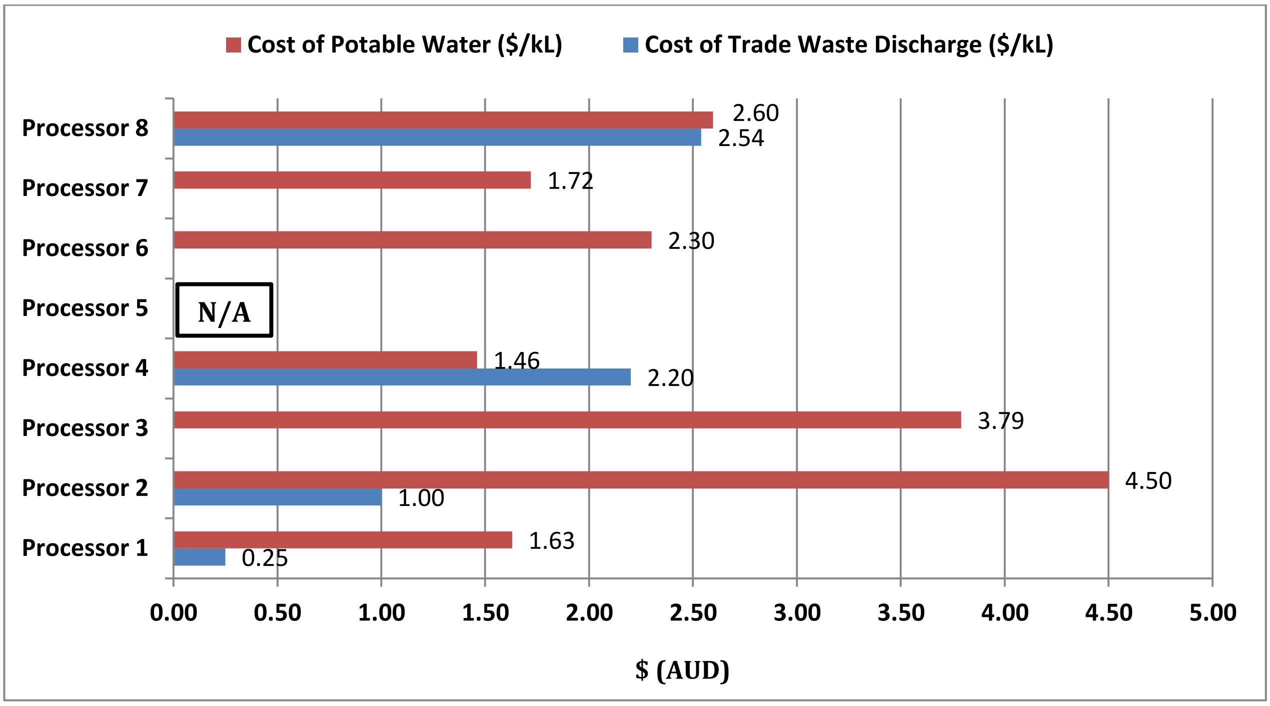

Figure 5-2: Cost of Potable Water and Trade Waste Disposal Obtained from Survey

As the processors are located in different states with some in regional locations, access and availability to municipal water supplies affects cost of potable water and trade waste disposal costs significantly. This resulted in the cost of potable water being highly variant with processors paying local water utilities prices from as low as $1.46/kL to as high as $4.50/kL. Trade waste disposal costs also fluctuated significantly with prices ranging from $0.25/kL to $2.54/kL. The cost of trade waste disposal is dependent on the quality and quantity of the wastewater received by the local municipal water treatment authority. The quality (strength) of the wastewater is determined via specific monitoring and sampling of the discharged wastewater effluent while the quantity (volume) is measured via flow meter readings. The disposal costs are proportional to the variation of effluent wastewater qualities and quantities that each processor discharges (Sydney Water, 2019, Water Corporation, 2019, Toowoomba Region Council, 2017). From Figure 5-2, it can be seen that majority of the processors relied on the local water utility for potable water supply or trade waste disposal except for processor 5 which acquired all its water from an aquifer and treated all wastewater on-site prior to discharge via irrigation.

Since the start of 2017, deficiencies in rainfall have affected most parts of New South Wales, Queensland, and South Australia with these deficiencies severely affecting regions in the northern Murray-Darling Basin (BOM, 2019a). Similar to the market price of water peaking at the height of the Millennium drought in 2007, water prices are forecasted to increase with the onset of the recent drought (BOM, 2019b). This concern is also echoed in participating processors' survey responses highlighting the growing uncertainty in the cost of potable water which is exacerbated by the amount of potable water available due to drought conditions and increasing demand.

5.1.2 Energy Usage in Red Meat Processing

From the survey data, electricity and natural gas were the main sources of energy utilised by all processors, however, some processors also utilised other fuel sources such as coal, diesel, unleaded petrol, biogas, Liquefied Petroleum Gas (LPG), and wood chips. Therefore, in order to better represent the amount of energy consumed by each processor, electricity, natural gas, and all alternative fuel sources were nominalised into MJ/t.HSCW. The table below lists the assumed energy source to energy (MJ) conversion factors used in this study (US EIA, 2019).

Table 5-4: Energy Conversion Factors for Each Energy Source

Energy Source	Base Unit	Energy Conversion Factor
Electricity	1 kWh	3.6 MJ
Coal	1 kg	29.0 MJ
Diesel	1 L	38.6 MJ
Unleaded Petrol	1 L	34.2 MJ
Biogas	1 m^3	22.0 MJ
Liquefied Petroleum Gas	1 L	23.6 MJ
Wood Chips	1 kg	10.7 MJ

The figure below shows the total energy consumption and the breakdown of the different energy sources utilised by the processors surveyed.

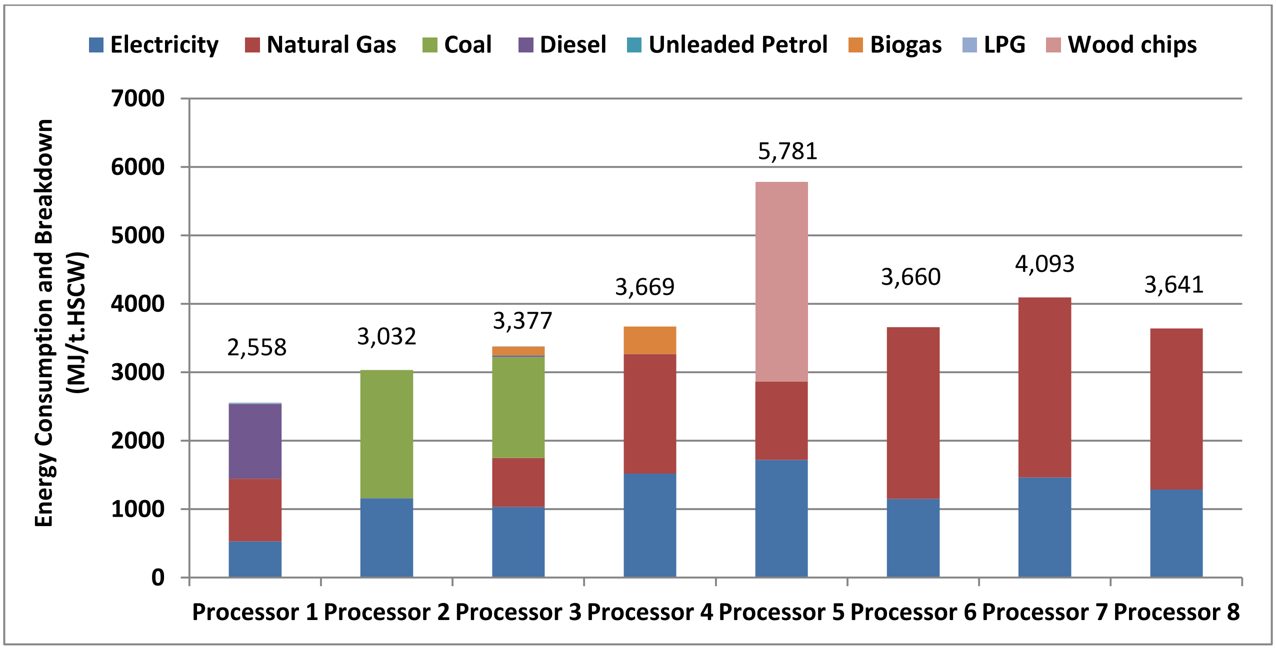

Figure 5-3: Total Energy Consumption and Breakdown Energy Sources in MJ per tonne HSCW

The total energy consumed by the processors ranged from 2558 MJ/t.HSCW to 5781 MJ/t.HSCW with an average energy consumption of 3726 MJ/t.HSCW. The 2019 average energy used of 3726 MJ/t.HSCW was relatively similar to the averages of 1998, 2003, and 2005 at 3200 MJ/t.HSCW, 3200 MJ/t.HSCW, and 3330 MJ/t.HSCW respectively. It was also observed that majority of the processors utilised mainly electricity and natural gas with some processors utilising coal and diesel. Amount of unleaded petrol and LPG used were minimal and mostly used as backup energy supplies to auxiliary services. It was also clear that only two processors (Processor 2 and 3) used biogas indicating the opportunities for biogas production to be considered by other processors. Whilst biogas was produced, no electricity cogeneration process was implemented thus these processors still primarily relied on traditional energy sources such as natural gas, electricity, and coal with biogas as a supplementary energy source. Of the eight processors, only one processor (Processor 5) extensively used wood chips to power their boilers which contributed significantly to the processor's energy consumption.

5.1.3 Additional Observations and Findings

Given the high levels of COD present in abattoir wastewaters, producing biogas from their wastewaters is a viable alternative to traditional energy sources. Biogas generation through anaerobic digestion is a proven method that has been adopted by the meat processing industry. Since 2007, there have been many studies establishing the feasibility of biogas production, via covered anaerobic lagoons and its associated variants, confirming that this would be the most viable way for red meat processors to achieve significant energy savings (Bulter and Johns, 2012, Assal and Schulz, 2013, Jensen and Tait, 2014, Johns Environmental, 2015, Duncan, 2018). More recently, emerging alternative energy production methods such as aggregated Waste to Energy (W2E) (Barnes and Forde, 2020) and renewable hydrogen generation (Forde and Barnes, 2020) have been explored with potential for implementation in the near future. Adoption of these alternative energy sources would yield more significant energy savings than heat recovery from individual "hot" streams given the streams' low volume and likely losses during heat exchange with "cold" streams. Therefore, this project focused on water recovery to identify economically viable strategies that would significantly reduce potable water consumption that can be implemented by the red meat processing industry.

The source of potable water used in abattoir processes are regulated by the 2008 AQIS meat notice (AQIS, 2008) which provides guidance to where recycled water, that has been treated to potable or fit-for-purpose standards, can be utilised on- or off-site. The main purpose of the meat notice was to reduce potable water consumption via water recycling technologies while mitigating food safety concerns through Hazard Analysis and Critical Control Points (HAACP).

The AQIS meat notice categorises waters of different qualities into four types: potable, indirect planned potable, direct planned potable, and reused waters. Potable water is derived from the conventional sources that are acceptable for human consumption. Indirect planned potable involves advanced treatment of wastewaters to produce a high quality product water that can then be used to augment or replenish drinking water catchments. The risk of producing non-compliant water is placed on the water authority supplying the water. Similar to indirect planned potable, direct planned potable water is also recycled water produced from advanced treatment processes, however, the water is to be solely used within the processor's establishment and must comply with the Australian Drinking Water Guidelines (ADWG). AQIS approval of proposed treatment processes as well as validation has to be conducted before recycled water can be use in meat processing. This option places the risk entirely on the processor that is operating the treatment system in place.

The main requirements of the AQIS 2008 meat notice's stance on direct planned potable recycling are listed below:

- Recycled water must stay on the establishment, with no on-sell of product water
- Exclusion of human effluent from wastewater streams
- No physical connection between potable and non-potable streams
- Utilise HACCP
- Adopt multiple barrier approach to prevent non-compliancy
- Ensure access to local potable supply or alternative in case of system failure
- Product water meets ADWG standards
- Recycled water is not a direct ingredient in meat products

Adoption and implementation of these recycling options can help processors reduce their overall potable water consumption, however, the requirement for recycled water to not be a direct ingredient in meat products severely limits the use of recycled potable water in abattoirs to anywhere outside the abattoir process hindering their reduction of potable water consumption during meat processing, which tend to consume large amounts of potable water. Furthermore, given that most meat processors tend to be export-registered establishments Tier 1 or 2, meat processors have to comply with Australian Standard for Hygienic Production and Transportation of Meat and Meat Products for Human Consumption **(**AS4696-2007) which, under sub-clause 21.6, stipulates that only potable water can be used in processing meat and meat products. The sub-clause severely limits recycled potable water to only be used in steam production (not in contact with meat/meat products), fire control, stockyard cleaning, and initial washing of animals.

Therefore, to the authors' best knowledge, the only option currently available for meat processors is water reuse. As per the AQIS 2008 meat notice, reuse of wastewater must meet the following requirements:

- Wastewater has to exclude human effluent
- No physical connection between potable and recycled streams
- Must follow HACCP principles
- Have access to alternative potable water supply

The reuse processes that are currently approved by AQIS are listed as follows:

- Collected steriliser and hand-wash water used for cattle yard wash down
- Steriliser water reused to wash dry landing area
- Reuse of filtered and temperature controlled carcase decontamination water
- Water from clean end of viscera table reused for initial viscera table wash
- Tertiary treated wastewater to be used for initial stockyard wash down
- Chlorinated tertiary treated wastewater for final stockyard wash down

5.2 Milestone 2 Findings and Outcomes

5.2.1 Breakdown of Abattoir Potable Water Requirements

Currently, meat processors are highly reliant on municipal potable water supplies for their internal production processes where water comes into direct contact with meat and meat surfaces. In order to propose strategies to reduce consumption of potable town water, it is important to first quantify the amount of water utilised in meat processing.

This report reviewed the available literature to establish the potable water consumption by various abattoir processes. Table 5-5 presents the breakdown of the average potable water usage across various abattoir processes derived from three available case studies conducted on 12 Australian red meat abattoirs. Water consumption values were averaged from case studies and normalised based on their associated tonne of hot standard carcase weights. The averaged potable water consumption was also similar to water usages of typical medium to large scale meat processors (AMPC, 2005) and hence, is representative of the average potable water consumption of various processes utilised in Australian red meat processing abattoirs.

Table 5-5: Water Usage of Various Red Meat Abattoir Processes

Abattoir Process	Average Water Consumed (L/t.HSCW)	Percentage of Overall Abattoir Water Usage	Typical Ranges (AMPC, 2005)	References
Antemortem Area	**1296**	**14%**	**7 - 24%**	**(MLA, 2002), (Johns, 2011), (Brooks, 2011)**
Slaughter and Evisceration	**3361**	**36%**	**44 - 60%**	**(MLA, 2002), (Johns, 2011), (Brooks, 2011)**
Boning Area	**958**	**10%**	**5 - 10%**	**(MLA, 2002), (Brooks, 2011)**
Offal processing	**1232**	**13%**	**7 - 38%**	**(Brooks, 2011)**
Rendering	**286**	**3%**	**2 - 8%**	**(MLA, 2002), (Johns, 2011), (Brooks, 2011)**
Plant Cleaning	**1011**	**11%**	**N.R.**	
Plant Services	**989**	**10%**	**1 – 6%**	
Amenities	**196**	**2%**	**2 – 5%**	
Overall	**9329**	**100%**		

N.R = Not reported and was probably accounted for in each individual process

It was clear from the review that potable water was mainly utilised in the slaughter and evisceration area, contributing to 36% of the abattoir's overall potable water consumption. The antemortem area (14%), offal processing (13%), plant cleaning (11%), and boning area (10%) were also significant contributors to water consumption.

Whilst the average potable water consumed by each abattoir process was in the same range as that of typical medium-large scale abattoirs (AMPC, 2005), the average water consumption of 9.33 kL/t.HSCW obtained from literature was 11% higher than the water consumption volume of 8.34

kL/t.HSCW obtained from the survey conducted in Milestone 1 of this project. This difference in water consumption could be attributed to improved water management since 2005 as well as variations in operational scale between the surveyed abattoirs and case study abattoirs. Majority of the abattoir processes fell within the typical range stated in the 2005 AMPC report, however, a significant discrepancy in the potable water usage of the slaughter and evisceration area was observed. As the water consumption for plant cleaning was not reported in the 2005 AMPC report, it is highly likely that the observed discrepancy was attributed to water consumed for plant cleaning being accounted together across the various abattoir processes thus reporting a higher than expected range of water consumption for the slaughter and evisceration area. This highlights the need for proper water metering to more accurately quantify the total water used in each abattoir process.

Notwithstanding the aforementioned discrepancy, the water consumption volume of modern abattoirs were still lower than the averages of 1998, 2003, and 2005 at 11.8, 10.6, and 10.4 kL/t.HSCW respectively (AMPC, 2005), indicating that efforts to reduce water usage since 1998 are having a positive effect in decreasing the industry's potable water consumption, however, more water savings can be achieved by abattoirs by augmentation of potable water with recycled or reused waters to reduce overall abattoir water consumption.

5.2.2 Wastewater Sources and Characterisation

Before the selection of potential wastewater streams suitable for reuse or recycle, it is necessary to assess the volumes and quality of each wastewater stream. From the survey data obtained in Milestone 1, along with the site-visit observations and correspondences with participating meat processors, it was clear that wastewater streams generated by various processes were not segregated and were only divided into "Red" and "Green" save-all pits. Similarly, there was a lack of water quality monitoring of individual wastewater streams and insufficient water metering devices to measure the water consumed by each abattoir process. Therefore, past reports and available literature combined with data obtained from the survey were reviewed to identify sources and volumes of wastewater produced from red meat processing.

Table 5-6: Volume of Abattoir Wastewater Streams

Wastewater Stream	Wastewater Volume L/t.HSCW	Wastewater Distribution %	References
Antemortem Area			
Cattle Wash	628	6.9%	(MLA, 2003), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Truck Wash	130	1.4%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Stockyard Wash	1406	15.6%	(MLA, 2003), (Warnecke et al., 2008), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Sub-total	**2164**	**23.9%**	
Slaughter and Evisceration with Boning Area			
Kill Floor	2518	27.9%	(Ruiz et al., 1997), (MLA, 2003), (Warnecke et al., 2008), (Muhirwa et al., 2010), (Johns, 2011), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Boning room	450	5.0%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2012)
Kill floor and Boning cleaning	690	7.6%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Sub-total	**3658**	**40.5%**	
Offal Processing Area			
Paunch dump and rinse	78	0.9%	(MLA, 2003), (Johns, 2011), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Rough offal wash	885	9.8%	(Ruiz et al., 1997), (MLA, 2003), (Nakhla et al., 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2012)
Red offal wash	448	5.0%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Sub-total	**1411**	**15.6%**	
By-Products Processing			
Rendering Condensates	202	2.2%	(Hansen and West, 1992), (Johns, 1995), (MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Blood Stickwaters	137	1.5%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2013)
High Temperature Stickwaters	85	0.9%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2013)
Combined Stickwaters	1008	11.1%	(Nakhla et al., 2003), (MLA, 2003), (Warnecke et al., 2008), (Jensen and Batstone, 2013)
Raw Material Bin	374	4.1%	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and

			Batstone, 2013)
Sub-total	**1806**	**20.0%**	
	Miscellaneous		
Side chiller wash	106	1.2%	(MLA, 2003), (Johns, 2011)
Boiler ash wash	124	1.4%	(MLA, 2003), (Johns, 2011)
Sub-total	**230**	**2.6%**	
Total	**9039**	**100.0%**	

From the data reviewed, wastewater is produced mainly from four main areas in red meat processing abattoirs: stockyard/antemortem area, slaughter and evisceration with boning area, offal processing area, and by-products processing area. Of all the processing areas, the slaughter, evisceration, and boning area produced the highest volume of wastewater, accounting for 40.5% of the abattoir's total wastewater production volume. The other significant contributors to the overall wastewater volume were the antemortem area (23.9%) followed by the by-products processing area (20.0%) and the offal processing area (15.6%).

Although these areas produced large volumes of wastewater, the associated wastewater qualities of the various streams were significantly different thus making certain streams unfeasible to be reused or recycled. Therefore, a more in-depth review of the water qualities of each wastewater stream needs to be performed to aid in stream selection for water reuse or recycling.

5.2.3 Wastewater Quality Characterisation

The report reviewed a wide range of case studies to collect volume and wastewater characterisation data of segregated waste streams involved in operation of red meat abattoirs. Analysing contaminant concentration data helped select the streams that were suitable for reuse or recycling and also identify the waste streams that contributed to majority of the final effluent's contaminant loading. Table 5-7 summarises the water qualities of various abattoir waste streams (Full table in Appendix B).

Table 5-7: Wastewater Characteristics of Various Abattoir Waste Streams in mg/L

Characteristic	TCOD	SCOD	TSS	TS	VS	BOD	O&G	TN	TKN	NH3-N	TP	References
Antemortem Area												
Cattle wash	2467	742	340	3272	2939	-	22	22	204	84	25	(MLA, 2003), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Truck wash	1727	253	1113	-	-	380	124	225	183	163	23	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Stockyard wash	11804	4491	1000	13444	11421	3190	919	413	327	106	90	(MLA, 2003), (Warnecke et al., 2008), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Slaughter and Evisceration with Boning Area												
Kill Floor	6819	2160	1339	3877	1734	10989	168	170	414	30	21	(Ruiz et al., 1997), (MLA, 2003), (Warnecke et al., 2008), (Muhirwa et al., 2010), (Johns, 2011), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Boning	202	72	44	340	-	-	46	10	3.4	0.3	0.7	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2012)
KF and Boning cleaning	5400	1542	3417	-	-	-	727	203	265	10	20	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Offal Processing Area												
Paunch dump and rinse	73613	6426	14900	133348	149909	-	1953	650	1713	103	568	(MLA, 2003), (Johns, 2011), (Jensen and Batstone, 2012), (Jensen and Batstone, 2013)
Rough offal wash	13533	1138	6434	13595	-	8509	4391	708	341	21	82	(Ruiz et al., 1997), (MLA, 2003), (Nakhla et al., 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2012)
Red offal wash	980	212	672	-	-	-	1358	36	10	1.0	7.0	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
By-Products Processing												
Rendering Condensates	1441	610	32	-	-	550	90	350	389	323	2.9	(Hansen and West, 1992), (Johns, 1995), (MLA, 2003), (Warnecke et al., 2008), (Johns, 2011)
Blood Stickwater	32004	8030	18150	22101	15451	21000	142	4817	3765	60	122	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2013)

HT Stickwater	**58994**	**3331**	**19657**	**40730**	**37398**	**-**	**14995**	**198**	**524**	**31**	**183**	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2013)
Combined Stickwater	**59020**	**6069**	**34444**	**20288**	**20881**	**77800**	**16202**	**3000**	**610**	**152**	**243**	(Nakhla et al., 2003), (MLA, 2003), (Warnecke et al., 2008), (Jensen and Batstone, 2013)
Raw Material Bin	**57502**	**20668**	**21370**	**30548**	**-**	**32000**	**4559**	**5200**	**2798**	**271**	**402**	(MLA, 2003), (Warnecke et al., 2008), (Johns, 2011), (Jensen and Batstone, 2013)
Miscellaneous												
Side chiller wash	**104**	**72**	**384**	**-**	**-**	**-**	**36**	**2.0**	**2.7**	**0.3**	**0.7**	(MLA, 2003), (Johns, 2011)
Boiler wash	**700**	**-**	**730**	**-**	**-**	**-**	**-**	**2.0**	**-**	**1.0**	**1.0**	(MLA, 2003), (Johns, 2011)

Table 5-8: Identification of Waste Streams Containing Highest Load of Each Contaminant

Contaminant	Highest Loading	Second Highest Loading	Third Highest Loading	Fourth Highest Loading
Total COD	Paunch dump and rinse	Combined Stickwater	HT Stickwater	Raw Materials Bin
Soluble COD	Raw Materials Bin	Blood Stickwater	Paunch dump and rinse	Combined Stickwater
Total Suspended Solids (TSS)	Combined Stickwater	Raw Materials Bin	HT Stickwater	Blood Stickwater
Oil and Grease (O&G)	Combined Stickwater	HT Stickwater	Raw Materials Bin	Rough Offal Wash
Total Nitrogen (TN)	Raw Materials Bin	Blood Stickwater	Combined Stickwater	Rough Offal Wash
Ammonia-N (NH3-N)	Rendering Condensates	Raw Materials Bin	Truck wash	Combined Stickwater
BOD	Combined Stickwater	Raw Materials Bin	Blood Stickwater	Kill Floor
Total Phosphorous (TP)	Paunch dump and rinse	Raw Materials Bin	Combined Stickwater	HT Stickwater

The waste streams were coloured coded to better highlight the waste streams that were major contributor of the main contaminants. From Table 5-8, it was clear that majority of the contaminant loads could be attributed to by-products processing area from the combined stickwater, raw materials bin, blood stickwater, and HT stickwater streams. The paunch dump and rinse stream from offal processing area is also a significant contributor to the final effluent’s total COD and total phosphorous load. These streams of high contaminant loads could potentially be segregated for nutrient recovery or have separate treatment processes to reduce the overall contaminant load of the final effluent discharged.

Given that the aim of this project was to reduce the potable water consumption of red meat processing abattoirs through implementation of water reuse or recycling technologies, more focus was placed on identifying waste streams that were of low contaminant loads and high flows. Analysis of water quality data showed that the waste streams had varying concentrations of different contaminants and wastewater volumes, therefore, the streams were ranked according to contaminant loading as well as volume produced to identify waste streams that were most feasible for reuse or recycling.

5.2.4 Wastewater Stream Selection

In order to identify waste streams that were most feasible for reuse or recycling, a ranking system was developed to prioritise waste streams reuse or recycle in terms of normalised volume and contaminant concentration.

5.2.4.1 Wastewater Quality and Volume Boundary Ranges

For ranking of waste streams with respect to wastewater quality parameters, the wastewater qualities of each waste stream were grouped into four categories: Low Strength, Moderate Strength, High Strength, and Very High Strength. Categorising waste streams based on their wastewater strengths helped rank the streams according to their treatability with low strength wastes being easier to treat and high strength wastes being more difficult and requiring more treatment. To help rank the streams into the four categories, the boundary ranges of each strength category were determined by calculating the lower quartile, median, and upper quartile concentrations of each contaminant parameter. Table 5-9 shows the boundary ranges for each contaminant.

Table 5-9: Boundary Ranges for Contaminant Concentration Ranking of Wastewater Qualities

Conc. Ranges	TCOD (mg/L)	SCOD (mg/L)	TSS (mg/L)	TS (mg/L)	VS (mg/L)	BOD (mg/L)	O&G (mg/L)	TN (mg/L)	TKN (mg/L)	NH3-N (mg/L)	TP (mg/L)
Low Strength	0-2000	0-700	0-500	0-3500	0-8000	0-500	0-100	0-140	0-140	0-10	0-12
Moderate Strength	2000-14000	700-1200	500-2800	3500-13400	8000-15500	500-6000	100-670	140-330	140-340	10-45	12-50
High Strength	14000-40000	1200-5000	2800-13000	13400-30000	15500-100000	6000-26500	670-2600	330-1450	340-740	45-160	50-190
Very High Strength	>40000	>5000	>13000	>30000	>100000	>26500	>2600	>3000	>740	>160	>190

Applying the boundary ranges to the wastewater characteristics data, weighting scores of 1 to 4 were assigned to each contaminant parameter according to their strength category. The full detailed scoring table for wastewater quality is in Appendix B. As not all wastewater streams contained the same 16 contaminants, the final quality score was scaled according to the number of contaminants present. The calculation below is an example of how the quality score was determined.

Table 5-10: Example Quality Score Calculation of Cattle Wash Waste Stream

Waste Stream	Score = 4	Score = 3	Score = 2	Score = 1
Cattle Wash	5	6	3	0
	4x5 = 20	3x6 = 18	2x3 = 6	1x0 = 0
Sub-score	20+18+6+0 = 44			
Number of Contaminants	14/16			
Final Quality Score	**44 x (16/14) = 51**			

5.2.4.2 Wastewater Streams Ranking

Table 5-11: Wastewater Quality Scoring Results

Waste Stream	Score = 4	Score = 3	Score = 2	Score = 1	Number of Contaminants	Total Quality Score
Antemortem Area						
Cattle Wash	5	6	3	0	14/16	**51**
Truck Wash	3	8	2	1	14/16	**47**
Stockyard Wash	0	5	8	2	15/16	**36**
Kill Floor and Boning Room						
Kill Floor	1	12	3	0	0	**46**
Boning Room	13	1	0	0	2	**63**
Kill floor and Boning Room Cleaning	1	5	3	0	7	**45**
Offal Processing						
Paunch dump and rinse	0	0	3	12	1	**20**
Rough offal wash	1	3	9	2	1	**36**
Red offal wash	7	3	3	3	0	**46**
By-Product Processing						
Rendering Condensates	9	1	2	1	3	**55**
Blood Stickwaters	0	4	6	6	0	**30**
HT Stickwaters	0	5	6	4	1	**34**
Combined Stickwaters	0	1	6	8	1	**25**
Raw Material Bin	0	0	1	14	1	**18**

Miscellaneous						
Side chiller wash	12	1	0	0	3	**63**
Boiler ash wash	5	1	0	0	10	**62**

Prior to ranking of waste streams, the total score based on the waste stream's quality was calculated (Table 5-11). Results show that wastewater from the boning room, side chiller wash, boiler ash wash, rendering condensates, kill floor, and cattle wash waste streams had water qualities that were suitable for water reuse or recycling due to their lower contamination loads.

Table 5-12: Wastewater Volume Scoring Results

Waste Stream	Wastewater Volume	Wastewater Distribution (%)	Total Volume Score
Antemortem Area			
Cattle Wash	628	6.78%	**4**
Truckwash	130	1.40%	**1**
Stockyard Wash	1406	15.17%	**10**
Kill Floor and Boning Room			
Kill Floor	2518	27.17%	**17**
Boning Room	450	4.85%	**3**
Kill floor and Boning Room Cleaning	690	7.44%	**5**
Offal Processing			
Paunch dump and rinse	78	0.84%	**1**
Rough offal wash	885	9.55%	**6**
Red offal wash	448	4.83%	**3**
By-product Processing			
Rendering Condensates	202	2.18%	**1**
Blood Stickwaters	137	1.48%	**1**
HT Stickwaters	85	0.92%	**1**
Combined Stickwaters	1008	10.87%	**7**
Raw Material Bin	374	4.03%	**2**
Miscellaneous			
Side chiller wash	106	1.14%	**1**
Boiler ash wash	124	1.34%	**1**
Total	**9269**	**100%**	**64**

For the wastewater volume to carry an equal weight to the wastewater quality's score, a weighted score was assigned to streams of low, moderate, high, and very high volumes based on the percentage distribution with respect to the total volume of wastewater produced and the wastewater quality's scoring criterion of 64 points.

Scoring of the wastewater streams based identified the streams that produced significant volumes of wastewater with high scores indicating high volumes produced. Based on the total volume score calculated, it can be concluded that the kill floor (17), stockyard wash (10), combined stickwaters (7), rough offal wash (6), and the kill floor and boning room cleaning waste (5) streams produced large volumes of wastewater. However, the volume of wastewater produced is not a good metric of reuse or recycle feasibility as streams such as the stockyard wash, combined stickwaters, and rough offal wash were also highly contaminated (Table 5-8 and Table 5-11). Therefore, both scores need to be taken into account to help rank the waste streams in terms of its reuse or recycle feasibility.

Table 5-13: Overall Score of Wastewater Streams

Waste Stream	Wastewater Quality Score	Wastewater Volume Score	Total Score
Boning Room	3	63	66
Side chiller wash	1	63	64
Kill Floor	17	46	63
Boiler ash wash	1	62	63
Rendering Condensates	1	55	56
Cattleyard Wash	4	51	55
Red offal wash	3	46	49
Kill floor and Boning Room Cleaning	4	45	49
Truckwash	1	47	48
Stockyard Wash	10	36	46
Rough offal wash	6	36	42
HT Stickwaters	1	34	35
Combined Stickwaters	7	25	32
Blood Stickwaters	1	30	31
Paunch dump and rinse	1	20	21
Raw Material Bin	2	18	20

From the overall scoring results the waste streams that were most feasible for reuse or recycling were from the boning room (66), side chiller wash (64), kill floor (63), boiler ash wash (63), rendering condensates (56), and the cattleyard wash (49). Table 5-14 shows the water qualities of the top six waste streams that were ideal candidates for water reuse or recycling.

Table 5-14: Waste Streams Most Feasible for Water Reuse or Recycling

Waste Streams	Volume (L/t.HSCW)	TCOD (mg/L)	SCOD (mg/L)	TSS (mg/L)	BOD (mg/L)	O&G (mg/L)	TN (mg/L)	NH3-N (mg/L)
Boning Room	450 (5%)	202	72	44	-	46	10	0.3
Side Chiller Wash	106 (1%)	104	72	384	-	36	2	0.3
Boiler Ash Wash	124 (1%)	700	-	730	-	-	2	1
Rendering Condensates	202 (2%)	1441	610	32	550	90	350	323

Cattleyard Wash	628 (7%)	2467	742	340	-	22	22	84
Kill Floor	2518 (27%)	6819	2160	1339	10989	168	170	30

Although wastewaters produced from the boning room, side chiller wash, boiler ash wash, cattleyard wash and rendering condensates were of low volumes, these streams still contributed to 1-7% of the abattoir's wastewater volumes each, which can still yield significant water savings when individually or collectively reused/recycled. More importantly, most of these streams contained low concentrations of contaminants and thus, have a great potential for direct water reuse or water recycling. However, when these streams are combined with the moderate strength stream of the kill floor, the potential water savings will be significantly increased due to the associated volume of the additional waste streams.

5.2.5 Review of Combined Waste Streams and Water Saving Considerations

In meat processing abattoirs, direct reuse of a waste stream is only applicable to streams of low contaminant loads for use in the same process or another process within the abattoir. Due to the health risks associated with direct reuse or recycling of wastewaters, establishments intending to implement these water reduction options must adhere to guidelines of the AQIS Meat Notice 2008/06 (AQIS, 2008) and provide full details to AQIS prior to construction with approval upon validation prior to use in production. For direct planned potable recycling, product water has to meet the requirements stipulated in the Australian Drinking Water Guidelines (NHMRC, 2011) and the Australian Standard for the Hygienic Production and Transportation of Meat and Meat Products (AS4696:2007).

Of the 16 identified contaminants, oil and grease (O&G) was the one contaminant that required its own pre-treatment step. Therefore, taking into account the potential extra capital expenditure of additional pre-treatment technologies required to remove O&G whilst maximising water production for increased water savings, a total of five water saving end-use purposes were considered to reduce potable water consumption in red meat processing with them having end purposes of direct reuse of wastewater, non-potable without O&G, non-potable water recycling, potable without O&G, and potable water recycling. Considering O&G concentrations, a total of eight waste streams (WS) were considered for the five end-use purposes.

Table 5-15: Comparison and Justification for Stream Considerations for Potential Water Saving End-purposes

Water Streams	Waste Stream Source	Direct Reuse	Non-potable Recycling (No O&G)	Non-potable Recycling	Potable Recycling (No O&G)	Potable Recycling	Potential Water Savings (L/t.HSCW)	Justification / Comments
Use of Boning Room waste stream (WS1)	Boning Room (S1)	✓	X	X	X	X	**450 (5%)**	▪ Low contaminant strength (low TCOD and TSS) ▪ Low volume of 450 L/t.HSCW (5% of total water consumed) ▪ Not feasible for non-potable or potable recycling ▪ Most feasible for direct reuse
Use of Side Chiller Wash waste stream (WS2)	Side Chiller Wash (S2)	✓	X	X	X	X	**106 (1%)**	▪ Low contaminant strength (low TCOD and TSS) ▪ Low volume of 106 L/t.HSCW (1% of total water consumed) ▪ Not feasible for non-potable or potable recycling ▪ Most feasible for direct reuse
Use of Boiler Ash Wash waste stream (WS3)	Boiler Ash Wash (S3)	✓	X	X	X	X	**124 (1%)**	▪ Low contaminant strength with moderate concentration of TSS which can be removed ▪ Low volume of 124 L/t.HSCW (1% of total water consumed) ▪ Not feasible for non-potable or potable recycling ▪ Most feasible for direct reuse
Use of Rendering Condensate waste stream (WS4)	Rendering Condensates (S4)	X	X	X	X	X	**202 (2%)**	▪ Moderate contaminant strength with moderate concentration of TCOD, BOD, and TN which can be removed via biological treatment ▪ No O&G removal required ▪ Low volume of 202 L/t.HSCW (2% of total water consumed) ▪ Not feasible for reuse or recycling on its own
Use of Cattleyard Wash waste stream (WS5)	Cattleyard Wash (S5)	X	✓	X	X	X	**628 (7%)**	▪ Moderate contaminant strength with moderate concentration of TCOD, BOD, and TN which can be removed via secondary biological treatment ▪ No O&G removal required

								▪ Moderate volume of 628 L/t.HSCW (2% of total water consumed) ▪ Not feasible for reuse or potable recycling on its own given low volume
Use of Kill Floor waste stream (WS6)	Kill Floor (S6)	X	X	✓	X	X	**2518 (28%)**	▪ Moderate contaminant strength with moderate concentration of TCOD, TSS, O&G, TN, and high concentration of BOD. ▪ Will require secondary biological treatment ▪ O&G removal pre-treatment is required ▪ High volume of 2518 L/t.HSCW (28% of total water consumed)
Use of Boning Room, Side Chiller, Boiler Ash Wash combined waste stream (WS7)	S1+S2+S3	✓	X	X	X	X	**680 (8%)**	▪ Combining the three low strength streams, the moderate TSS of the boiler ash stream is diluted making it feasible for direct reuse with minimal pre-treatment ▪ No O&G removal required ▪ Combined volume of 680 L/t.HSCW (6% of total water consumed) ▪ Feasible for direct reuse
Use of five streams of lowest contaminant loads combined (WS8)	S1+S2+S3 +S4+S5	X	✓	X	✓	X	**1510 (17%)**	▪ Combining the five low strength streams, the wastewater has low TCOD, BOD, O&G, TN, and moderate TSS ▪ No O&G removal required ▪ Combined volume of 1510 L/t.HSCW (17% of total water consumed) ▪ Feasible for non-potable and potable recycling
Use of all six waste streams combined (WS9)	All Streams Combined	X	X	✓	X	✓	**4028 (44%)**	▪ Combining the six streams, the wastewater has moderate TCO, TSS, O&G, and TN ▪ O&G removal required ▪ Combined volume of 4028 L/t.HSCW (44% of total water consumed) ▪ Feasible for non-potable and potable recycling

Table 5-16: Water Saving Options Chosen for Various End-use Purposes

End-use Purpose	Water Saving Options (WSO)	WSO Description	WSO Chosen	Potential Water Savings (L/t.HSCW)
Direct Reuse	WSO 1	Boning room (WS1) direct reuse to antemortem area	WSO 4	680 (8% of total potable water usage)
	WSO 2	Side Chiller Wash (WS 2) direct reuse to antemortem area		
	WSO 3	Boiler Ash Wash (WS 3) direct reuse to antemortem area		
	WSO 4	Combined boning room, side chiller, and boiler ash (WS 7) direct reuse to antemortem area		
Class A Non-potable without O&G	WSO 5	Cattleyard Wash (WS 5) to non-potable Class A	WSO 7	2518 * (28% of total potable water usage)
	WSO 6	Combined five lowest contaminant streams (WS 8) to non-potable Class A		
Class A Non-potable Recycling	WSO 7	Kill floor wastewater (WS 6) to non-potable Class A		
	WSO 8	All six streams combined (WS 9) to non-potable Class A		
Potable Water without O&G	WSO 9	Combined five lowest contaminant streams (WS 8) to potable water	WSO 10	2820 [1] ** (31% of total potable water usage)
Potable Water Recycling	WSO 10	All six streams combined (WS 9) to potable water		

* Treated water can only be used for non-potable processes
** Treated water can be used in any process
[1] Assuming 70% recovery using reverse osmosis/electrodialysis

From the comparison of the eight waste streams, ten WSOs were proposed with four WSOs for direct reuse to antemortem area, four for Class A non-potable recycling, and two for potable water recycling (**Table 5-16**).

5.2.5.1 Direct Reuse Water Saving Options

Table 5-17: Water Quality and Volume of Combined Waste Streams for WSO1

Waste Streams	Volume (L/t.HSCW)	TCOD (mg/L)	SCOD (mg/L)	TSS (mg/L)	O&G (mg/L)	TN (mg/L)	NH3-N (mg/L)	TP (mg/L)
Boning Room	450 (5%)	202	72	44	46	10	0.3	0.7
Side Chiller Wash	106 (1%)	104	72	384	36	2.0	0.3	0.7
Boiler Ash Wash	124 (1%)	700	-	730	-	2.0	1.0	1.0
Total	**680 (7%)**	**277**	**72**	**222**	**44**	**7.3**	**0.4**	**0.7**

Analysis of the wastewater qualities of the selected and combined waste streams concluded that only WS 1, 2, 3, and 6 were suitable for direct reuse in the antemortem area (**Table 5-15**). As the individual wastewater volumes of the boning room, side chiller wash, and boiler ash wash waste streams were low, direct reuse of each individual stream alone will not yield significant water savings. However, combining all these low contaminant streams (WS6) yielded significant water savings of 680 L/t.HSCW reducing total abattoir potable water consumption by 8% (204 kL/day[2]). Table 5-17 shows the water quality and volume of combined wastewaters from the three streams calculated based on concentration loading and volume of each contaminant. Due to the higher contaminant loads of the rendering condensates, cattleyard wash, and kill floor waste streams, combining any of these streams with WS6 will render WS 6 not suitable for direct reuse. Therefore, WSO 4, which is to directly reuse WS6 in the antemortem area, was the only feasible direct reuse option.

5.2.5.2 Non-potable Water Recycling Water Saving Options

The next water saving opportunity was to treat the waste streams to a Class A, non-potable water.

Class A water can be used for the following processes:

- Stockyard and truck washing (Antemortem area)
- Cattle drinking water (Antemortem area)
- Amenities and fire control (Amenities)
- Cooling, boiler systems, and team production (no contact with meat) (Plant services)
- Inedible offal processing
- Cleaning in place systems (Plant services)

Table 5-18: Class A Water Quality

Water Parameters	Post-Tertiary Treated Water Quality
BOD	< 5.0 mg/L
TSS	< 1.0 mg/L
TN	< 5.0 mg/L
TP	< 0.1 mg/L
Turbidity	< 0.2 NTU
Fecal Coliform *(E. coli)*	< 2 CFU/ 100 mL

From the abattoir process water consumption analysis, it was observed that meat processors could only use non-potable water in three abattoir processes; plant services (989 L/t.HSCW), amenities (196 L/t.HSCW), and antemortem area (1296 L/t.HSCW), utilising a total of 2481 L/t.HSCW. Non-potable water cannot be used in any other process, therefore, it is economically unfeasible to produce an excess of non-potable water, hence, treating a combined stream of all six streams together (WSO 8) is not feasible as that produces a total of 4028 L/t.HSCW of non-potable water which is 62% in excess of the non-potable water requirements. Of the three remaining non-potable WSOs proposed, WSO 5 was not feasible as it only produced 628 L/t.HSCW while still requiring the same treatment processes necessary for WSO 6 and 7, therefore only WSO 6 and 7 were considered. WSO 6 and 7 have their advantages and disadvantages with WSO 7 producing 67% more non-potable water than WSO 6 (2518 vs 1510 L/t.HSCW) and meeting the non-potable water requirements sufficiently (2481 L/t.HSCW), however, unlike treating wastewater for WSO 6, treatment processes for WSO 7 will require an O&G removal pre-treatment which introduces additional capital and operational expenditure to the process. However, as the O&G concentration being moderately low and with the main aim of the project to minimise water consumption, especially for processors in drought affected locations, the increased water consumption savings of WSO 7 (saving a total of 744 kL/day[2]) outweighs the additional costs involved and thus, WSO 7 is chosen.

5.2.5.3 Potable Water Recycling Water Saving Options

To produce treated water that can be utilised in any abattoir process and to achieve higher water savings potable water recycling needs to be considered. Assuming a typical 70% recovery rate of dissolved ion removal technologies (reverse osmosis/electrodialysis) and based on the volume of wastewater treated, WSO 9 has the potential to produce 1057 L/t.HSCW (317 kL/day[2]) while WSO 10 produces 2820 L/t.HSCW (846 kL/day[2]) which translates to significant potable water savings. The 2.7 times higher potable water produced would again outweigh the additional capital and operational costs of an O&G pre-treatment process required. Furthermore, implementation of WSO 10 will allow the abattoir to be more climate independent and reduce its reliance on potable town water by 31%, indirectly alleviating the potable water requirements of processors and local communities in drought affected regions.

[2] Assuming abattoir production of 300 t.HSCW/day

5.2.6 Selection of Treatment Technologies

Wastewater treatment technologies consist of physical, chemical, and biological processes for removal of solids, organic matter, pathogens, nutrients, and dissolved metals from wastewaters. The number of treatment processes required for wastewater treatment varies according to the specific reuse or recycling application and its associated treated water quality requirements with the wastewaters requiring primary, secondary, and tertiary treatments.

Whilst majority of the treatment technologies available for treating red meat processing wastewaters are similar to that used in municipal wastewater treatment abattoir wastewaters tend to contain high concentrations of O&G. Therefore, for abattoir wastewater treatment, an additional pre-treatment process of O&G removal is necessary depending on the concentration present in the waste stream. Figure 5-4 shows the available treatment technologies for non-potable and potable water recycling specifically for abattoir wastewaters.

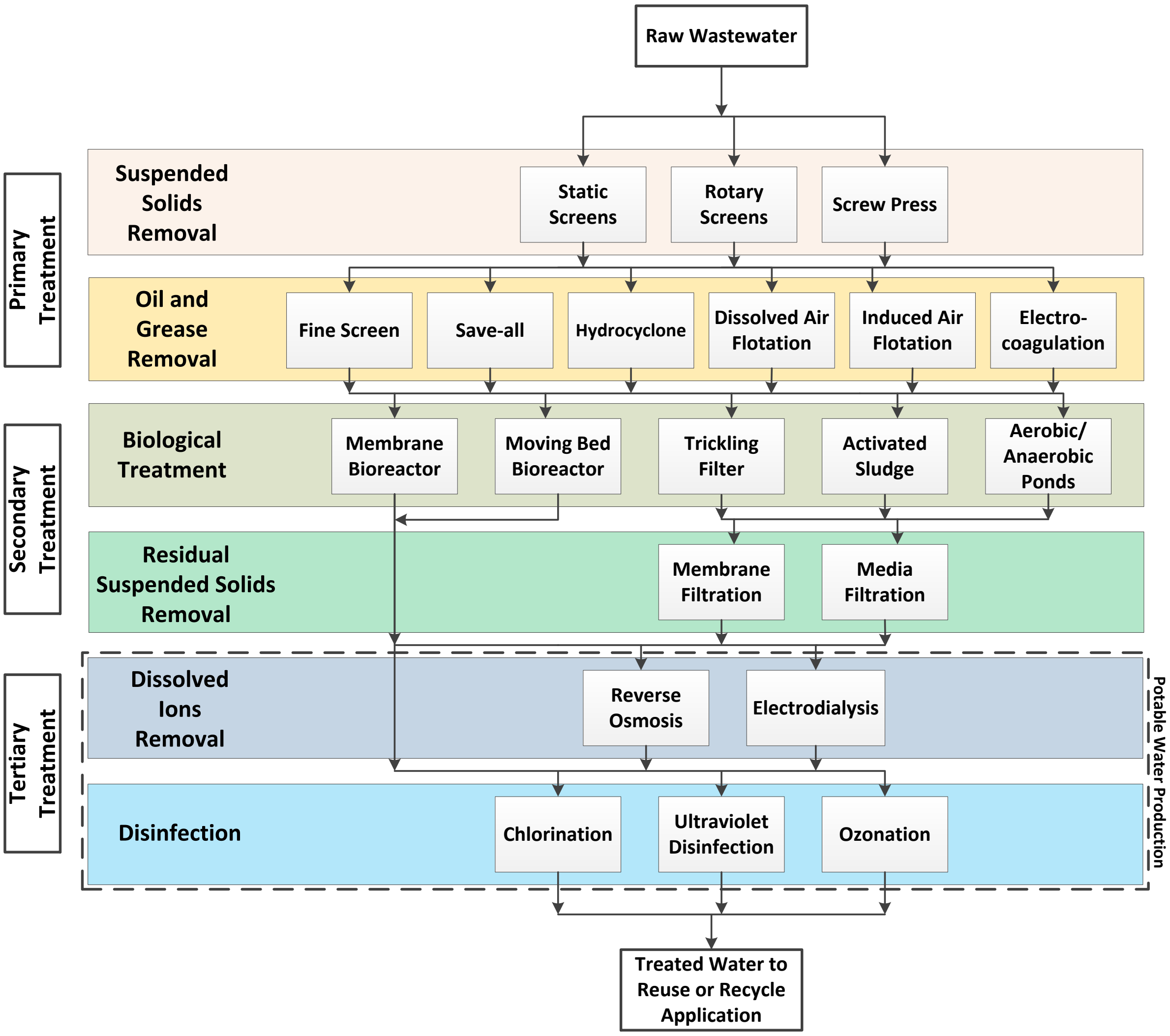

Figure 5-4: Available Treatment Technologies for Non-potable and Potable Recycling for Abattoir Wastewaters

5.3 Milestone 3 Findings and Outcomes

From the review and ranking of abattoir waste streams conducted in MS2, it was evident that the waste streams from the cattleyard wash, boning room, kill floor, side chiller wash, boiler ash wash, and rendering condensates were the most feasible for reuse or recycling. Based on the water quality parameters of individual, and combinations, of the selected waste streams, one direct water reuse scenario and two water recycling scenarios were proposed. The direct reuse scenario consisted of combining waste streams from the boning room, side chiller wash, and boiler ash wash waste for reuse in the stockyard as wash down water (S1) while the other two water recycling scenarios were to treat the kill floor waste stream to a non-potable Class A water (S2) and treating of all six waste streams to potable water (S3) respectively. All three scenarios proposed in MS2 were initially designed based on the water quality of the waste streams with treatment trains selected accordingly, and therefore, prior to the process modelling in MS3, the microbial risk needed to be first assessed to determine the required Log Removal Values (LRV) for each reuse/recycle option before an improved Multi-Criteria Assessment (MCA) can be conducted to select the most appropriate non-potable treatment train. Subsequently, process modelling was performed to determine the optimal operational parameters of the selected treatment trains.

5.3.1 Quantitative Microbial Risk Assessment (QMRA)

5.3.1.1 Selection of Reference Pathogens

There is a wide array of microbial pathogens present in raw industrial and municipal wastewaters. They can be divided into four categories, namely bacteria, viruses, protozoa and helminth. However, in the case of abattoir wastewaters, a previously commissioned Meat & Livestock Australia (MLA) report that reviewed over 52 pathogens, identified the six pathogens most commonly present in abattoirs that have great potential to pose a risk to human health in the Australian meat industry (Jain et al., 2003). Of the six, the three waterborne pathogens (*Escherichia coli O157:H7*, *Campylobacter jejuni* and *Cryptosporidium parvum*) and additional viral pathogen (*Rotavirus*) were selected as reference pathogens given that these four arise from cross-contamination from faecal sources during slaughter and processing (FSANZ, 2013). Further justifications for the four pathogens are described in **Table 5-19**.

Table 5-19: Rationale for Selection of Reference Pathogens

Reference Pathogens	Rationale
Escherichia coli O157:H7	*Escherichia coli* resides as a commensal gram-negative bacterium that occurs naturally in the digestive systems of animals and humans, While, main trains are harmless, of concern is the *Escherichia coli* O157:H7, which is shed in the faeces of cattle and can contaminate meat during processing (Mittal, 2004). *Escherichia coli* O157:H7 has the highest disease burden per case (Havelaar and Melse, 2003). Associated illnesses include abdominal cramping, watery or bloody diarrhoea, and its infection is always correlated with beef products (Haas et al., 2000), drinking water and recreational waters (Jain et al., 2003).
Campylobacter jejuni	*Campylobacter jejuni* is ranked the second to pose health risk by waterborne pathway after *Cryptosporidium parvum*. It is found in the intestinal tracks of healthy cattle and is the most common cause of bacterial gastroenteritis in Australia (Jain et al., 2003). *Campylobacter* is known to cause acute diarrhoea lasting for two to three days.
Cryptosporidium parvum	Cryptosporidium parvum poses the highest risk to human health. It is found in gastrointestinal contentment of cattle. Human infection is mainly caused by ingestion of contaminated water. It is ranked the highest risk waterborne pathogen to human in developed countries, due to its resistance to chlorination, and reasonably high infection rate

	(Teunis et al., 2002).
Rotavirus	Viral pathogens were not included in the six pathogens originally investigated due to viral pathogens in animals being considered unlikely to pose a significant health risk to humans, however, Rotavirus has caused viral gastroenteritis worldwide with a relatively high infectivity compared with other waterborne viruses and its high resistance to conventional wastewater treatment processes (Ruggeri et al., 2015). Rotavirus, commonly found in young calves, can also be transmitted through the faecal-oral route and directly from person to person. Furthermore, in accordance with the AGWR's guideline of considering a comprehensive range of hazards, Rotavirus was also selected as a reference pathogen to represent viral hazards.

5.3.1.2 Concentration of Reference Pathogens

As previously observed from MS1, meat processors did not segregate their wastewater streams and combined all waste streams together for comingled wastewater treatment prior to irrigation or trade waste discharge. This meant that abattoirs were only able to monitor the final effluent water quality, therefore, resulting in limited information on water quality and concentration of pathogens present in individual waste streams.

For the QRMA, concentration of the reference pathogens in the selected waste streams were estimated from values obtained from previous studies and other published literature sources (**Table 5-20**). The microbial concentrations were subsequently normalised based on the waste stream's flow against the combined wastewater volume. The concentration of *Escherichia coli* and *Cryptosporidium parvum* in kill floor wastewater were adapted from the normalised 95th percentile concentration of each pathogen in the combined wastewater prior to wastewater treatment (Pither, 2017). Of the six wastewater streams considered for reuse/recycling (stockyard wash, boning room, side chiller wash, boiler wash, rendering condensates, and kill floor waste), only wastewater from the boiler wash and rendering condensates were deemed to have a negligible microbial pathogen concentration given that the boiler wash stream does not come into contact with carcass and that the temperature of the rendering condensates is above 100 ^{o}C (Jain et al., 2003). For the waste streams from the stockyard wash, boning room, and side chiller wash, only *Escherichia coli* was detected (FSANZ, 2013).

Given that no specific concentration data was found for *Campylobacter jejuni* and *Rotavirus*, the concentrations of these two reference pathogens were sourced from municipal wastewater. This follows the risk maximisation principle and yields a more conservative estimate given that the pathogen concentrations from municipal wastewater are higher than what is expected in the kill floor wastewater (NRMMC, 2006).

Table 5-20: Concentrations of Selected Reference Pathogens

Reference	Stockyard Wash	Boning Room	Side Chiller Wash	Kill Floor

pathogens				
***Escherichia coli* (CFU/L)**	14.8	10.6	2.5	59.5
***Cryptosporidium parvum* (Oocysts/L)**	N/A	N/A	N/A	500
***Campylobacter jejuni* (CFU/L)**	N/A	N/A	N/A	7000
Rotavirus **(PFU/L)**	N/A	N/A	N/A	8000

5.3.1.3 Pathogen Dose and Exposure

In order to calculate the microbial risk of each water reuse/recycling option, the pathogen dose, exposure volumes, and frequencies need to be established. The exposure volumes and frequencies associated with the different reuse/recycling activities were estimated and adapted from the AGWR, which provides exposure volumes and frequency values for end-uses such as crop irrigation, municipal landscaping, and other urban uses with uncontrolled access. Further justification for exposure volume and frequencies are shown in **Table 5-21** below.

Table 5-21: Estimated Exposure Volumes and Frequencies Associated with Different End-uses

Comparable exposures abattoir (Activity)	Exposure Volume (L)	Frequency (Events/year)	Estimation Basis
Direct Reuse			
Stockyard washing	0.001	240	The exposure of stockyard wash, cattle drinking water was adapted from that of municipal irrigation from AGWR, because people were not likely to have large amount of direct exposure to the spray (Pither, 2017).
Class A Non-Potable Water Recycling			
Truck washing	0.068	240	The volume of ingestion of spray aerosols generated from 10 minutes of car wash was estimated to be 0.004L (Sinclair et al., 2016). Therefore, assuming abattoir personnel spend three hours a day and solely on truck wash, a conservative estimation of exposure was 0.068L.
Stockyard washing	0.001	240	As per AGWR (NRMMC, 2006)
Cattle drinking water	0.001	240	

Fire control	0.020	50	
Cooling systems	0.001	240	
Boiler systems	0.001	240	
Steam production	0.001	240	
Cleaning in place	0.020	240	
Cross-connection of recycled water systems with drinking water mains	1.000	0.365	Accidental direct ingestion occurs when there is a cross-connection of recycled water systems with drinking water mains and was estimated to have a 0.1% likelihood (NRMMC, 2006), therefore, its exposure volume was estimated as 1 L of cold, unboiled drinking water (WHO, 2012) with a frequency of 0.365.
Potable Water Recycling			
Potable drinking water	1.000	365	Similarly, it was estimated that daily human consumption was 2 L per day with 1 L consumed cold and unboiled (WHO, 2012)

5.3.1.4 Microbial Risk and Minimum Treatment Train LRV Quantification

With the pathogen concentrations, exposure volumes, and event frequencies established, the microbial risk was quantified and the subsequent required LRV for each reference pathogen was calculated. Utilising the AGWR established DALYd for *Campylobacter jejuni*, *Cryptosporidium parvum,* and *Rotavirus,* the pathogen dose associated with each reuse/recycling option's activities were calculated (NRMMC, 2006). DALYd for *Escherichia coli* was back-calculated from the dose-response model shown in Section 4.1.3.

Of the four LRVs calculated for reference pathogen and its associated abattoir activity, the highest LRV determines the minimum LRV the proposed treatment train is required to achieve to mitigate all the microbial risks established by the QRMA. **Table 5-22** shows the minimum LRV values required by the treatment train to achieve for each reuse/recycling option.

Table 5-22: Minimum LRV Required for Mitigation of Microbial Risks

	Escherichia coli		***Campylobacter jejuni***		***Cryptosporidium parvum***		***Rotavirus***	
DALYd	0.0838		0.037		0.016		0.0025	
Abattoir Activity	**Dose (CFU)**	**LRV**	**Dose (CFU)**	**LRV**	**Dose (oocysts)**	**LRV**	**Dose (PFU)**	**LRV**
Direct Reuse								
Stockyard washing	3.1	**2**	N/A	-	N/A	-	N/A	-
Non-potable Class A Water								

Truck washing	971	**5**	114240	**7**	8160	**6**	130560	**8**
Stockyard washing	14	**3**	1680	**5**	120	**4**	1920	**6**
Cattle drinking water	14	**3**	1680	**5**	120	**4**	1920	**6**
Fire control	60	**3**	7000	**6**	500	**5**	8000	**7**
Cooling systems	14	**3**	1680	**5**	120	**4**	1920	**6**
Boiler systems	14	**3**	1680	**5**	120	**4**	1920	**6**
Stream production	14	**3**	1680	**5**	120	**4**	1920	**6**
Cleaning in place systems	286	**4**	33600	**6**	2400	**6**	38400	**8**
Cross-connection of recycled water systems	22	**3**	2555	**5**	182.5	**5**	2920	**7**
Potable Drinking Water								
Potable drinking water	2.66E9	**11**	2.56E6	**8**	7.30E5	**8**	2.92E6	**10**

5.3.2 Selection of Treatment Trains

5.3.2.1 Treatment Train for Direct Reuse

The combined waste streams from the boning room, side chiller wash, and boiler ash wash were suitable for direct reuse as stockyard wash down water given the low chemical contaminant and microbial loads in three streams. However, as the boiler ash wash waste stream contained a moderate amount of Total Suspended Solids (TSS), a filter screen is required to remove most of the suspended solids before chlorination can be performed. Therefore, the proposed treatment train for direct reuse consisted of a static screen followed by disinfection via chlorination (Figure 5-5).

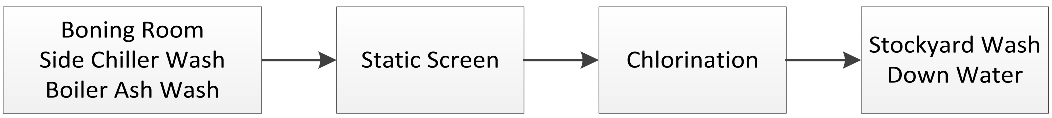

Figure 5-5: Treatment Train for Direct Reuse as Stockyard Wash Down Water

Direct reuse as stockyard wash down water is considered a low-risk option, therefore, the treatment train was required to achieve a minimum 2 Log-removal and maintain the stipulated residual chlorine concentration of 0.2-2.0 mg/L (WA Health, 2011).

Table 5-23: Indicative LRV of Proposed Direct Reuse Treatment Train

Direct Reuse Option	
	Escherichia coli
Static screen	0 - 0.5
Chlorination	2.0 - 6.0
Treatment Train LRV Total	**2.0 - 6.5**
Required Minimum LRV	**2.0**

From the indicative LRV calculated, it is clear that the proposed direct reuse treatment train was able to achieve a LRV of 2.0 to 6.5 (NRMMC, 2006) which met the required LRV of 2.0 for direct reuse as long as the residual chlorine concentration was monitored and maintained at 0.2 – 2.0 mg/L.

5.3.2.2 Treatment Train for Non-potable Class A Water Production

From MS2, it was observed that meat processors could only use non-potable water in three abattoir processes: plant services (989 L/t.HSCW), amenities (196 L/t.HSCW), and antemortem area (wash down) (1296 L/t.HSCW) used a total of 2481 L/t.HSCW. Non-potable water cannot be used in any other process, therefore, it would be economically unfeasible to produce it in excess, and hence, only the kill floor waste stream succinctly met the non-potable water consumption requirements.

Conventional end-of-pipe wastewater treatment utilised by abattoirs typically consists of primary treatment to reduce the TSS concentration followed by Oil and Grease (O&G) removal prior to the secondary biological nutrient removal process (Warnecke et al., 2008). However, given that the O&G concentration in the kill floor wastewater stream was low, the treatment trains for non-potable Class A water production did not require an O&G pre-treatment process. A total of three non-potable Class A treatment trains, ranging from a train consisting of conventional treatment processes to one utilising well-established, high efficiency processes, were proposed.

Non-potable Treatment Train 1

Figure 5-6: Treatment Train 1 for Non-potable Class A Water Production

Due to the significantly high concentration of nutrients present in the kill floor wastewater, a biological nutrient removal process needs to be utilised to reduce the Total Phosphorous and Nitrogen loads to the non-potable Class A water quality requirements. Therefore, an activated sludge process was selected given that it was the most conventional nutrient removal technique used in wastewater treatment (Sampson et al., 2005). With the nutrients removed sufficiently, the residual solids in the secondary effluent were then removed via coagulation and media filtration. For this treatment train, two disinfection steps had to be performed due to the high LRV requirements of *Campylobacter jejuni*, *Cryptosporidium parvum,* and *Rotavirus.*

Table 5-24: Indicative LRV of Proposed Non-potable Treatment Train 1

Non-potable Treatment Train 1				
	Escherichia coli	*Campylobacter jejuni*	*Cryptosporidium parvum*	*Rotavirus*
Static screen	0 - 0.5	0 - 0.5	0 - 0.5	0 - 0.1
Activated Sludge	1.0 - 3.0	1.0 - 3.0	0.5 - 1.0	0.5 - 2.0
Coagulation and media filtration	0 - 1.0	0 - 1.0	1.5 - 2.5	0.5 – 3.0
Chlorination	2.0 - 6.0	2.0 - 6.0	0 - 0.5	1.0 - 3.0
UV light	2.0 - 6.0	2.0 - 6.0	>3.0	>1.0
Treatment Train LRV Total	**5.0 - 15.5**	**5.0 - 15.5**	**4.5 - >7.5**	**3.0 - >9.1**
Required Minimum LRV	**5.0**	**7.0**	**6.0**	**8.0**

Non-potable Treatment Train 2

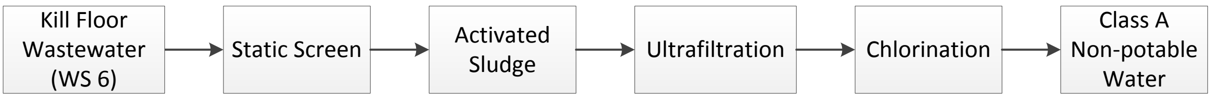

Figure 5-7: Treatment Train 2 for Non-potable Class A Water Production

Non-potable Treatment Train 2 use Ultrafiltration (UF) to replace the conventional coagulation and media filtration process of treatment train 1. The UF membrane process not only has a better pathogen removal efficiency (NRMMC, 2006) and a smaller process footprint, but it also eliminated the operational costs associated with chemical coagulant dosing and the need for double disinfection with cost-effective chlorination being the only process necessary to achieve the minimum required LRV (Table 5-25).

Table 5-25: Indicative LRV of Proposed Non-potable Treatment Train 2

Non-potable Treatment Train 2				
	Escherichia coli	*Campylobacter jejuni*	*Cryptosporidium parvum*	*Rotavirus*
Static screen	0 - 0.5	0 - 0.5	0 - 0.5	0 - 0.1
Activated Sludge	1.0 - 3.0	1.0 - 3.0	0.5 - 1.0	0.5 - 2.0
Ultrafiltration Membrane	3.5 - >6.0	3.5 - >6.0	>6.0	2.5 - >6.0
Chlorination	2.0 - 6.0	2.0 - 6.0	0 - 0.5	1.0 - 3.0
Treatment Train LRV Total	**6.5 - >15.5**	**6.5 - >15.5**	**6.5 - >8.0**	**4.0 - >11.1**
Required Minimum LRV	**5.0**	**7.0**	**6.0**	**8.0**

Non-potable Treatment Train 3

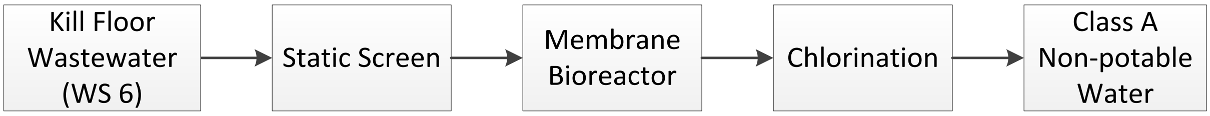

Figure 5-8: Treatment Train 3 for Non-potable Class A Water Production

A Membrane Bioreactor (MBR) treatment train was proposed to further reduce the footprint, performance consistency, and CAPEX/OPEX. This replaced the activated sludge and membrane filtration process and combined nutrient and residuals solids removal into one process.

Table 5-26: Indicative LRV of Proposed Non-potable Treatment Train 3

Non-potable Treatment Train 3				
	Escherichia coli	*Campylobacter jejuni*	*Cryptosporidium parvum*	*Rotavirus*
Static screen	0 - 0.5	0 - 0.5	0 - 0.5	0 - 0.1
Membrane Bioreactor	3.5 - >6.0	3.5 - >6.0	>6.0	2.5 - >6.0
Chlorination	2.0 - 6.0	2.0 - 6.0	0 - 0.5	1.0 - 3.0
Treatment Train LRV Total	**5.5 - 12.5**	**5.5 - >12.5**	**6.0 - >7.0**	**3.5 - >9.1**
Required Minimum LRV	**5.0**	**7.0**	**6.0**	**8.0**

From the calculated LRVs of the three proposed treatment trains, it was clear that all trains can achieve the minimum LRV required for mitigation of the microbial risks whilst treating the chemical contaminants to the required effluent water quality. As each treatment train has its advantages and disadvantages, a MCA was conducted to select the most appropriate treatment train for non-potable Class A water production. The SWOT analysis of each proposed treatment train can be found in Appendix A.

5.3.3 MCA of Non-Potable Class A Treatment Trains

The criteria of process maturity, complexity, stability, capital expenditure, operational expenditure, process equipment footprint, and environmental impacts were evaluated for each technology with the weighting of each criterion determined via a pairwise comparison. Based on the initial SWOT analysis, scores were assigned to the criterion for each non-potable treatment train. Additional justifications and weighting percentage calculation for each MCA criterion can be found in Appendix D.

Table 5-27: Criterion and MCA Scores for Each Non-potable Treatment Trains

	Process Maturity	Process Complexity	Process Stability	CAPEX	OPEX	Process Footprint	Environ. Impacts	Total Score
Weighting Percentage (%)	32.2	6.4	12.8	20.6	20.6	3.1	4.3	
Treatment Train 1	4	1	1	4	4	1	1	**5.2**
Treatment Train 2	5	3	4	3	2	3	3	**7.4**
Treatment Train 3	4	5	5	2	3	5	4	**9.0**

Treatment train 3 out-scored the other two trains on four of the seven criteria with Train 3 scoring high on process complexity, stability, footprint, and environmental impacts. Adoption of membrane technologies resulted in Train 3 scoring lower on CAPEX and OPEX, however, when taking into account all criteria, the MCA confirmed that Train 3 was the most ideal for non-potable Class A water production.

5.3.4 Treatment Process Train for Potable Water Production

In order to produce water for direct potable recycling, an additional Reverse Osmosis (RO) treatment process is used to remove dissolved ions and pathogens (**Figure 5-9**). Subsequently, chlorine disinfection is used to effectively and rapidly disinfect pathogens in the final treated water. RO technology was selected over alternative dissolved ion removal technologies, such as Electrodialysis Reversal (EDR), due to its superior pathogen removal efficiency.

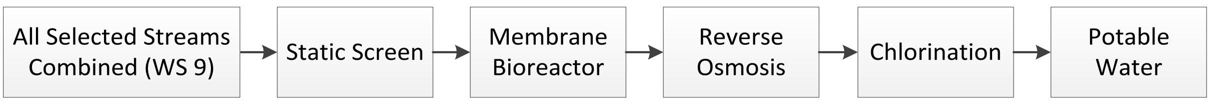

Figure 5-9: Treatment Train for Potable Water Production

Table 5-28: Indicative LRV of Proposed Potable Water Treatment Train

	Potable Water Treatment Train			
	Escherichia coli	*Campylobacter jejuni*	*Cryptosporidium parvum*	*Rotavirus*
Static screen	0 - 0.5	0 - 0.5	0 - 0.5	0 - 0.1
Membrane Bioreactor	3.5 - >6.0	3.5 - >6.0	>6.0	2.5 - >6.0
Reverse Osmosis	>6.0	>6.0	>6.0	>6.0
Chlorination	2.0 - 6.0	2.0 - 6.0	0 - 0.5	1.0 - 3.0
Treatment Train LRV Total	**11.5 - >18.5**	**11.5 - >18.5**	**12.0 - >13.0**	**9.5 - >15.1**
Required Minimum LRV	**11.0**	**8.0**	**8.0**	**10.0**

5.3.5 Process Modelling of Selected Reuse/Recycling Options

With the appropriate treatment trains established, the selected non-potable Class A treatment train 3 was modelled using the EnviroSim BioWin software to determine the required operating parameters that ensure that the effluent quality met Class A standards.

Similarly, for the potable water recycling option, a BioWin model was first used to model the biological nutrient removal processes with the DuPont WAVE software subsequently used to simulate and determine the optimal RO design and associated dissolved salt removal efficiency.

5.3.5.1 Non-potable Class A Treatment Train Base Case Model

By assuming abattoir meat production of 300 t.HSCW/day, AO-MBR process with kill floor wastewater as influent was required to treat 755 m^3 of wastewater per day. The MBR zone sizes were adjusted proportionally to the flow rate of influent wastewater. The volume of the anoxic zone, aerobic zone, and MBR tank were reduced to 205 m^3, 485 m^3, and 107 m^3, respectively, with the sludge production rate decreased to 36.3 m^3/day. The COD fractions are summarised in **Table 5-29**.

Table 5-29: COD Fractions of Non-potable Class A Influent

COD Fractions	Proportion
Readily Biodegradable Soluble COD (F_{BS})	0.1700
Slowly Biodegradable COD (F_{XSP})	0.6906
Unbiodegradable Soluble COD (F_{US})	0.0535
Unbiodegradable Particulate COD (F_{UP})	0.1153

Modelling results of the Non-potable Class A base case model showed that the Train 3 produced 719 m^3/day of effluent also meeting non-potable Class A standards of BOD, TN, TP, and TSS at <5.0 mg/L, <5.0 mg/L, <0.5 mg/L, and <1.0 mg/L, respectively. The modelled MBR achieved an effective removal efficiency of 98% for total nitrogen, 99% for total phosphorous, and >99% removal for suspended solids and Biological Oxygen Demand (BOD).

Table 5-30: Non-potable Class A Influent and Effluent Water Quality

Water Quality Parameters	MBR Influent	MBR Effluent
Liquid Volume (m^3)	755	719
COD (mg/L)	6819	370
BOD (mg/L)	3397	0.9*
Total Suspended Solids (mg/L)	2974	<0.1*
Total Volatile Solids (mg/L)	2472	<0.1
Total Nitrogen (mg/L)	276	4.3*
Total Kjeldahl Nitrogen (mg/L)	149	4.1
Ammonia (mg/L)	14	0.5
Nitrate (mg/L)	127	0.1
Total Phosphorous (mg/L)	42	0.2*
Total Sulphate (mg/L)	10	10
Sodium (mg/L)	49	49

Calcium (mg/L)	43	55
Magnesium (mg/L)	12	8.4

* Water quality parameters monitored for Class A non-potable water

5.3.5.1.1 Non-potable Class A Optimised Model

With the base case model effectively removing the required nutrients and suspended solids, optimisation was conducted to reduce the MBR's footprint and energy consumption. Given that the optimisation of RR, HRT, and SRT had no significant impact on the concentration of TSS, TN, and BOD, these concentrations were not reported. As the phosphate accumulating process mainly occurred in the aerobic zone, the concentration of phosphate after the aerobic zone was monitored to determine the conditions which led to a phosphate deficiency in the modelled MBR with the effluent's TP and specific energy consumption being the main parameters that were monitored for optimisation. The volume of the membrane zone could not be reduced given that a fixed number of membranes were required to treat the 755 m^3/day influent volume.

Recycle Ratio Optimisation

The RR was conducted with the volume of anoxic, aerobic, membrane zone, and sludge production rate maintained at 205 m^3, 485 m^3, 107 m^3, and 36.3 m^3/day, respectively. A range of RRs, from 325% to 600%, was considered to determine the optimal RR for MBR operation.

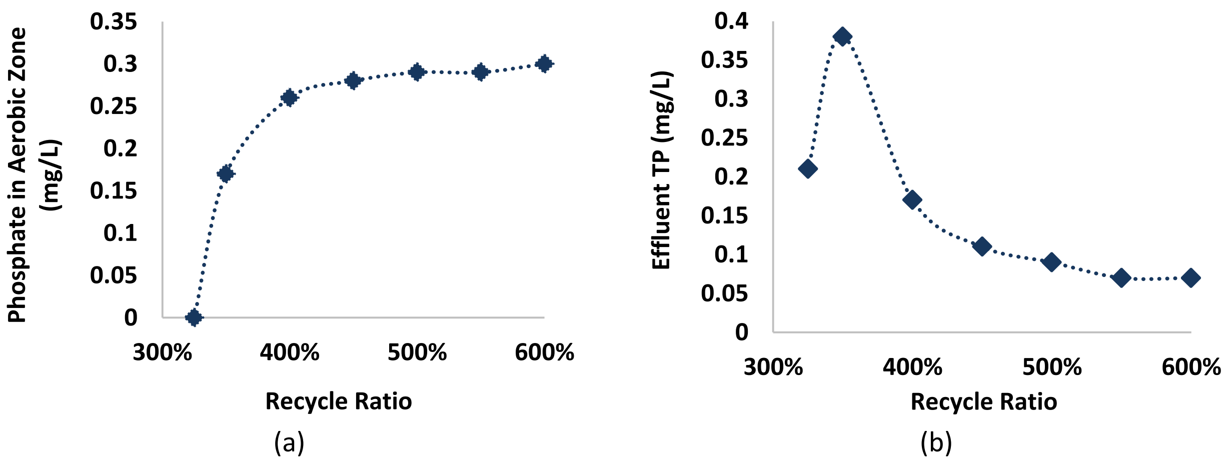

Figure 5-10: Effect of Changing Recycle Ratio on (a) Phosphate Concentration in Aerobic Zone and (b) Effluent's TP Concentration

From **Figure 5-10**(a), it can be seen that increasing RR over 450% had a minimal impact on the phosphate concentration in the aerobic zone with the concentration of phosphate increasing from 0.28 to 0.30 mg/L. However, decreasing the RR below 400% resulted in a drop in phosphate concentration from 0.25 to 0 mg/L which caused the MBR to have poor nitrogen removal. It was also observed that varying RR did not affect phosphorous removal with the TP concentration always kept below 0.5 mg/L (**Figure 5-10**(b)). Whilst increasing the RR would yield a slightly higher phosphorous removal, operating at higher RRs would increase the energy consumption required to recycle sludge from the membrane zone to the anoxic zone. Therefore, a RR of 450% was deemed to be optimal as not only was the TP concentration in the effluent maintained at 0.11 mg/L, but the phosphate concentration in the aerobic zone was also 0.28 mg/L, preventing the occurrence of phosphate deficiencies in the MBR.

Anoxic Zone Hydraulic Retention Time Optimisation

Optimisation of the anoxic zone's HRT was performed by keeping the RR at 450% and other parameters constant. The anoxic zone's HRT was decreased from 1.18 to 0.12 hrs reducing the anoxic zone's volume and the MBR's overall footprint. Reducing the HRT did not affect the concentration of phosphates in the aerobic zone and the TN in the effluent, therefore, the only metric used to determine the optimal anoxic HRT was the TP concentration of the effluent.

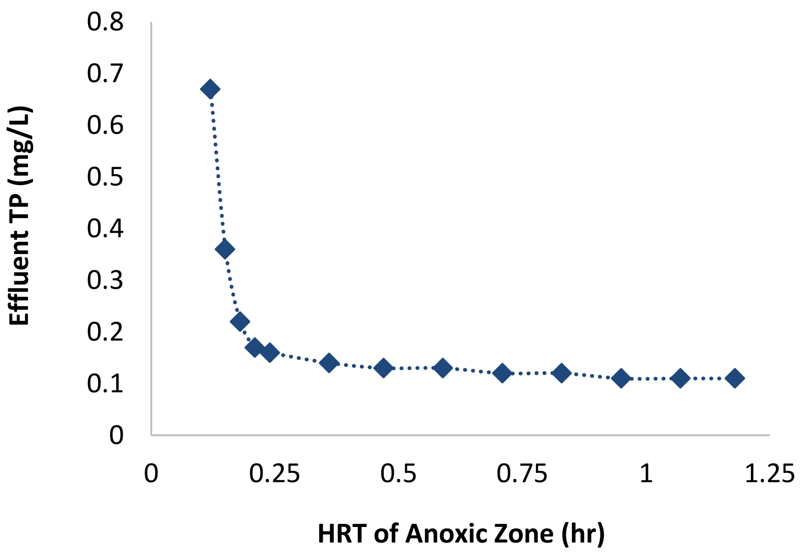

Figure 5-11: Effect of Changing HRT of Anoxic Zone on Effluent's TP Concentration

From **Figure 5-11**, the optimal HRT for the anoxic zone was determined to be 0.21 hrs with the TP in the effluent at 0.17 mg/L, which was well below the Class A limit of 0.5 mg/L. Whilst the HRT could be further decreased to 0.15 hrs producing effluent of TP at 0.34 mg/L, the MBR would be operating too close to the 0.5 mg/L upper limit and might not be able to cope with sudden unexpected variations in influent quality. Furthermore, at such low HRTs, controlling of the anoxic zone's HRT would be complicated and more at risk of producing non-compliant water should the HRT drop below the 0.15 hours. Reducing the anoxic zone's HRT to 0.21 hours translated to a 82% reduction in zone volume from 205 to 36.9 m^3, significantly reducing the MBR's overall footprint.

Aerobic Zone Hydraulic Retention Time Optimisation

The aerobic zone's HRT was optimised via the same method with the HRT adjusted whilst monitoring the phosphate concentration in the aerobic zone as the TP and TN were not significantly affected by changes in aerobic zone's HRT unless a phosphate deficiency occurs resulting in an increase in TN concentration. As such, the aerobic zone's HRT was reduced from the base case's 2.8 hours.

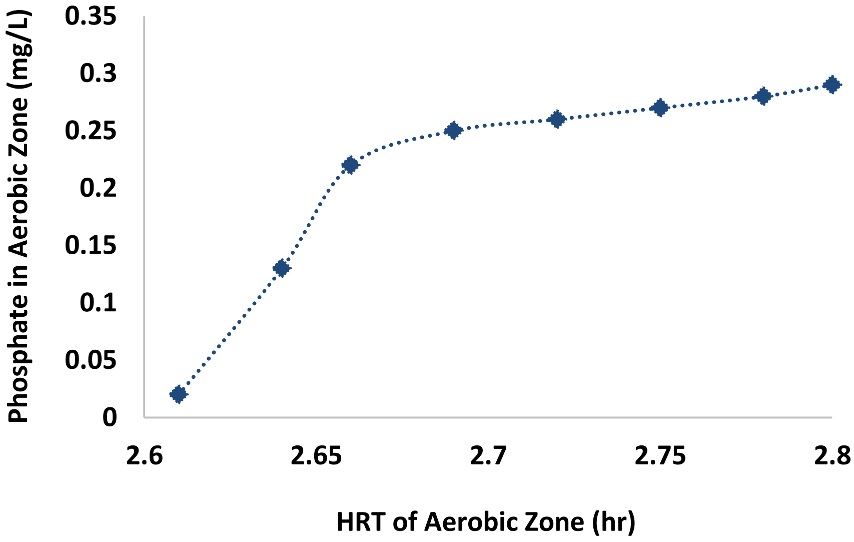

Figure 5-12: Effect of Changing HRT of Aerobic Zone on Phosphate Concentration

Optimisation of the aerobic zone's HRT showed that 2.69 hours was the optimal HRT for the aerobic zone to avoid the system from becoming phosphate deficient. The HRT of the aerobic zone could not be further optimised with the 0.11 hour decrease reducing the aerobic zone's volume from 485 to 466 m^3.

MBR's Solid Retention Time Optimisation

With the optimal HRT of the anoxic and aerobic zones, the SRT of the MBR could be optimised. Increasing the SRT resulted in a reduction in sludge production rate which, in turn, reduced the amount of sludge that has to be periodically disposed.

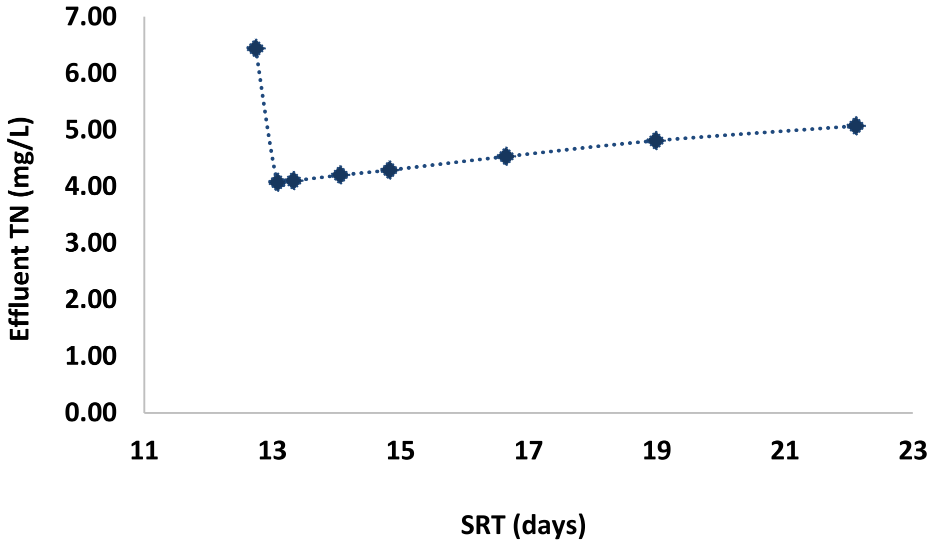

Figure 5-13: Effect of Changing MBR SRT on Effluent's TN Concentration

From **Figure 5-13**, it can be seen that no phosphate deficiencies occurred if the SRT was maintained above 13.1 days with a deficiency only occurring when the SRT was reduced to 12.7 days resulting in a high TN concentration of 6.44 mg/L. However, given that the aim of the SRT optimisation was to identify the maximum SRT at which the MBR could operate at, the SRT was increased till the TN concentrations approached the 5.0 mg/L limit. Optimisation showed that the MBR could be operated at a maximum SRT of 19.0 days where the TN concentration in the effluent reached 4.81 mg/L. Increasing the SRT from the base case's 13.3 days to the optimised model's 19.0 days resulted in a reduction in sludge production rate from 36.3 to 25.4 m^3/day.

Comparison of Optimised and Base Non-potable Class A Models

Table 5-31: Summary of Non-potable Class A MBR Optimisation Results

	Base Case Model	Optimised Model
BOD (mg/L)	0.88	0.83
Total Nitrogen (mg/L)	4.24	4.48
Total Phosphorous (mg/L)	0.32	0.08
Total Suspended Solids (mg/L)	<0.10	<0.10
Recycle Ratio	400%	450%
Volume of Anoxic Zone (m^3)	205	36.9
Volume of Aerobic Zone (m^3)	485	466
Volume of Membrane Zone (m^3)	107	107
Sludge Production Rate (m^3/day)	36.3	25.4
Specific Energy Consumption (kWh/m^3)	0.25	0.15

Comparing the base case and the optimised model, it is clear that both models produced effluent that met the non-potable Class A standards. However, by slightly increasing the RR and reducing the volumes of the anoxic and aerobic zones, as well as reducing the sludge production rate, the optimised MBR was able to produce 719 m^3/day of non-potable Class A water at a 40% lower specific energy consumption rate (0.25 to 0.15 kWh/m^3) whilst being 23% smaller (797 to 610 m^3).

5.3.5.2 Potable Water Treatment Train

To produce treated water that can be used in any abattoir process and to achieve more significant water savings, potable water recycling using Waste Stream 9 (WS9) as the source water was considered. WS9 was the combined stream of all six waste streams (stockyard wash, boning room, side chiller wash, boiler wash, rendering condensates, and kill floor) and accounted for 4028 L/t.HSCW of wastewater produced. Assuming an abattoir production of 300 t.HSCW/day, the six waste streams produce a total of 1208 m^3/day of wastewater.

Following the same optimisation method for the biological nutrient removal of the non-potable Class A treatment train, a MBR treating the combined waste stream was simulated. BioWin modelling results concluded that the optimised MBR was able to effectively remove BOD, TSS, TN, and TP (Table 5-32) producing 1162 m^3/day of water that could be further treated by the RO system to produce potable water. The optimised MBR was also 21% smaller (1211 to 955 m^3) and more energy efficient with a 41% lower specific energy consumption (0.17 to 0.10 kWh/m^3) (

Table **5-33**).

Table 5-32: Potable Water Treatment Train's Optimised MBR Influent and Effluent Water Qualities

Water Quality Parameters	MBR Influent	MBR Effluent
Liquid Volume (m^3)	1208	1162
COD (mg/L)	4766	303
BOD (mg/L)	2311	0.82
Total Suspended Solids (mg/L)	2544	<0.10
Total Volatile Solids (mg/L)	2055	<0.10
Total Nitrogen (mg/L)	251	3.61
Total Kjeldahl Nitrogen (mg/L)	123	3.48
Ammonia (mg/L)	34.5	0.24
Nitrite (mg/L)	0	0.05
Nitrate (mg/L)	128	0.83
Total Phosphorous (mg/L)	30.0	0.09
Total Sulphate (mg/L)	8.50	9.98
Sodium (mg/L)	52.0	52.0
Calcium (mg/L)	27.0	35.0
Magnesium (mg/L)	13.0	10.3

Table 5-33: Optimised MBR Design for Potable Water Treatment Train

	Base Case Model	Optimised Model
Recycle Ratio	400%	300%
Volume of Anoxic Zone (m^3)	328	118
Volume of Aerobic Zone (m^3)	776	730
Volume of Membrane Zone (m^3)	107	107

Sludge Production Rate (m^3/day)	58	41
Specific Energy Consumption (kWh/m^3)	0.17	0.10

Given that the MBR did not remove the dissolved salts present in the combined wastewater, the effluent from the MBR was further treated via a RO system to remove all dissolved salts and to meet the minimum LRV values for potable water production.

5.3.5.2.1 Reverse Osmosis System Design

The design objective was to identify the optimal RO system configuration and operational conditions. The RO net water recovery and the specific energy per cubic metre of water produced were the metrics of feasibility. From the BioWin modelled quality data of the MBR effluent, the Total Dissolved Solids (TDS), based of concentration of cations and anions, was calculated as 301 mg/L with an estimated conductivity of 598 µS/cm.

With the defined feed water characteristics, a single pass, one-stage RO system configuration was used to determine the maximum recovery that can be achieved with the lowest number of membrane elements/pressure vessels (Base Case). Given the high volume of wastewater to be treated, the membrane selected for the RO system was the FilmTec XLE-440, which is ideal for producing high-quality permeate at low energy costs. The XLE-440 has a typical salt rejection of 99.0% (97.0% minimum) and is capable of producing 53 m^3/day of permeate from its 41 m^2 membrane surface area. Simulations were performed at a design temperature of 25 °C and pH of 7.0. With the base case established, modifications were made to increase RO water recovery yielding 3 additional RO system designs.

RO System Design 1: Single Stage RO

Results from the base case model stated that the maximum recovery achievable with a minimum of 32 XLE-440 elements (4 pressure vessel, 8 elements per vessel configuration) was 69%, translating to a total of 802 m^3/day of water recovered with a specific energy consumption of 0.29 kWh/m^3 (**Figure 5-14**). The flow rates, TDS concentrations, and pressures of the various streams are tabulated in **Table 5-34** with full RO system design report in Appendix B.

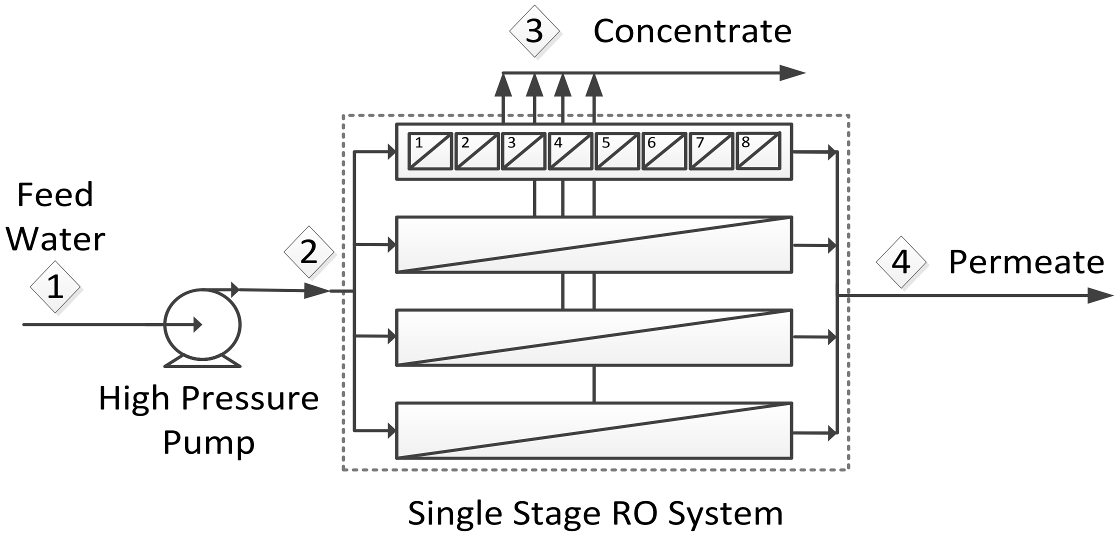

Figure 5-14: 8-Element, 4 Pressure Vessel RO System Design 1

Table 5-34: RO System Design 1 Parameters Overview

RO System Parameters	Design 1 – Single Pass, One-stage
Design temperature (°C)	25.0
pH	7.00
Number of membrane elements	32
Total membrane area (m^2)	1308
Stream 1 – Feed Water	
Feed flow rate (m^3/day)	1162
Feed TDS (mg/L)	301
Stream 2 – Feed Water after Pump	
Feed pressure (bar)	5.71
Stream 3 – Concentrate	
Concentrate flow rate (m^3/day)	360
Concentrate TDS (mg/L)	942
Concentration factor	3.23
Stream 4 - Permeate	
Permeate flow rate (m^3/day)	802
Average flux (LMH)	26.5
Permeate TDS (mg/L)	12.6
RO system recovery (%)	69.0
Specific energy consumption (kWh/m^3)	0.29

With the base case achieving a 69% recovery in a 4 pressure vessel, 8-element configuration, alternative system designs were considered to maximise the overall recovery. There are multiple techniques that allow for RO recovery to be increased but each technique has its own advantages and disadvantages. Recovery can be increased through concentrate recirculation, concentrate staging, flow distribution, and permeate staging, however, only concentrate recirculation and concentrate staging were considered as flow distribution and permeate staging are mainly used for systems that cannot achieve sufficient dissolved ion removal in high salinity applications such as desalination of seawater or brackish water.

RO System Design 2: Single Stage RO with Concentration Recirculation

Concentrate recirculation is commonly used when the number of membrane elements is too small to achieve the target system recovery in a single stage RO system. Concentrate recirculation involves diverting a fraction of the concentrate stream back to the feed for mixing with the incoming feed before being treated through the RO stage (Figure 5-15). An advantage of recirculating the concentrate stream is that water recovery is increased whilst maintaining the footprint of the RO system and foregoing the CAPEX for an extra RO stage. However, the disadvantage of this configuration is that it needs a larger feed pump to handle higher feed flow associated with the recirculation.

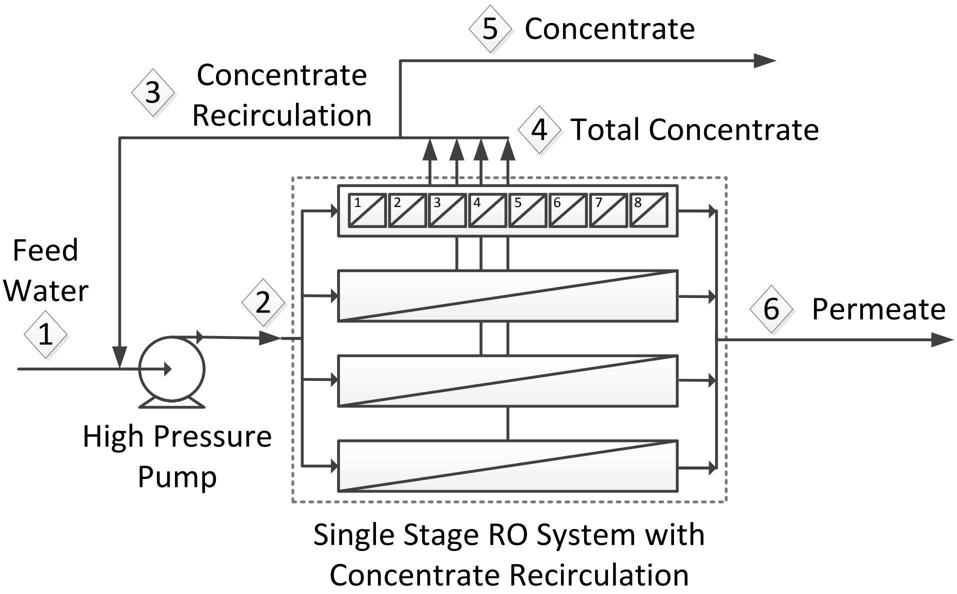

Figure 5-15: RO System Design 2 with Concentrate Recirculation

A sensitivity analysis was conducted to identify the optimal concentrate recirculation percentage for maximum water recovery and compare their associated energy consumptions. **Figure 5-16** shows the various achievable recoveries at their corresponding concentrate recirculation percentages and specific energy consumptions.

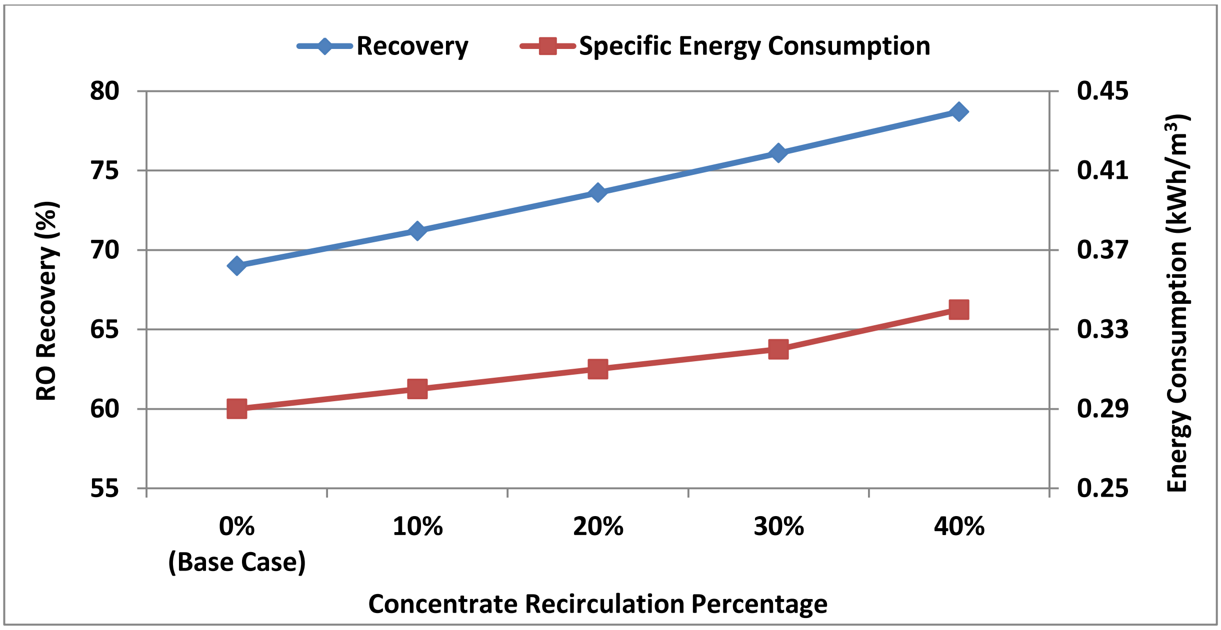

Figure 5-16: RO Recovery and Specific Energy Consumption at Varying Concentration Recirculation Percentages for Single Stage RO System

Results from the sensitivity analysis suggest that recirculating 40% of the concentrate stream back to the RO system increased recovery from 69.0% to 78.7% with insignificant changes in the permeate's TDS, increasing from 12.6 mg/L to 15.6 mg/L at the respective recoveries. This resulted in an additional 113 m^3 of potable water recovered per day, however, it increased the specific energy consumption by 0.05 kWh/m^3 reaching a total value of 0.34 kWh/m^3. From the survey responses of MS1, which stated that the cost of potable water ranged from as low as \$1.46/m^3 to as high as \$4.50/m^3 while the cost of electricity ranged from \$0.007/kWh to \$0.235/kWh, it is clear that the cost-savings of the increased water recovery would outweigh the increase in energy consumption given the relatively low cost of energy compared to that of potable water.

Table 5-35 shows the parameters of the optimised one-stage RO system with optimum 40% concentration recirculation. Design simulation reports for all other recirculation percentages can be found in Appendix B.

Table 5-35: RO Design 2 System Parameters Overview

RO System Parameters	Optimised Design 2 – 40% Conc. Recirculation
Design temperature (°C)	25.0
pH	7.00
Number of membrane elements	32
Total membrane area (m^2)	1308
Stream 1 – Feed Water	
Feed flow rate (m^3/day)	1162
Feed TDS (mg/L)	301
Stream 2 – Feed Water after Concentrate Recirculation	
Net feed flow rate (m^3/day)	1326
Feed pressure (bar)	6.74

Feed TDS with concentrate recirculation (mg/L)	432
Stream 3 – Concentrate Recirculated	
Concentrate recycle rate (m^3/day)	165
Stream 4 – Total Concentrate	
Total Concentrate flow rate (m^3/day)	411
Stream 5 – Concentrate after Recirculation	
Concentrate flow rate (m^3/day)	246
Concentrate TDS (mg/L)	1357
Concentration factor	4.69
Stream 6 – Permeate	
Permeate flow rate (m^3/day)	915
Average flux (LMH)	29.2
Permeate TDS (mg/L)	15.6
RO system recovery (%)	78.7
Specific energy consumption (kWh/m^3)	0.34

RO System Design 3: Two-Stage RO System with Concentration Staging

Another alternative to concentrate recirculation is concentrate staging where an additional RO stage is introduced to the RO system. Staging involves using the concentrate stream from the first stage as feed in the second stage in order to achieve a higher net overall water recovery. It is not uncommon in some applications to use up to three RO stages with a tapered number of pressure vessels in each stage to maintain similar feed and concentrate flow rates between each stage's pressure vessels as well as to ensure that the flow rates stay within the specified limits of the selected membrane type. Tapering is critical to avoid excessively high flows to lead vessels, resulting in high pressure drops, or low flows to tail vessels, resulting in insufficient turbulence to prevent scale formation.

In order to compare Design 2 and Design 3, the water recovery was maintained at 78.7% to determine the minimum number of extra RO membranes required in the second stage of the RO system. The configuration of the two-stage RO system is shown in **Figure 5-17**.

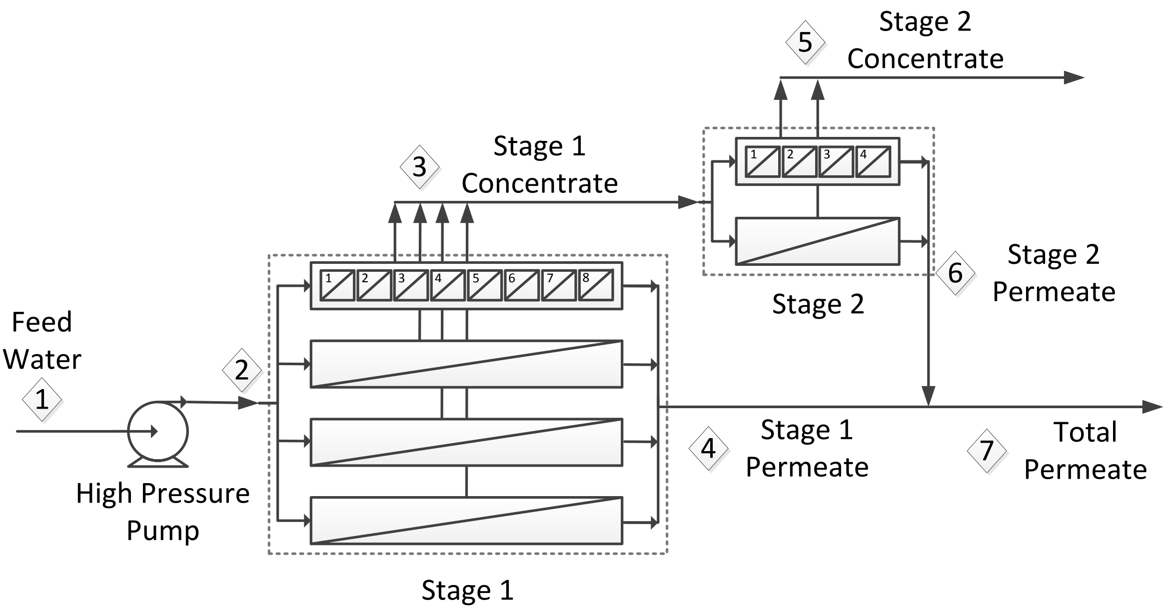

Figure 5-17: Optimised RO System Design 3 with Concentrate Staging

From the RO design simulation, the minimum number of extra RO membranes was 8 membranes in a 2 pressure vessel with 4 elements per vessel. As the TDS of Stage 1's concentrate was higher, at 941 mg/L, the FilmTec ECO Platinum-440 membrane type was chosen for the second RO stage given its high salt rejection and ability to treat up to 2000 mg/L of salt. Utilising an additional RO stage is often attended by a higher CAPEX and larger process footprint due to the extra membranes/pressure vessels required, however, a staged system consumes less energy compared to a single-stage system with concentration recirculation given that the latter needs a larger feed pump and higher energy consumption. This configuration was 28% more energy efficient (0.26 kWh/m^3) compared to Design 2, for the same recovered amount of water.

Table 5-36: RO Design 3 System Parameters Overview

RO System Parameters	Optimised Design 3 – Two-Stage RO System
Design temperature (°C)	25.0
pH	7.00
Number of membrane elements	40
Total membrane area (m^2)	1635
Stream 1 – Feed Water	
Feed flow rate (m^3/day)	1162
Feed TDS (mg/L)	301
Stream 2 – Feed Water after Pump	
Net feed flow rate (m^3/day)	1162
Feed pressure (bar)	5.40
Stream 3 – Stage 1 Concentrate/Stage 2 Feed	
Stage 2 feed flow rate (m^3/day)	360
Stage 2 feed pressure (bar)	3.64
Stage 2 feed TDS (mg/L)	941
Stream 4 – Stage 1 Permeate	
Permeate flow rate (m^3/day)	802
Permeate TDS (mg/L)	12.6
Stream 5 – Stage 2 Concentrate	
Concentrate flow rate (m^3/day)	247
Concentrate TDS (mg/L)	1367
Concentration factor	4.69
Stream 6 – Stage 2 Permeate	
Permeate flow rate (m^3/day)	113
Permeate TDS (mg/L)	6.76
Stream 7 – Final Total Permeate	
Permeate flow rate (m^3/day)	915
Average flux (LMH)	23.3
Final Permeate TDS (mg/L)	11.8
Overall RO system recovery (%)	78.7
Specific energy consumption (kWh/m^3)	0.25

RO System Design 4: Two-stage RO System with Concentration Recirculation

Similar to Design 2, the recovery of the two-stage system can be maximised through the implementation of concentrate recirculation. With the additional stage of RO membranes, allowing for production of more water, higher concentrate recirculation percentages of up to 50% can be used to increase recovery (**Figure 5-18**). A range of concentration recirculation percentages were considered aiming for lower energy consumption with respect to total water recovery.

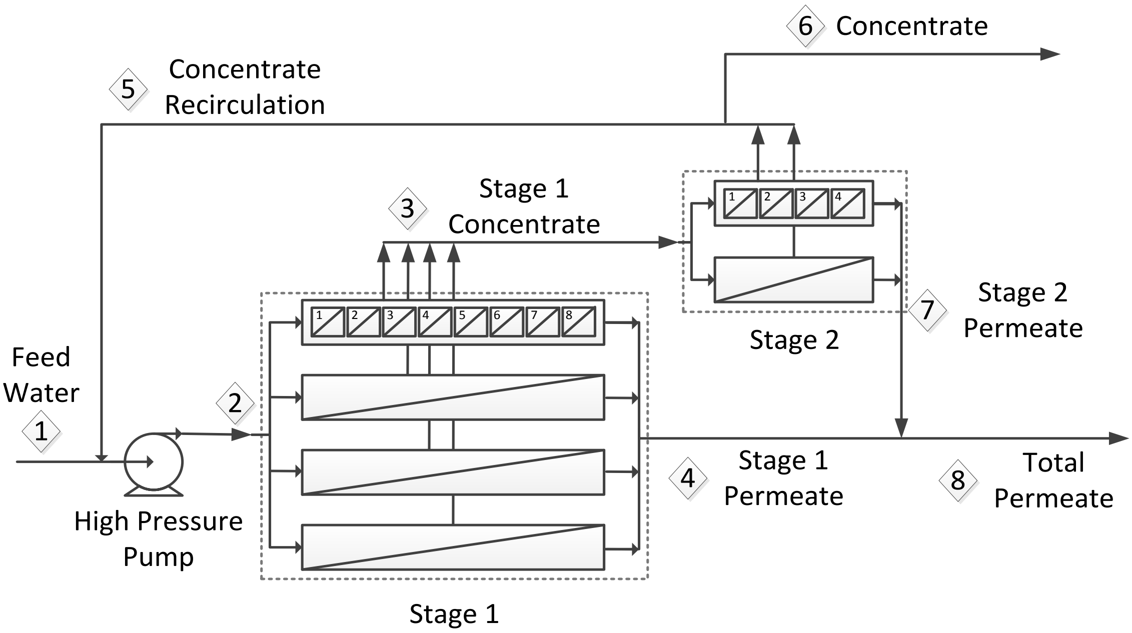

Figure 5-18: Two-stage RO Design with Concentrate Recirculation

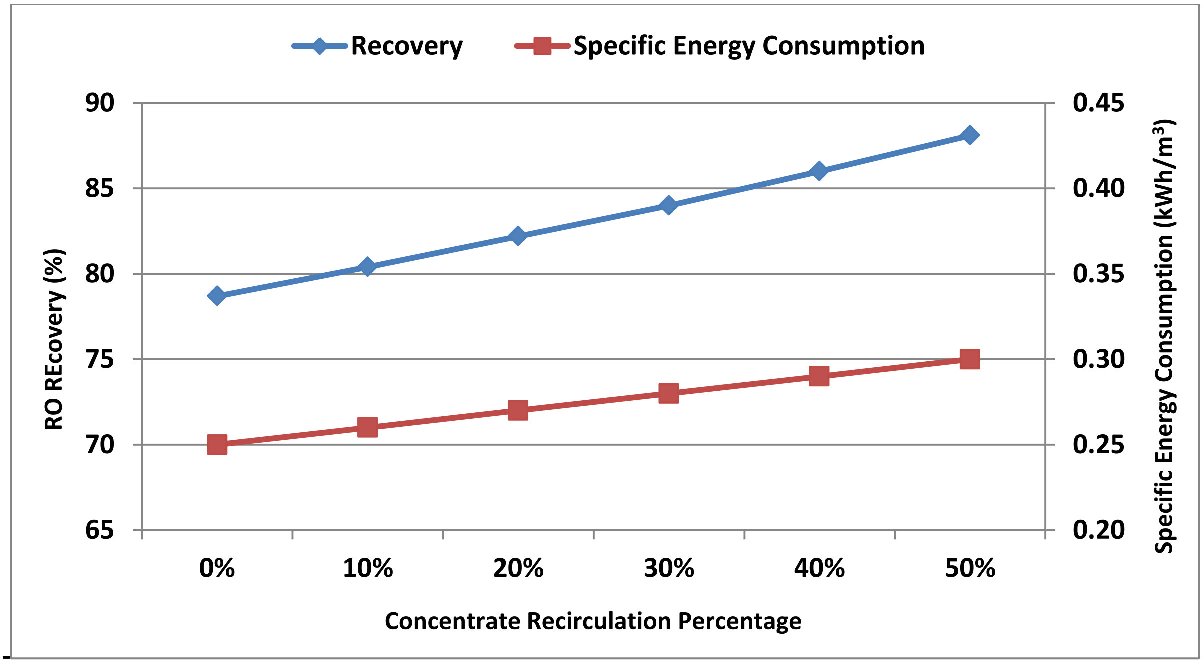

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Figure 5-19: RO Recovery and Specific Energy Consumption at Varying Concentration Recirculation Percentages for Two-Stage RO System

Recirculating 50% of the concentrate from the second stage back to the first stage allowed the two-stage RO system to achieve a maximum recovery of 88.1%, increasing the total water recovered to 1066 m^3/day. As per the findings of Design 2, increasing the concentrate recirculation percentage resulted in a linear increase in the specific energy consumption, however, the energy required to achieve a recovery of 88.1% was similar to that of the single stage RO system with 10% concentrate recirculation achieving a water recovery of 71.2%. Likewise, the two-stage RO design with 40%

concentrate recirculation recovered 86.0% of water, which is higher than the 69.0% recovery achieved by the single stage RO system (Design 1) at a similar specific energy consumption of 0.29 kWh/m^3.

Therefore, these observations suggest that a two-stage RO system with concentrate recirculation is a superior performing design compared to a single stage RO given that it can recover more water with an overall lower specific energy consumption at equivalent recovery rates. The only disadvantage of a two-stage RO system is that the design is more CAPEX intensive given the attended cost of extra membranes and the larger feed pump required, however, this increase in CAPEX would be offset by the long-term savings from reducing potable water purchased from the local water utility. More in-depth ROI analysis as well as environmental burdens throughout the assets' life-cycle will be investigated in the next milestone of this project (MS4).

Table 5-37: RO Design 4 System Parameters Overview

RO System Parameters	Optimised Design 4 – Two-Stage with 50% Concentrate Recirculation
Design temperature (°C)	25.0
pH	7.00
Number of membrane elements	40
Total membrane area (m^2)	1635
Stream 1 – Feed Water	
Feed flow rate (m^3/day)	1162
Feed TDS (mg/L)	301
Stream 2 – Feed Water after Pump with Recirculation	
Net feed flow rate (m^3/day)	1300
Feed pressure (bar)	6.42
Feed TDS with concentrate recirculation (mg/L)	523
Stream 3 – Stage 1 Concentrate/Stage 2 Feed	
Stage 2 feed flow rate (m^3/day)	399
Stage 2 feed pressure (bar)	3.92
Stage 2 feed TDS (mg/L)	1662
Stream 4 – Stage 1 Permeate	
Permeate flow rate (m^3/day)	902
Permeate TDS (mg/L)	19.1
Stream 5 – Stage 2 Concentrate Recirculation	
Concentrate flow rate (m^3/day)	139
Stream 6 – Stage 2 Concentrate	
Concentrate flow rate (m^3/day)	139
Concentrate TDS (mg/L)	2384
Concentration factor	8.40
Stream 7 – Stage 2 Permeate	
Permeate flow rate (m^3/day)	121
Permeate TDS (mg/L)	11.3
Stream 8 – Final Total Permeate	
Permeate flow rate (m^3/day)	1023
Average flux (LMH)	27.1
Final Permeate TDS (mg/L)	18.2
Overall RO system recovery (%)	88.1

Specific energy consumption (kWh/m^3)	0.30

RO Concentrate Waste Disposal

From the findings of MS2, a typical abattoir produces a total of 2781 m^3/day of wastewater with the six selected waste streams for potable water recycling accounting for 43% of the total wastewater volume (1208 m^3/day). The remaining 1573 m^3/day of wastewater, with a TDS of 726 mg/L TDS, is treated via the existing on-site water treatment processes prior to local council sewer discharge or via irrigation. Given that all four RO designs produced a waste concentrate stream of varying concentrations and volumes, the blending of these waste concentrate streams with the remaining 1573 m^3/day of wastewater was considered. The TDS of the blended effluent achieved by each of the four RO designs were compared to ascertain if blending would have a significant impact on the final effluent's TDS.

Table 5-38: Concentration of Total Dissolved Solids in Final Wastewater After Blending

	No Blending	Design 1	Design 2	Design 3	Design 4
	Remaining Waste Streams	Single Stage RO System	Single Stage with 40% CR	Two-Stage RO System	Two-Stage with 50% CR
Concentrate Volume (m^3/day)	-	360	247	247	139
Concentrate TDS (mg/L)	-	942	1357	1367	2384
Total Wastewater Volume (m^3/day)	1573	1933	1820	1820	1712
Final TDS (mg/L)	726	738	783	784	832

It is clear from **Table 5-38** that blending the concentrate stream from the RO design 4 with the remaining waste streams was the only option achieving a slight impact on the final wastewater's TDS concentration. Blending lower concentrations of waste concentrate from RO Designs 1, 2, and 3 resulted in insignificant changes to the final wastewater's TDS concentration, however, blending the more concentrated waste from Design 4 resulted in a 15% increase in TDS concentration from 726 to 832 mg/L. Although the TDS of the final wastewater is higher, it is still well-below the 4000 mg/L limit for sewer disposal (AMPC, 2005) and would fall into the "medium strength salinity" category (600-1000 mg/L), which is suitable for irrigation after being treated via existing on-site treatment processes in accordance with the regulations stipulated in the local Environmental Protection Authority's (EPA) irrigation guidelines (DEC, 2004).

5.4 Milestone 4 Findings and Outcomes

5.4.1 Overall LCA Results

The previous milestones have established that recycling abattoir wastewater to potable standards was the most ideal way for meat processors to achieve significant water savings. There were two ways that potable water could be recovered from abattoir wastewater; 1) Internal recycling utilising a

Membrane Bioreactor (MBR) and a Reverse Osmosis (RO) unit to treat six selected waste streams or 2) End-of-Pipe (EoP) recycling which involves using an Ultrafiltration (UF) membrane unit and a RO unit to produce 1023 m^3/day of potable water, reducing the abattoir's potable water consumption by 37%.

Results from the LCA of the two potable recycling scenarios were normalised against the base case scenario to ascertain the environmental impacts associated with adoption of internal and EoP recycling scenarios.

Table 5-39 presents a summary of the LCA scores for each recycling scenario with respect to the 10 chosen environmental impact indicators. Negative changes indicated an environmental benefit while positive changes indicated an environmental burden with significant impacts deemed to have occurred when the final impact score exceeded +/- 10% changes.

Table 5-39: Summary of LCA Scores for Each Recycling Scenario

LCA Impact Indicator	Unit/L Potable Water	Base Case	Internal Recycling	End-of-Pipe Recycling
Global warming Potential	kg CO_2 eq	1.09E-02	1.16E-02 (+6.4%)	1.12E-02 (+2.8%)
Stratospheric ozone depletion	kg CFC-11 eq	6.69E-08	6.76E-08 (+1.0%)	6.74E-08 (+0.7%)
Fine particulate matter formation	kg PM2.5 eq	7.69E-06	8.28E-06 (+7.7%)	7.89E-06 (2.6%)
Photochemical ozone formation	kg NO_x eq	4.13E-05	4.26E-05 (+3.1%)	4.20E-05 (+1.7%)
Terrestrial acidification	kg SO_2 eq	2.29E-05	2.51E-05 (+9.6%)	2.38E-05 (+3.9%)
Freshwater eutrophication	kg P eq	4.79E-06	6.05E-06 (+26.3%)	5.26E-06 (+9.8%)
Freshwater ecotoxicity	kg 1,4-DCB	1.24E-04	1.56E-04 (+25.8%)	1.36E-04 (+9.7%)
Mineral resource scarcity	kg Cu eq	7.42E-07	4.99E-07 (-32.7%)	5.08E-07 (-31.5%)
Fossil resource scarcity	kg oil eq	7.83E-04	9.57E-04 (+22.2%)	8.51E-04 (+8.7%)
Water consumption	m^3	1.01E-03	6.43E-04 (-36.3%)	6.44E-04 (-36.2%)

It was clear that from the LCA results that internal and EoP potable water recycling both yielded an environmental benefit with respect to mineral resource scarcity with decreases in LCA impact indicator scores of -33% and -32% for internal and EoP recycling scenarios respectively. Similarly, LCA impact indicator scores for water consumption also decreased by 36% for both recycling scenarios. These findings were expected given that both recycling scenarios recovered potable water and significantly reduced the volume of freshwater consumed which, in turn, decreased the amount of minerals required to conventionally produce potable water.

Apart from the two aforementioned impact indicators, EoP recycling did not have a significant impact on all other impact indicators with less than 10% increase in LCA impact indicator scores observed. Whilst internal recycling also did not result in a significant environmental burden for global warming potential, stratospheric ozone depletion, fine particulate matter formation, photochemical ozone formation, and terrestrial acidification, it did cause environmental burdens with respect to freshwater eutrophication, freshwater ecotoxicity, and fossil resource scarcity increasing the impact score by 26%, 26%, and 22% respectively. Detailed LCA results and interpretations are in Appendix G.

5.4.2 Economic Cost-Benefit Analysis Results

5.4.2.1 CAPEX and OPEX Estimates

An economic cost benefit assessment was conducted to compare and determine the economic viability of the two potable water recycling scenarios. The CAPEX and OPEX of water treatment technologies for internal and EoP recycling were scaled via the power law exponent cost correlation with costs index-adjusted to 2019 (Latest available CEPCI value). The cost estimates from various case studies reported in the literature are presented in Table 5-40.

Table 5-40: Estimated CAPEX and OPEX Values from Case Studies and Literature

	Capital Expenditure (AUD)	Operational Expenditure (AUD/year)	Reference
		Membrane Bioreactors	
Case Study 1	$1,278,399	$191,760	(Verrecht et al., 2010)
Case Study 2	$1,862,840	$279,426	(Holt and James, 2006)
Case Study 3	$1,909,167	$286,375	
Case Study 4	$1,238,549	$185,782	
Case Study 5	$1,844,597	$276,690	
Average	$1,626,710	$244,007	-
		Ultrafiltration Membrane Units	
Case Study 1	$279,390	$41,909	Porat Water Solutions
Case Study 2	$529,489	$79,424	SAMCO Tech
Case Study 3	$412,841	$61,927	(Drouiche et al., 2001)
Average	$523,103	$79,815	-
		Reverse Osmosis Units	
Case Study 1	$923,508	$138,527	(Mrayed et al., 2006)
Case Study 2	$917,684	$137,653	

Case Study 3	$490,737	$73,611	(Holt and James, 2006)
Case Study 4	$1,294,833	$194,225	(Pazouki et al., 2020)
Average	$906,691	$136,004	-

Table 5-41: Estimated Total CAPEX and OPEX for Internal and End-of-Pipe Potable Water Recycling

Process	Estimated CAPEX (AUD)	Estimated OPEX (AUD/year)
Internal Potable Water Recycling (MBR + RO)		
Membrane Bioreactor	$1,626,710	$244,007
Reverse Osmosis Unit	$906,691	$136,003
Estimated Total	**$2,533,401**	**$380,010**
End-of-Pipe Potable Water Recycling (UF + RO)		
UF Membrane Unit	$523,103	$79,815
Reverse Osmosis Unit	$906,690	$136,003
Estimated Total	**$1,438,793**	**$215,818**

For internal potable water recycling, the total CAPEX for the MBR-RO system was estimated to be $2,533,401 AUD with a yearly OPEX of $380,010 AUD while for EoP potable water recycling, the total CAPEX for the UF-RO system was estimated to be $1,438,793 AUD incurring an OPEX of $215,818 AUD/year (Table 5-41).

With the average CAPEX and OPEX of each treatment technology estimated, the total cost of the MBR-RO system and UF-RO system for internal and EoP potable water recycling scenarios respectively, were calculated and used as input values for the discounted cash flow calculations.

5.4.2.2 Net Present Value and Return on Investment Analysis

The Net Present Value (NPV) and Return on Investment (ROI) rate used to evaluate the economic feasibility of each recycling scenario. NPV discounted cash flow calculation is a method to determine the current value of future cash flows generated by each potable water recycling option. The breakdown of inputs for discounted cash flow calculations and subsequent NPV and ROI calculations are detailed in the following sections.

5.4.2.2.1 Total Capital Investment Costs

The Total Capital Investment (TCI) costs for both potable recycling scenarios were calculated based on an assumption that the Working Capital (WC) was 15% of the Fixed Capital Investment (FCI) costs. Table 5-42 summarises the capital costs used in the NPV and ROI calculations. The TCI of internal and EoP recycling were calculated to be $2,980,472 AUD and $1,692,698 AUD respectively. The internal recycling option's MBR-RO system was more CAPEX intensive given that it required a dedicated MBR for nutrient removal however, this translated to a reduction in operational expenditure incurred as less wastewater was required to be treated via the conventional WWTP.

Table 5-42: Total Capital Investment Costs for Internal and End-of-Pipe Recycling

	Internal Recycling (MBR-RO)	End-of-Pipe Recycling (UF-RO)
Fixed Capital Investment (FCI) costs (AUD)	$2,533,401	$1,438,793
Working Capital (WC) (AUD)	$447,071	$253,905
Total Capital Investment Costs (TCI) (AUD)	**$2,980, 472**	**$1,692,698**

5.4.2.2.2 Total Revenue and Annual Operational Expenditure

Given that the potable water recycling scenarios are not revenue generating, the financial savings accrued from reduced potable water purchased from local water utility was considered as revenue to offset the yearly operation expenditure (assuming 300 operational days). From Milestone 1, the cost of potable water was shown to vary from $1.46 AUD/kL to $4.50 AUD/kL, therefore, for the OPEX calculations, an average cost of $2.98 AUD/kL was used. For the EoP potable water recycling scenario, combined abattoir wastewater had to be first treated via a conventional WWTP incurring an average treatment cost of $ 1.395 AUD/kL (Milestone 1). This additional cost is on top of the OPEX incurred by the UF-RO system for EoP recycling. Table 5-43 provides a calculation and breakdown of the total annual revenue and OPEX of both recycling scenarios.

Table 5-43: Total Annual Revenue and OPEX for Internal and End-of-Pipe Recycling

	Internal Recycling (MBR-RO)	End-of-Pipe Recycling (UF-RO)
	Total Annual Revenue	
Volume of potable water recovered (kL/day)	1023	
Cost of water (AUD/kL)	$2.98	
Total Annual Revenue (Financial savings) (AUD/year)	**$914,562**	
	Total Annual OPEX	
Volume of wastewater requiring conventional treatment (kL/day)	-	1440
Cost of conventional wastewater treatment (AUD/kL)	-	$1.395
Conventional treatment cost (AUD/year)	-	$602,640
Potable water treatment OPEX (AUD/year)	$380,010	$215,819
Total Annual OPEX incurred	**$380,010**	**$818,459**

The annual revenue (financial savings) for both potable recycling scenarios was calculated to be $914,562 AUD/year as both recovered the same volume of potable water. The annual OPEX for EoP recycling was significantly higher given the extra cost of $602,640 AUD/year incurred from conventional wastewater treatment. This resulted in an annual OPEX of $380,010 and $818,459 for the internal and EoP recycling options respectively.

The TCI CAPEX estimates concluded that EoP recycling was significantly less capital intensive compared to internal recycling, however, this option relied on the existing conventional WWTP for nutrient removal prior to recycling, thus, resulting in EoP recycling having an OPEX that was two times higher than that of the internal recycling option.

5.4.2.2.3 NPV and ROI Rate Projections

<u>**Internal Potable Water Recycling NPV/ROI Projection**</u>

Table 5-44: NPV of Internal Potable Water Recycling over 15 Years

Year	Book Value	Capital Movement (CM)	Depreciation (D)	Revenue (R)	Expenditure (PC(E))	Profit After Tax (PAT)	Net Present Value (NPV)
0	0	-2,533,401	0		0	0	-2,533,401
1	2,533,401	-447,071	0	0	0	0	-2,980,025
2	2,026,721	0	506,680	914,562	380,010	19,510	-2,454,885
3	1,621,377	0	405,344	914,562	380,010	90,445	-1,960,580
4	1,297,101	0	324,275	914,562	380,010	147,194	-1,490,992
5	1,037,681	0	259,420	914,562	380,010	192,592	-1,041,233
6	830,145	0	207,536	914,562	380,010	228,911	-607,396
7	664,116	0	166,029	914,562	380,010	257,966	-186,357
8	**531,293**	**0**	**132,823**	**914,562**	**380,010**	281,210	**224,379**
9	425,034	0	106,259	914,562	380,010	299,805	626,807
10	340,027	0	85,007	914,562	380,010	314,682	1,022,520
11	306,025	0	34,003	914,562	380,010	350,384	1,402,705
12	275,422	0	30,602	914,562	380,010	352,765	1,781,501
13	247,880	0	27,542	914,562	380,010	354,907	2,159,013
14	223,092	0	24,788	914,562	380,010	356,835	2,535,333
15	200,783	0	22,309	914,562	380,010	358,570	**2,910,544**

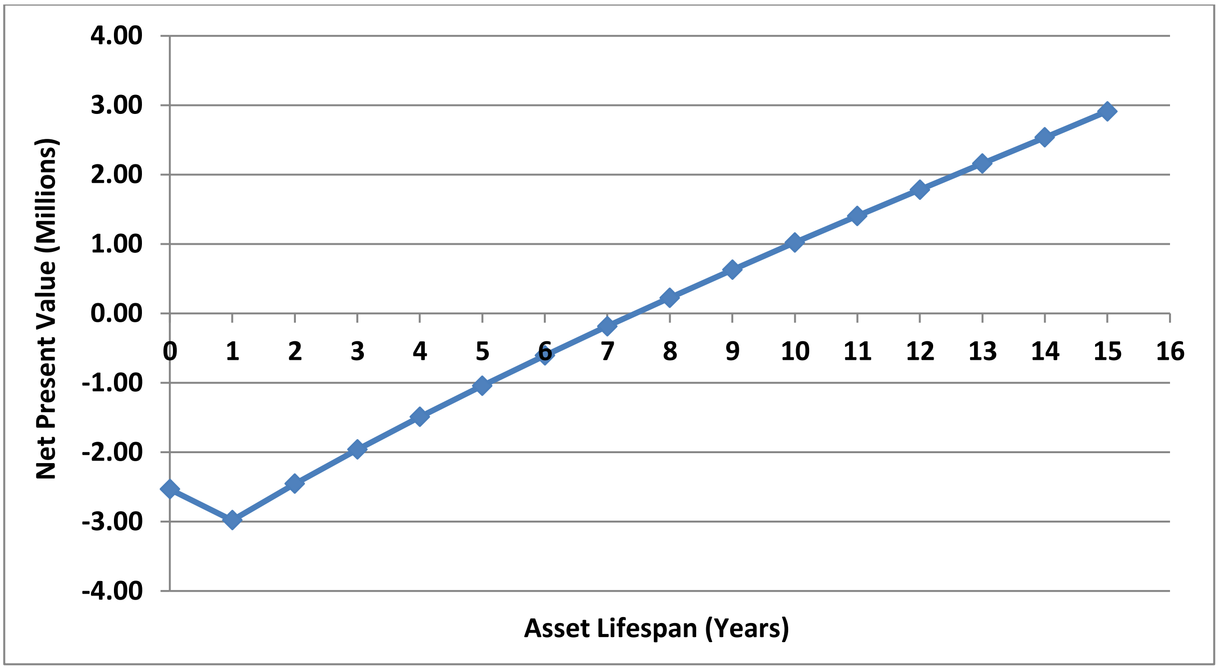

Figure 5-20: NPV Projection for Internal Potable Water Recycling Over the 15-Year Asset Lifespan

From the discounted cash flow NPV calculation, the internal potable water recycling scenario achieved capital recovery on the 8th year of operation with a NPV of $224,379 AUD. The internal recycling option had an NPV of $2,910,544 AUD after 15 years of operation. Based on the average profit after tax over the 15 years, the ROI rate was calculated to be 10.2%.

End-of-Pipe Potable Water Recycling NPV/ROI Projection

Table 5-45: NPV of End-of-Pipe Potable Water Recycling over 15 Years

Year	Book Value	Capital Movement (CM)	Depreciation (D)	Revenue (R)	Expenditure (PC(E))	Profit After Tax (PAT)	Net Present Value (NPV)
0	0	-1,438,793	0	0	0	0	-1,438,793
1	1,438,793	-253,905	0	0	0	0	-1,692,444
2	1,151,035	0	287,759	914,562	818,459	-134,159	-1,539,151
3	920,828	0	230,207	914,562	818,459	-93,873	-1,403,225
4	736,662	0	184,166	914,562	818,459	-61,644	-1,281,192
5	589,330	0	147,332	914,562	818,459	-35,861	-1,170,276
6	471,464	0	117,866	914,562	818,459	-15,234	-1,068,258
7	377,171	0	94,293	914,562	818,459	1,267	-973,364
8	301,737	0	75,434	914,562	818,459	14,468	-884,178
9	241,389	0	60,347	914,562	818,459	25,029	-799,566
10	193,112	0	48,278	914,562	818,459	33,478	-718,624
11	173,800	0	19,311	914,562	818,459	53,754	-646,357
12	156,420	0	17,380	914,562	818,459	55,106	-574,735

13	140,778	0	15,642	914,562	818,459	56,323	-503,700
14	126,700	0	14,078	914,562	818,459	57,418	-433,198
15	114,030	0	12,670	914,562	818,459	58,403	**-363,182**

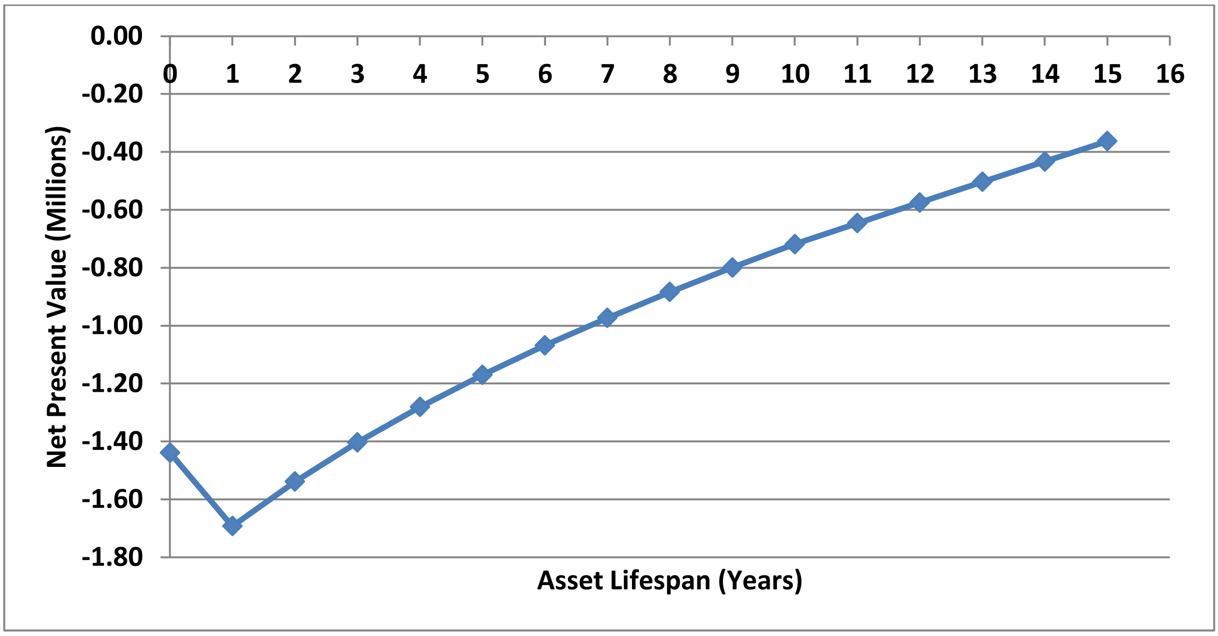

Figure 5-21: NPV Projection for End-of-Pipe Potable Water Recycling Over the 15-Year Asset Lifespan

NPV projection and ROI calculation concluded that EoP potable water recycling did not reach its capital recovery point over its projected 15-year asset lifespan. This recycling option had a negative NPV ($-363,182 AUD) after 15 years indicating that the present value exceeded the present value of revenue (savings) at the current discount rate and that this option would not be economically feasible with the ROI rate calculated to be 0.072%.

Despite the EoP recycling option having a 57% lower TCI CAPEX of $1,692,698 AUD than that of the internal recycling option at $2,980, 472 AUD, the EoP recycling option could not break-even and achieve a positive NPV and had a poor ROI rate of 0.072% over 15 years. This indicated that the main driver for economic feasibility was the Profit After Tax (PAT) generated by the recycling option. As the expenditure incurred by each recycling option could not be changed, the revenue (financial savings) was the only variable that could influence the PAT. The financial savings achieved by each recycling option is predominantly dependent on the cost of potable water, therefore, a sensitivity analysis was conducted to investigate the impact of the purchase price of potable water on the recycling options' NPVs.

5.4.2.2.4 Sensitivity Analysis of Potable Water Price on NPV

From Milestone 1, it was clear that the geographical location of the abattoir determined the processor's access and availability to municipal water supplies which, in turn, affects the cost of potable water significantly with potable water cost prices ranging from as low as $1.46/kL to as high as $4.50/kL. Therefore, the sensitivity analysis was performed using these reported costs prices of potable water to better ascertain the economic feasibility of both recycling options.

Table 5-46: Results of Sensitivity Analysis of Potable Water Price on Options' NPV

	Potable Water Cost Price (AUD/kL)	**1.45**	**2.98**	**4.50**
Internal Recycling (MBR-RO)	NPV (AUD)	$-1,622,400	$2,910,544	$7,443,489
	ROI Rate (%)	-2.7%	10.2%	23.1%
	Capital Recovery Point	Not Reached	8 Years	5 Years
End-of-Pipe Recycling (UF-RO)	NPV (AUD)	$-4,896,127	$-363,182	$4,169,763
	ROI Rate (%)	-22.6%	0.07%	22.8%
	Capital Recovery Point	Not Reached	Not Reached	5 Years

Sensitivity analysis of potable water cost price concluded that the cost of potable water had a significant impact on the NPV and ROI rates of each recycling option (Table 5-46). At a low cost price of $1.45 AUD/kL, both recycling options had a negative NPV and ROI rate, indicating that both options would not be economically feasible for adoption. However, in locations where water availability is low and demand is high, a cost price of $4.50 AUD/kL would allow for both recycling options to achieve capital recovery after 5 years at a ROI rate of 23.1% (NPV=$7,443,489) and 22.8% (NPV=$4,169,763) for internal and EoP recycling options respectively.

6 CONCLUSIONS AND RECOMMENDATIONS

Project Conclusions

Reviewing the current legislation and regulations concluded that, unless there is a change in the legislation around the use of potable water in direct contact with meat and meat products, there are limited areas where water can be recycled or reused. Notwithstanding this conclusion, this project identified waste streams that could be directly reused or treated to non-potable Class A standards for use in processes external to meat processing as well as the techno-economic feasibility of recycling wastewaters to potable water standards. Review and ranking of the waste streams concluded that the cattleyard wash, boning room, kill floor, side chiller wash, boiler ash wash, and rendering condensates were most feasible for reuse or recycling.

For direct reuse, the combined waste stream of the boning room, side chiller wash, and boiler ash wash wastewaters was the most feasible yielding a potential water saving of 680 L/t.HSCW (204 kL/day[1]) reducing total abattoir potable water consumption by 8%. The microbial risk associated with direct reuse as stockyard wash down water recommended that a static filter screen be used to remove the majority of the suspended solids before disinfection with chlorine to achieve the minimum required 2 Log-removal and the stipulated residual chlorine concentration of 0.2-2.0 mg/L for water reuse.

To achieve more significant water savings, non-potable water recycling needs to be considered. Of the four non-potable water recycling options, recycling the kill floor wastewater to a non-potable Class A treated water is recommended as it produces 2518 L/t.HSCW, meeting the non-potable water requirements sufficiently and potentially yielding water savings of 755 m^3/day[1], reducing water consumption by 28%. Although this option reduces amount of water consumed, the recycled water is a Class A non-potable water thus only has limited uses in an abattoir. QMRA concluded that a MBR followed by chlorine disinfection was deemed to be the most feasible as it was able to combine nutrient and residuals solids removal into one process reducing the treatment train's footprint and improving its performance consistency whilst achieving the required LRVs for the four reference pathogens. The 755 m^3/day kill floor waste stream was treated via an optimised MBR design consisting of an anoxic, aerobic, and membrane zone of 41 m^3, 461 m^3, and 107 m^3 respective volumes. The MBR had a specific energy consumption rate of 0.15 kWh/m^3 when operated at a RR of 450% and a sludge production rate of 25.4 m^3/day, producing 719 m^3/day of water that met non-potable Class A water quality standards.

To produce treated water that can be used in any abattoir process, and to achieve more significant water savings, potable water recycling using wastewater from the six selected waste streams combined was considered. These streams accounted for a total of 1208 m^3/day of wastewater which was first treated through an MBR for nutrient removal followed by a RO system for dissolved solids removal.

The optimised MBR in the potable water treatment train was determined to have anoxic, aerobic, and membrane zone volumes of 118 m^3, 730 m^3, and 172 m^3 respectively. The specific energy consumption of the MBR operating at a RR of 300% and a sludge production rate of 40.6 m^3/day was 0.10 kWh/m^3 and produced 1162 m^3/day of water with a TDS of 301 mg/L at an estimated conductivity of 598 µS/cm, which was subsequently used as feed for the RO system. A two-stage RO system with 50% concentrate recirculation was able to achieve a maximum recovery of 88.1%, yielding a total of 1023 m^3/day of potable water at a specific energy consumption of 0.30 kWh/m^3.

Lifecycle assessment results concluded that potable water recycling increased the environmental burden for majority of the environmental impact indicators given the extra energy and material inputs required regardless of recycling configuration, however, it generated an environmental benefit for the mineral resource scarcity and freshwater consumption impact indicators due to the reduction of potable water consumption (36% reduction).

Comparing between recycling options, internal recycling did contribute to a higher environmental impact with respect to freshwater eutrophication, ecotoxicity, and fossil resource scarcity, which was due to the increased electricity consumption required by the MBR. The increase in these three environmental impact indicators' scores could be attributed to generation of electricity from non-renewable sources. The impact scores will potentially be lower should renewable energy sources be considered in the future.

From an economic standpoint, although the internal recycling option's initial capital cost was significantly higher than the EoP option, internal recycling was economically more feasible given that it had an ROI of 10.2%, a positive NPV of $2,910,544 AUD after 15 years, and achieved capital recovery after 8 years. On the other hand, the EoP recycling option did not reach capital recovery after 15 years, at a low ROI rate of 0.072%, resulting in a negative NPV of $-363,182 AUD.

Sensitivity analysis showed that the cost of potable water had a significant impact on the NPV and ROI rates of each recycling option with positive NPVs of $7,443,489 AUD and $4,169,763 AUD projected for internal and EoP recycling, respectively, when potable water cost was high at $4.50 AUD/kL due to low water availability. Conversely, when the cost price was low at $1.45 AUD/kL, both options had negative NPVs of $-1,622,400 AUD and $-4,896,127 AUD and were unable to achieve capital recovery after 15 years at ROI rates of -2.7% and -22.6%, respectively.

Taking into account current climate projections tending towards warmer temperatures and lower rainfall precipitation and the ever-increasing water demand (CSIRO, 2020), the likelihood of the potable water prices remaining low is unlikely, with the lower availability driving the potable water prices towards higher prices. Tendency towards higher potable water prices economically favours internal recycling as it was able to break-even in 8 years when potable water was at a moderate price of $2.98 AUD/kL.

Recommendations and Future Work

It should be noted that the proposed treatment trains would certainly benefit greenfield abattoirs, or abattoirs considering upgrading as currently, abattoirs do not segregate their waste streams. Therefore, proper hydraulic planning prior to abattoir construction is recommended to allow for easier access to individual waste streams and minimise the potential for cross-contamination of waste between streams.

The proposed treatment trains would still be viable for established processors, given that additional investment to retrofit plumbing for waste segregation would be outweighed by the recovery of water from low strength waste streams whilst still being able to produce biogas/irrigation water from the high strength waste streams, further improving the water-saving benefits and reducing reliance on town potable water supply.

For the adoption of direct planned potable recycled water, consultation with the relevant industry stakeholders and health regulators is critical for the establishment of validation guidelines for potable recycled water to be used in direct contact with meat products whilst not affecting the meat processor’s export market access.

With the validation guidelines, pilot testing of the proposed potable water recycling treatment trains is recommended to allow for technical validation of treatment processes and monitoring of final product water quality to ensure compliance with food safety and AQIS legislations.

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8 APPENDICES

8.1 Appendix A – Red Meat Processor Survey

Survey sent to all participating meat processors

<u>Survey of Operating Data from Australian Abattoirs</u>

Dear (Abattoir Manager),

The University of New South Wales (UNSW), in collaboration with the Australian Meat Processor Corporation (AMPC), is conducting a technical and economic feasibility study to investigate possible methods to reduce water and energy use within meat abattoirs. However, to complete this task, we require some operational data from your abattoir.

Please provide as much of the following data that you have on record.

<u>General Guidance</u>

Any of the data from the below categories is useful, even if it is not recorded for the entire period, or if it is only recorded at irregular or long intervals.

Ideally, datasets would over a continuous 12-month period, preferably, datasets would be available digitally.

Ideally, samples taken continuously or daily would be best, however, weekly or monthly averages are still useful if daily values are not available. No detail is too small.

Please indicate units where values are presented, especially with weekly/monthly values (e.g. are they sum values for the whole month or average daily values, do they include weekend days/days with no production, etc.).

Please indicate if a value is an estimate.

<u>Important Process Information Requested (High Priority)</u>

Process Flow Diagrams / Piping and Instrumentation Diagrams

Water quality and Temperature measurements of wastewater streams (especially raw effluent and after treatment prior to discharge)

<u>Abattoir-Wide Operational Data (High Priority)</u>

Animals Slaughtered (Qty)

Average Carcass Mass/Meat Production (kg)

Potable Water Used (kL)

Water Discharged to Trade Waste (kL)

Water Discharged to other areas (kL) (If discharged, outline where to e.g. ponds system, treatment plant, etc.)

Electricity Consumed (kWh or MJ)

Gas Consumed (MJ or m3)

Coal Consumed (kg or MJ, indicate source or quality if known) (if applicable)

Any other fuel consumed on site

Site Economic Analysis

Cost of Water ($/kL)

Provider of Water (Municipal Water Authority)

Cost of Trade Waste Discharge ($/kL)

Cost of Electricity ($/kWh)

Cost of Gas ($/MJ or equivalent)

Cost of Coal ($/MJ or equivalent)

Existing Water Treatment Options on site.

Number of Staff on site

Typical Hours worked per week by all abattoir staff

Site-specific Questions

Is there anything unique or different about your site, or something that could be focused on from your perspective?

Do you discharge your wastewater to someone other than the local trade waste provider? If yes, provide details.

Do you hold an EPA licence for the discharge of waters (of any kind, including stormwater) off your site? If yes, provide details.

Have you encountered any restrictions on the supply or the refusal to supply basic resources, specifically: electricity, natural gas, potable water and coal? If yes, from whom and for what reason? Was this adequately explained to you by the provider?

Have you had a water treatment plant or wastewater services provider contact you about what waste and when your site discharges wastewater, and if so, what information did they ask for you for?

Do you recycle or reuse water on site now? If yes provide details.

Is your site considering the reuse of water in the near future? If yes provide details.

Is there anything else, generally, but with a focus on water and energy consumption, that you feel is unique about your site (include items which are good about your site, and items which are poor about your site).

All data collected will be kept in the strictest confidence in accordance with AMPC agreements

8.2 Appendix B – Wastewater Characteristics of Various Abattoir Processes

Characteristic	TCOD	SCOD	TSS	TS	VS	BOD	O&G	TN	TKN	NH3-N	TP	FRP	Cl	Ca	Mg	Na
Antemortem Area																
Cattle wash	2467	742	340	3272	2939	-	22	22	204	84	25	16	-	56	27	119
Truck wash	1727	253	1113	-	-	380	124	225	183	163	23	30	120	31	13	114
Stockyard wash	11804	4491	1000	13444	11421	3190	919	413	327	106	90	36	-	139	48	417
Slaughter, Evisceration, and Boning																
Kill Floor	6819	2160	1339	3877	1734	10989	168	170	414	30	21	22	44	24	12	49
Boning	202	72	44	340	-	-	46	10	3.0	0.3	0.7	0.1	32	15	3	18
KF and Boning cleaning	5400	1542	3417	-	-	-	727	203	265	10	20	12	-	-	-	-
Offal Processing																
Paunch dump and rinse	73613	6426	14900	133348	149909	-	1953	650	1713	103	568	262	512	270	74	1162
Rough offal wash	13533	1138	6434	13595	-	8509	4391	708	341	20.8	82	55	184	10	11	436
Red offal wash	980	212	672	-	-	-	1358	36	10	1.0	7.0	4.2	96	44	9.0	54
By-Products Processing																
Rendering Condensates	1441	610	32	-	-	550	90	350	389	323	2.9	-	32	0.8	0.8	0.2
Blood Stickwater	32004	8030	18150	22101	15451	21000	142	4817	3765	60	122	50	3590	12	8.7	1936
HT Stickwater	58994	3331	19657	40730	37398	-	14995	198	524	31	183	22	44	33	14	296
Combined Stickwater	59020	6069	34444	20288	20881	77800	16202	3000	610	152	243	48	-	246	18	51
Raw Material Bin	57502	20668	21370	30548	-	32000	4559	5200	2798	271	402	192	1595	47	36	983
Miscellaneous																
Side chiller wash	104	72	384	-	-	-	36	2.0	3.0	0.3	0.7	0.1	32	15	3.0	18
Boiler wash	700	-	730	-	-	-	-	2.0	-	1.0	1.0	1.0	-	-	-	-

8.3 Appendix C – Ranked Wastewaters According to Quality Boundary Ranges

Characteristic	TCOD	SCOD	TSS	TS	VS	BOD	O&G	TN	TKN	NH3-N	TP	FRP	Cl	Ca	Mg	Na
Antemortem Area																
Cattle wash	2467	742	340	3272	2939	-	22	22	204	84	25	16	-	56	27	119
Truck wash	1727	253	1113	-	-	380	124	225	183	163	23	30	120	31	13	114
Stockyard wash	11804	4491	1000	13444	11421	3190	919	413	327	106	90	36	-	139	48	417
Slaughter, Evisceration, and Boning																
Kill Floor	6819	2160	1339	3877	1734	10989	168	170	414	30	21	22	44	24	12	49
Boning	202	72	44	340	-	-	46	10	3.4	0.3	0.7	0.1	32	15	3.0	18
KF and Boning cleaning	5400	1542	3417	-	-	-	727	203	265	10	20	12	-	-	-	-
Offal Processing																
Paunch dump and rinse	73613	6426	14900	133348	149909	-	1953	650	1713	103	568	262	512	270	74	1162
Rough offal wash	13533	1138	6434	13595	-	8509	4391	708	341	21	82	55	184	10	11	436
Red offal wash	980	212	672	-	-	-	1358	36	10	1.0	6.6	4.2	96	44	9.0	54
By-Products Processing																
Condensates	1441	610	32	-	-	550	90	350	389	323	2.9	-	32	0.8	0.8	0.2
Blood Stickwater	32004	8030	18150	22101	15451	21000	142	4817	3765	60	122	50	3590	12	8.7	1936
HT Stickwater	58994	3331	19657	40730	37398	-	14995	198	524	31	183	22	44	33	14	296
Combined Stickwater	59020	6069	34444	20288	20881	77800	16202	3000	610	152	243	48	-	246	18	51
Raw Material Bin	57502	20668	21370	30548	-	32000	4559	5200	2798	271	402	192	1595	47	36	983
Miscellaneous																
Side chiller wash	104	72	384	-	-	-	36	2.0	2.7	0.3	0.7	0.1	32	15	3.0	18
Boiler wash	700	-	730	-	-	-	-	2.0	-	1.0	1.0	1.0	-	-	-	-

8.4 Appendix D – MCA Score Justification, Pairwise Comparison, and SWOT

Score	1	2	3	4	5
Process Complexity	The process includes pretreatment, biological treatment, multiple steps in disinfection and solid removal process	The process includes pretreatment, biological treatment followed by multiple steps in residual solid removal process and one disinfection process	The process consists of pretreatment, biological treatment process, followed by single residual solid removal process and one disinfection process	The treatment process train consists of pretreatment, biological treatment and residual solid removal process is integrated followed by single disinfection process	No pre-treatment is required, and integrated biological treatment biological treatment and residual solid removal process are integrated followed by single disinfection process
Process Maturity	Process is only proven on lab scale	Lab or pilot scale testing has been established with some results available	Process has been established in pilot scale in other industries	Full-scale process has been used in other industries	Full-scale process has been used to treat abattoir wastewaters
Capital Expenditure (CAPEX)	High CAPEX due to the high cost of implementing novel processes	Medium high CAPEX. Process requires some specialised equipment of high cost.	Medium CAPEX. Process required single specialized equipment but requires multiple well-established technologies	Medium low CAPEX. Process train has no novel technology but requires multiple well-established technologies	Low CAPEX. Process train utilises well-established processes that are well optimised and cost-effective
Process stability	Multiple treatment technologies in the train are sensitive and potential not cope with large variations in influent	One or two treatment technologies in the train are sensitive to influent quality. Moderate variation in effluent quality	One or two treatment technologies in the treatment process train are sensitive but low effect on effluent	Treatment process train has technologies have low sensitivity to influent water quality	All process in treatment train has high stability and can cope with variations in influent quality

	quality		quality		
Operational Expenditure (OPEX)	**Substantial operating cost due to high chemical, energy, maintenance, and labour costs**	**Medium high operating cost due to the implementation of energy intensive processes which also require regular maintenance**	**Medium OPEX due to moderate high energy labour, and maintenance but relatively low cost in chemicals required**	**Medium low OPEX due to low energy, maintenance cost, but relatively, moderate labour and chemical costs**	**Low OPEX due to low energy, labour, maintenance and chemicals costs**
Process Footprint	**The treatment process train includes multiple technologies with large footprints with extra pretreatment or disinfection processes included**	**One technology in treatment process train has large footprint with extra pretreatment or disinfection processes included**	**One technology in treatment process train has large footprint with no extra pretreatment or disinfection processes**	**The treatment process train has processes with small or medium footprint with extra, pretreatment or disinfection processes included**	**All technologies in treatment process train requires small footprint with no extra pretreatment or disinfection processes required**
Environmental Impacts	**Multiple processes require chemical inputs, and large amount of waste produced during the process; adverse visual impact**	**Multiple processes require chemical input, and large amount of waste produced; moderate visual impact**	**Multiple processes require chemical input with small amount of sludge production; moderate visual impact**	**One or two chemical inputs required and small amount of waste produced; moderate-low visual impact**	**Treatment processes require minimal chemical inputs with small amount of waste production; low visual impact**

	Process Stability	Process Complexity	Process Maturity	CAPEX	OPEX	Environment	Footprint
Process Stability	1	5	3	2	2	7	6
Process Complexity	1/5	1	1/3	1/4	1/4	3	2
Process	1/3	3	1	1/2	1/2	5	3

Maturity							
CAPEX	1/2	4	2	1	1	6	5
OPEX	1/2	4	2	1	1	6	5
Environment	1/7	1/3	1/5	1/6	1/6	1	1/2
Footprint	1/6	1/2	1/3	1/5	1/5	2	1

Non-potable Treatment Train 1 SWOT Analysis

Strengths	Weaknesses
- Treatment process consists of well-established treatment technologies. - Media filtration is not vulnerable to O&G content compared with membrane filtration, and does not require periodical replacement of membranes. - Ultraviolet irradiation is good for virus removal, and excellent for protozoa removal.	-Treatment process train requires largest footprint. - High capital cost and operational cost for activated sludge. - Coagulation requires chemical input. - Media filtration performs poorly in removing pathogens and organisms. - Chlorination is Less efficient for wastewater with high concentration of ammonia, due to the formation of chloramines. - Chlorination is temperature and pH dependent. - Process trains consist of two disinfection processes.
Opportunities	**Threats**
- Mature technology. - Treatment process is successful and efficient in removing TSS, O&G, COD, BOD TP, TN and bacterial presented in wastewater to Class A standard. - The effluent after treatment train is suitable as input of reverse osmosis process to produce potable water.	- Removal efficiency of media filtration relay on operating condition and feed water quality, unstable kill floor wastewater quality can result in high levels of particulate break though in a medial filter. - Activated sludge is vulnerable to uneven loads or high in fat. -The chlorination arises safety concern due to highly toxic and corrosive ability.

Non-potable Treatment Train 2 SWOT Analysis

Strengths	Weaknesses
- Ultrafiltration has been implemented in wastewater treatment of red meat abattoir.	- High costs of periodic membrane replacement

- Any residue TSS could be perfectly removed by membrane filtration. - Membrane filtration takes less footprint compared with media filtration. - Only chlorination was required for the disinfection process.	
Opportunities	**Threats**
- The effluent after treatment train is suitable as input of RO process to produce potable water.	- Membrane fouling

Non-potable Treatment Train 3 SWOT Analysis

Strengths	Weaknesses
- MBR has Small footprint, lower sludge production. - Overall process has the lowest footprint, because it combines biological treatment and residual solid removal process together. - Only chlorination required for the disinfection process. - Fully automate MBR plant requires less labor	- High costs of periodic membrane replacement.
Opportunities	**Threats**
- The effluent after treatment train is suitable as input of reverse osmosis process and electrodialysis to produce potable water.	- Membrane fouling. - Higher change of mechanical failure.

8.5 Appendix E – LCA Impact Indicators

Definitions of Impact Indicators

1. Global warming potential/Climate change

Global warming potential quantifies the emissions of greenhouse gases, the unit of measurement is the kilogram of carbon dioxide equivalent (kgCO2 eq). An emission of a greenhouse gas (kg) will lead to an increased atmospheric concentration of greenhouse gases which, in turn, will increase in the global mean temperature. Increased temperature ultimately results in damage to human health, terrestrial ecosystems and freshwater ecosystems. The emission of methane and nitrous oxide from the biological treatment processes both contribute the global warming potential. Electricity consumed in various process all produce greenhouse gases.

2. Ozone depletion potential

The ozone depletion potential quantifies the emissions of chlorofluorohydrocarbons (CFCs) and chlorinated hydrocarbons (HCs) into the atmosphere, which induces the damage to human health. The unit of measurement is micrograms CFC-11 (trichlorofluoromethane) equivalent (µg CFC-11 eq). Emissions of Ozone Depleting Substances (ODSs) ultimately lead to damage to human health because of the resultant increase in UVB-radiation. This increased radiation negatively affects human health, thus increasing the incidence of skin cancer and cataracts.

Like global warming potential, the ozone depletion potential is greatly affected by the energy intensive processes. Besides, the emissions associated with membrane manufacture, replacement and production of cleaning chemicals also greatly affect the ozone depletion potential. So, ozone depletion potential is a vital mid-point indicator to compare the performance between the base case and the potable water recycling treatment process.

3. Ionizing radiation

The ionizing radiation quantifies the anthropogenic emission of radionuclide which are generated in the nuclear fuel cycle or human activities. It is not expected to change as a result of wastewater treatment, so ionizing radiation is considered less relevant to this LCA study.

4. Fine particulate matter formation

The particulate matter formation potential quantifies the creation of airborne particulate matter in the atmosphere. The unit of measurement is kilograms of particulate matter smaller than 2.5 µm (kg (PM2.5) eq). Particulate matter is known to cause respiratory diseases and distress in humans, however the creation of particles under 2.5 µm is particularly deadly, due to their ability to penetrate deep into the lungs and enter the bloodstream unfiltered. The higher power and the embodied energy in membrane related activity is likely to results more fine particulate matter formation due to the combustion of fossil fuels to generate electricity.

5. Photochemical Oxidant Formation/Photochemical ozone formation

The photochemical ozone formation potential quantifies the creation of the chemicals responsible for photochemical ozone. It includes two mid-point impact categories. Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NOx and Non-Methane Volatile Organic Compounds (NMVOCs). Ozone concentrations lead to an increased frequency and severity of respiratory distress in humans, such as asthma and Chronic Obstructive

Pulmonary Diseases (COPD). Additionally, ozone can have a negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors. So, it was reflected in two midpoint impact category one for human health and one for ecosystem.

6. Acidification Potential (AP)/Terrestrial Acidification (TA)

Acidification potential quantifies the creation of precursors of acid rain. The unit of measurement is kilograms of sulfur dioxide equivalent (kg SO2 eq). An emission of NOx, NH3 or SO2 is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution H+ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear. The acidification potential is highly relevant to the burning of fossil fuels, so it is also included in the LCA calculation.

7. Freshwater Eutrophication/ Eutrophication potential

The eutrophication potential quantifies the potential for over fertilization of soil and water. The unit of measurement is kilograms of phosphorus equivalent (kg P eq). Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen. Environmental impacts related to freshwater eutrophication are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions into fresh water, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae, and heterotrophic species such as fish and invertebrates. This ultimately leads to relative loss of species. In this work, emission impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction following an increase in phosphorus concentrations in fresh water. The eutrophication potential is highly correlated to the wastewater treatment process, so it is also included in the LCA study for this project.

8. Freshwater Ecotoxicity

The toxicity can be sub-divided into human to human toxicity (cancer), human toxicity (non-cancer) and ecotoxicity accounts for the environmental persistence (Marine, terrestrial and freshwater). The unit of measurement is 1kg of 1,4-dichlorobenzene-equivalents (1,4DCB-eq).

9. Water Consumption

The water consumption causes the reduction in the freshwater availability, this will further cause the water shortage for irrigation and results damage to human health, it also causes reduction in plant diversity and changed rive discharges which arise the disappearance of species.

10. Land Use

The impact pathway of land use includes the direct, local impact of land used on terrestrial species via change of land cover and the actual use of the new land. Change of land cover directly affects the original habitat and the original species composition accordingly. The land use itself further disqualifies the land as a suitable habitat for many species. The land use is considered less relevant to this LCA study as the abattoir land is considered "developed" and additional construction has no additional environmental impact.

11. Mineral resource scarcity/Abiotic Depletion of Minerals

The abiotic depletion of mineral quantifies the consumption of non-renewable mineral resources (but not fossil fuels). The unit of measurement is the kilogram of mineral ore equivalent (kg mineral ore eq). The increase in abiotic mineral depletion is expected due to the embodied mineral use in production of chemicals for the treatment process and polymeric membrane replacement.

12. Fossil fuel scarcity/Abiotic Depletion of fossil fuels

The abiotic depletion of fossil fuels quantifies the consumption of non-renewable fossil fuels. The unit of measurement is the kilogram of crude oil equivalent (oil-eq/kg). The high fossil fuel scarcity potential processes in the boundary of the LCA study is the electricity.

8.6 Appendix F – LCA Inventory

Potable Tap Water Production Inventory

In this LCA study, Australia-specific LCA Inventory data was sourced from the Ecoinvent 3 database with global data used when certain data was not available for Australia. As previously established, the internal and EoP water recycling recovered 1023 m^3/day of potable water and was used to supplement the potable water consumption of 2799 m^3/day by the abattoir process resulting in a 36.5% reduction in the potable water drawn from the town water supply. Therefore, the volume of potable tap water that was required for both recycling scenarios was calculated to be 0.635L/functional unit (Table 1).

Table 1: Normalised Volume of Potable Town Tap Water Required for Each LCA Scenario

Process	Base Case	Internal Recycling	EoP Recycling	Unit	Rationale
Tap water production	1.000	0.635	0.635	L/Functional unit	For base case scenario, all potable water was sourced from potable town tap water production. For internal and EoP recycling, 36.5% was sourced from on-site recycling reducing potable town tap water production requirements to 0.635L/functional unit.

Wastewater Pumping Inventory

In the base case scenario, pumping of wastewater from the abattoir process to the wastewater treatment was achieved via vertical multistage electric pumps. Assuming a daily abattoir operational time (including non-meat processing activities) of 20 hours, the pumps were required to deliver an average of 140 m^3/hour of wastewater to discharge all 2781 m^3/day of wastewater to the conventional WWTP. Based on this flowrate and assuming a pump efficiency of 85%, the estimated power required by the pump was 18.91 kW, which translated to 486 J/functional unit (Lowara, 2015).

For the internal potable recycling scenario, the segregated wastewater, with volume of 1208 m^3/day, was pumped at a flowrate of 61 m^3/hour to the MBR-RO system while the remaining 1573 m^3/day of wastewater was pumped to the conventional WWTP at a flowrate of 79 m^3/hour. At these flowrates, the estimated power consumption for both pumps was 27.90 kW resulting in the pumping energy for the internal water recycling scenario to be 718 J/functional unit.

Similarly, for the EoP potable recycling scenario, all wastewater was pumped to conventional WWTP at an energy consumption rate of 486 J/functional unit. Subsequently, 1440 m^3/day of treated effluent was then delivered to the advanced potable water treatment process requiring an additional pumping energy of 434 J/Functional unit resulting in a total pumping energy consumption of 920 J/functional unit.

Table 2 summarises the pumping energy required for delivery of wastewater to conventional WWTP and potable recycling scenarios. It should be noted that these energy consumption values only apply for wastewater delivery excluding MBR and RO processes, which were calculated separately.

Table 2: Energy Consumption Attributed to Pumping of Wastewater to Treatment Processes

Process	Base Case	Internal Recycling	EoP Recycling	Unit	Rationale
Wastewater pumping	486	718	920	J/Functional unit	For base case, a single pump was required to deliver 139 m^3/hour wastewater to conventional WWTP. For internal recycling scenario, two pumps were required to deliver 60 m^3/hour of wastewater to MBR-RO and 79 m^3/hour of wastewater to conventional WWTP. For EoP scenario, one pump was required to deliver 139 m^3/hour wastewater to conventional WWTP, and second pump was required to deliver 60 m^3/hour of treated effluent after WWTP to advanced potable water recycling process.

Conventional Wastewater Treatment Inventory

In the Ecoinvent 3 database, a build-in model to estimate a wastewater treatment plant's inventory was not available, therefore, literature values and process engineering principles were used to estimate the energy consumption and other environmental emission inventories based on the influent wastewater's nutrient load and volume.

The typical overall energy consumption for the sewage treatment and sludge management was reported to be 0.4227 kWh/kL of wastewater to be treated (Pakenas, 2004) with the distribution of the energy consumption for conventional WWTP processes summarised in the Table 3 (Daw et al., 2012).

Table 3: Energy Consumption Distribution of Conventional WWTP Processes

Conventional WWTP Process	Energy Consumption Proportion
Aeration	77.9%
Pumping	18.9%
UV Disinfection treatment	3.1%

Other Processes	0.1%

The energy consumption attributed to the aeration in the nutrient removal process is strongly correlated to the concentration of nitrogen in the wastewater and can be estimated by determining the energy required to remove 1kg of Nitrogen in wastewater (Jensen et al., 2005, Mogens, 2012). Based on the energy consumption proportions of the various processes, the energy requirements required for aeration in the biological nutrient removal process was estimated to be 0.329 kWh/kL with the remaining 22% (0.0934 kWh/kL) attributed to pumping, UV disinfection, and other conventional processes.

Similarly, to estimate the environmental emission inventories, emission rates were obtained from literature and/or calculated based on the wastewater quality obtained from Milestone 2. The emission of N_2O from WWTP is dependent on the Total Nitrogen removal rate (Kampschreur et al., 2009, Parravicini et al., 2016). The methane emission rate was dependent on COD load of wastewater and was estimated to be 8.7g CH_4/kg COD of influent to WWTP, with COD and TP removal rate at 96% and 90% respectively (Parravicini et al., 2016). The CO_2 emission rate from COD oxidation was estimated to be 0.08 kg CO_2/kg COD (Campos et al., 2016) while NH_3 and NO_x emission rates were estimated to be 0.0001 kg NH_3/kg N and 0.0453 kg NOx/kg N respectively (Mogens, 2012, Kalbar et al., 2013). Table 4 summarises the inventory data associated with all three LCA scenarios.

Table 4: Inventory Data for All Three LCA Scenarios

Process	Base Case	Internal Recycling	EoP Recycling	Unit	Rationale
Total volume of wastewater to be treated	0.9936	0.6196	1.1429	L/functional unit	Base case consumed 2799 m^3/d of potable water and produced 2781 m^3/d of wastewater. Internal recycling reduced potable water consumption by 36.5% producing 1.5% of concentrate which was treated via conventional WWTP. EoP recycling treated all 2781 m^3/d of wastewater with advanced water treatment producing additional 15% concentrates that was returned to conventional WWTP.
Energy consumption without	334	208	384	J/functional unit	0.0934 kWh/kL of wastewater treated via conventional WWTP (Daw

aeration					et al., 2012)
Energy consumption for aeration	9364	8084	9414	J/functional unit	Energy estimated based on Nitrogen load obtained via mass balance and literature values.
Gas Emission from Conventional WWTP					
Process	**Base Case**	**Internal Recycling**	**EoP Recycling**	**Unit**	**Rationale**
NOx emission	3.54E-05	3.06E-05	3.56E-05	kg/functional unit	0.0453 kg NOx/kg TN (Mogens, 2012, Kalbar et al., 2013)
N_2O emission	5.86E-06	5.06E-06	5.89E-06	kg/functional unit	0.0075 kg N2O/kg TN (Parravicini et al., 2016)
CO_2 emission	1.27E-03	1.12E-03	1.27E-03	kg/functional unit	0.08 kg CO2/kg TCOD (Campos et al., 2016)
CH_4 emission	1.38E-04	1.22E-04	1.38E-04	kg/functional unit	0.0087 kg CH4/kg TCOD (Parravicini et al., 2016)
Effluent Discharged from Conventional WWTP					
Process	**Base Case**	**Internal Recycling**	**EoP Recycling**	**Unit**	**Rationale**
TCOD	6.36E-04	5.59E-04	6.15E-04	kg/functional unit	96% removal efficiency (Parravicini et al., 2016)
TN	7.81E-05	6.74E-05	7.34E-05	kg/functional unit	90% removal efficiency (Parravicini et al., 2016)
BOD	4.11E-04	3.59E-04	4.08E-04	kg/functional unit	96% removal efficiency
TSS	1.49E-03	1.29E-03	1.49E-03	kg/functional unit	81% removal efficiency (Baharvand and Mansouri Daneshvar, 2019)
TP	8.15E-06	7.42E-06	7.38E-06	kg/functional unit	90% removal efficiency (Parravicini et al., 2016)
O&G	8.56E-04	8.40E-04	8.54E-04	kg/functional unit	70% removal efficiency (Dehghani et al., 2014)
Cl	2.73E-04	2.87E-04	2.72E-04	kg/functional unit	0% removal efficiency due to minimal salt removal via conventional systems
Ca	7.32E-05	8.53E-05	7.28E-05	kg/functional unit	
Mg	3.28E-05	3.59E-05	3.26E-05	kg/functional unit	
Na	2.37E-04	2.54E-04	2.36E-04	kg/functional unit	

Membrane Bioreactor and UF/MF Membrane Inventory

Only the internal recycling scenario used a membrane bioreactor for nutrient removal prior to RO treatment. The production rate, energy consumption, and the corresponding characteristics of the waste sludge and effluent were simulated by using BioWin software and is detailed in Milestone 3.

The data inventory for the MBR and the UF/MF membranes is summarised in Table 5. Data inventory for operation of membrane processes is summarised in Table 6.

Table 5: Inventory Data for MBR and MF/UF Membranes

Process	Internal Recycling	EoP Recycling	Unit	Rationale
		Membrane Manufacturing		
Mesh Screen (HDPE)	0.404	-	kg/module	(Tangsubkul et al., 2006)
Glue (Polyurethane)	1.33	-	kg/module	
Potting Sleeves (ABS) (kg)	0.248	-	kg/module	
Casing (ABS) (kg)	12.7	-	kg/module	
Membrane Fibers (PP)	1.2	-	kg/module	
Polypropylene	-	61	kg/module	
Membrane mass	15.882	61	kg/module	
Manufacturing energy	1588	6100	MJ/module	
		Membrane Transport		
Membrane Packaging (HDPE)	0.81	5.28	kg/module	0.84m^2 per module for C2, 5.5 m^2 for C3 0.96kg/m^2 1mm thick HDPE black plastic bag
Packaging	0.56	3.66	kg/module	Assuming 1.86m^2 per module, 0.3kg/m^2 corrugated cardboard
Membrane transport	500	500	km	Arbitrary distance
		Membrane Cleaning		
NaOH	1.02	3.38	mg/L	(Tangsubkul et al., 2006) for internal recycling scenario. DuPont WAVE Simulation for EoP scenario.
Citric Acid	-	0.73	mg/L	Simulated via DuPont WAVE
NaOCl	-	23.35	mg/L	
HCl	-	1.19	mg/L	
Chemical transport	500	500	km	Arbitrary distance

Table 6: Data Inventory for Operation of Membrane Processes

Process	Internal Recycling	EoP Recycling	Unit	Rationale
Total volume of	0.4316	0.5119	L/functional	Internal recycling treated 1208

wastewater to be treated			unit	m^3/day of wastewater while EoP recycling treated 1433 m^3/day.
Membrane modules required	84	20	Modules	MF membranes with membrane area of 15m^2, is typically operated at a flux of 40 LMH (Tangsubkul et al., 2006) UF membranes for EoP recycling was simulated via DuPont WAVE
Membrane consumption rate	5.56E-08	1.12 E-08	Module/L	Module consumption to treat 1 L of wastewater (250 days per year, and 5-year lifespan)
Energy consumption	8507	238	J/L	Value for IR was simulated by BioWin Value of EoP was from DuPont WAVE
NOx emission	1.14E-05	-	kg/L	0.0453 kg NOx/kg TN (Mogens, 2012, Kalbar et al., 2013)
N_2O emission	1.88E-06	-	kg/L	0.0075 kg N2O/kg TN (Parravicini et al., 2016)
CO_2 emission	3.81E-04	-	kg/L	0.08 kg CO2/kg TCOD (Campos et al., 2016)
CH_4 emission	4.15E-05	-	kg/L	0.0087 kg CH4/kg TCOD (Parravicini et al., 2016)

Reverse Osmosis System Inventory

The RO membrane operation was modelled using the DuPont Water Application Value Engine (WAVE). Both internal recycling and EoP recycling scenarios included RO treatment to produce potable water. For the internal recycling scenario, the RO system was a two-stage RO with 50% concentrate recirculation configuration (Full details in Milestone 3 report). For the EoP recycling scenario, a two-stage design with 25% concentrate recirculation was considered.

Table 7: Data Inventory for Reverse Osmosis System

Process	Internal Recycling	EoP Recycling	Unit	Rationale
Total volume of wastewater to be treated by RO	0.4151	0.4827	L/functional unit	1162 m^3/day for internal recycling scenario 1352 m^3/day for EoP recycling scenario
RO Membrane modules required	40	72	modules	Modelled using DuPont WAVE
RO Membrane Mass	11.8	11.8	kg/module	Polyamide Thin Film Composite, 26lb per module
RO Membrane Transport	500	500	km	Arbitrary distance
RO Module	2.75E-08	4.26E-08	Module/L	Module consumption to treat

consumption rate				1 L of wastewater (1162 m^3/day, 250 days per year, and 5-year lifespan)
RO Energy consumption	1080	1030	J/L	Modelled using DuPont WAVE
EDTA Demand for cleaning RO membrane	19.98	19.98	mg/L	Assuming 7 CIPs per annum (Negaresh and Leslie, 2012)
EDTA transport	500	500	km	Arbitrary distance

Chlorination/De-chlorination System Inventory

Both internal and EoP recycling scenarios used a chlorination/de-chlorination process to produce potable water meeting drinking water standards. As the volume of potable water recovered from both scenarios was the same, the data inventory for the chlorination/de-chlorination process was also the same.

Table 8: Data Inventory for Chlorination/De-chlorination System

Process	Value	Unit	Rationale
Volume of wastewater treated via the chlorination/de-chlorination process	0.37	L/functional unit.	1023 m^3/day of RO permeate produced
NaOCl demand for chlorination	1.83E-06	kg/Functional unit	Assuming final chlorination level of 5mg/L
NaOCl transport	500	km	Arbitrary distance
$Na_2S_2O_5$ Demand (for de-chlorination)	4.93E-06	kg/Functional unit	Assuming chlorine residual of 0.5 mg/L. and the 3mg $Na_2S_2O_5$ is required to remove 1mg of Cl-
$Na_2S_2O_5$ Transport	500	km	Arbitrary distance

8.7 Appendix G – LCA Detailed Results/Discussion

In order to better understand the factors that resulted in the significant environmental benefits or burdens of each impact indicator, the following sections breakdown and discuss how the scores for each environmental impact indicator were calculated.

Global Warming Potential

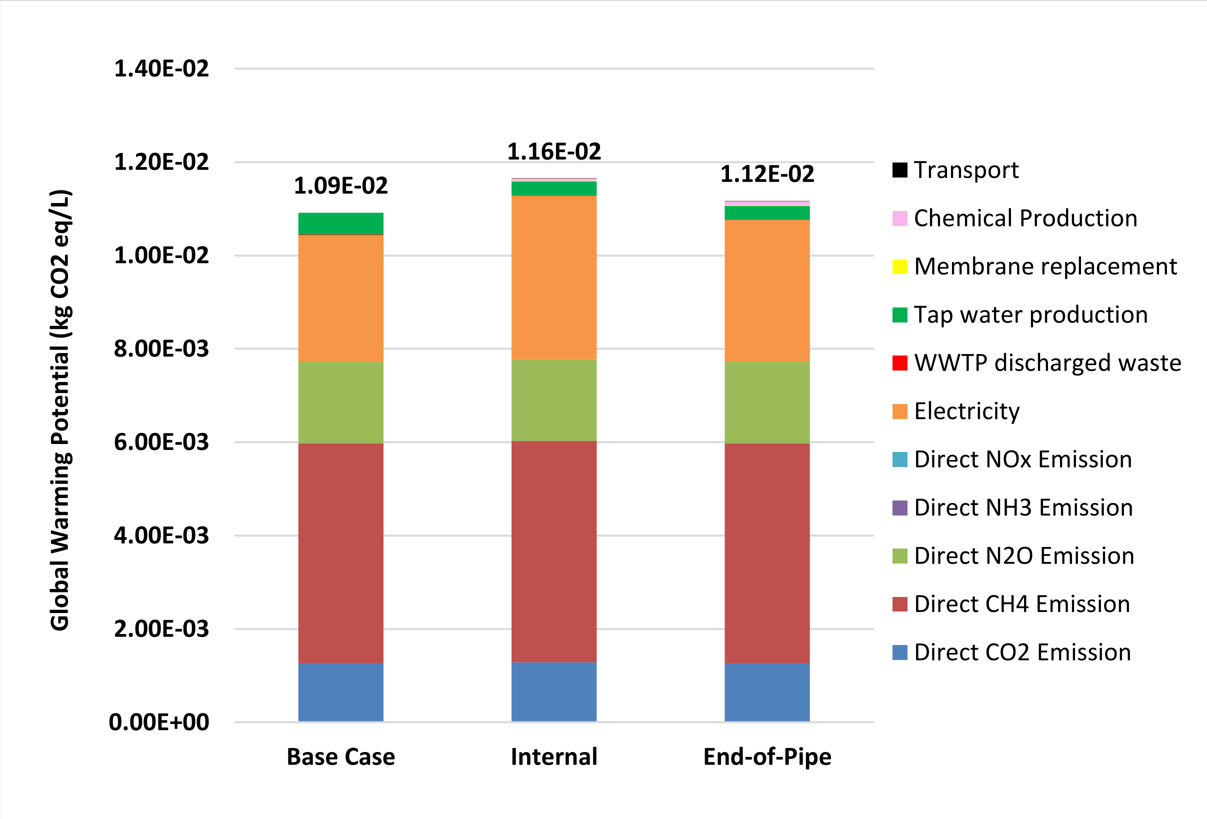

Figure 1: Breakdown of Factors Contributing to Global Warming Potential for Base and Recycling Scenarios

Global warming potential quantifies the emissions of greenhouse gases with the unit of measurement being a kilogram of carbon dioxide equivalent produced per litre of potable water produced (kg CO_2eq/L). From Figure 1, the Internal recycling scenario resulted in a 6% increase in global warming potential while EoP recycling resulted in a 3% increase. The increased environmental burden was mainly attributed to the increased electricity consumed by the MBR-RO and the UF-RO treatment processes direct emission of CO_2, N_2O and CH_4 from all three scenarios being the same given that the nutrient removal processes treated the same abattoir wastewater. Other factors such as WWTP waste discharges, membrane replacement, chemical production, tap water production, and transport did not contribute to global warming potential burdens significantly.

Stratospheric Ozone Depletion

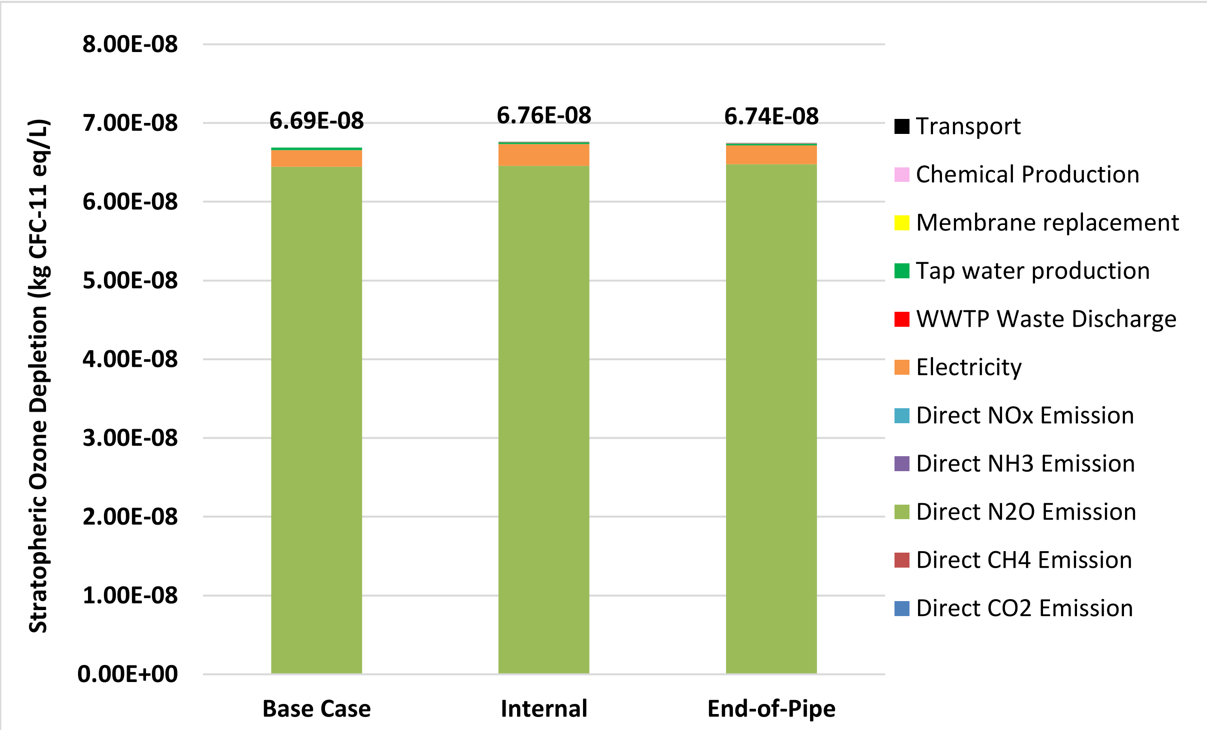

Figure 2: Breakdown of Factors Contributing to Stratospheric Ozone Depletion for Base and Recycling Scenarios

Stratospheric ozone depletion potential quantifies the emission of the ozone depleting substances and is measured in the units of kg CFC-11 (trichlorofluoromethane) equivalent per litre of potable water produced (kg CFC-11 eq/L). It is clear that implementation of potable water recycling, regardless of recycling configuration, resulted in insignificant increases in stratospheric ozone depletion potential with impact scores of 6.69×10^{-8}, 6.76×10^{-8}, and 6.74×10^{-8} kg CFC-11 eq/L for base case, internal recycling, and EoP recycling respectively. Direct N_2O emission associated with N_2O gases emitted from nutrient removal was the largest contributor to stratospheric ozone depletion potential but was similar for all three scenarios.

Fine Particulate Matter Formation and Terrestrial Acidification

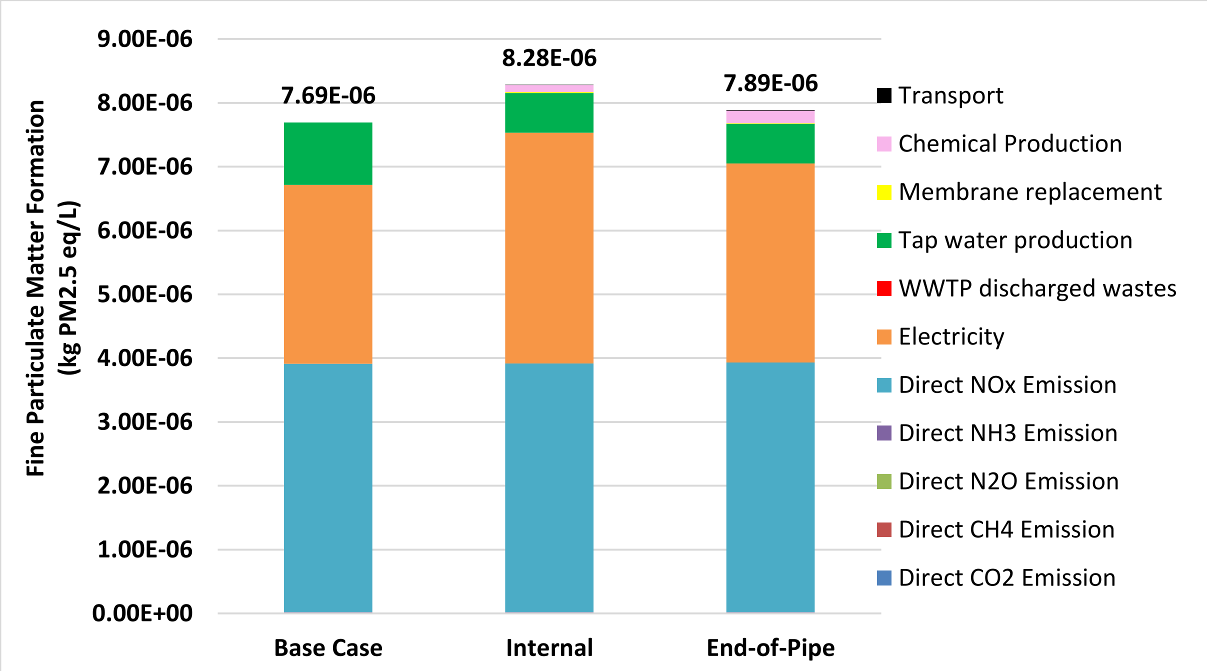

Figure 3: Breakdown of Factors Contributing to Particulate Matter Formation Potential for Base and Recycling Scenarios

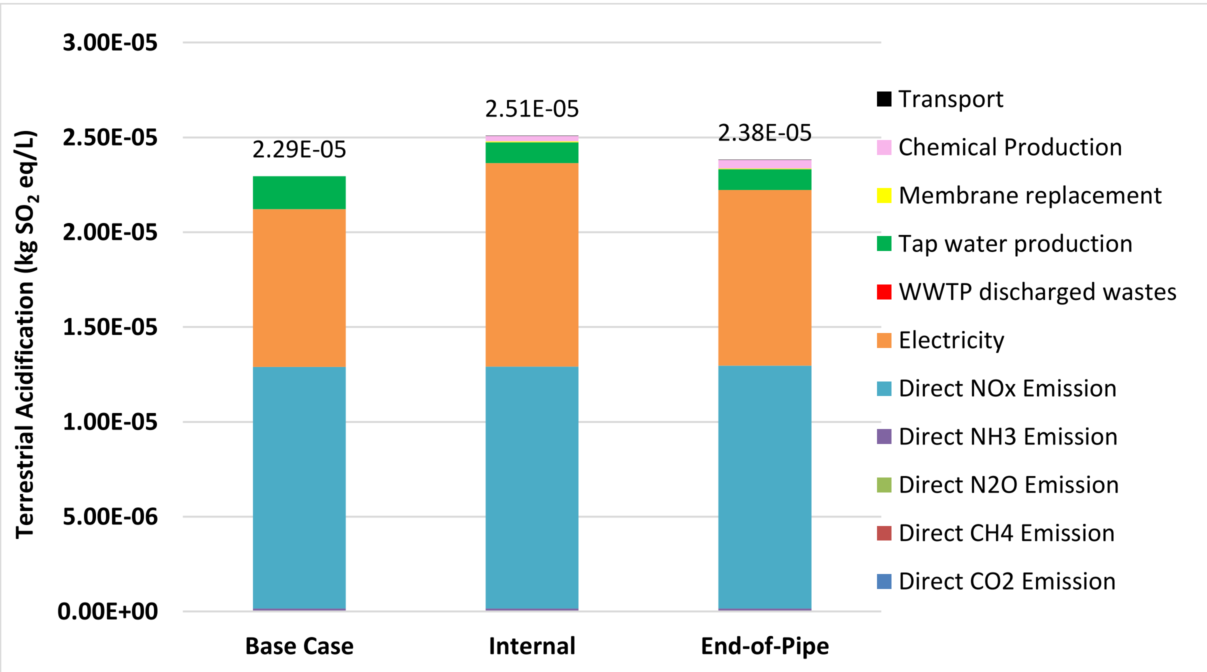

Figure 4: Breakdown of Factors Contributing to Terrestrial Acidification for Base and Recycling Scenarios

The particulate matter formation potential quantifies the generation of airborne particulate matter in the atmosphere. The indicator's measurement unit is kilograms of particulate matter smaller than

2.5 µm per litre of potable water produced (kg (PM2.5) eq/L). Adoption of potable water recycling did not significantly increase the particulate matter formation potential with internal and EoP recycling increasing overall impact indicator's score by 8% and 3% respectively. Again, this increase was largely attributed to fine particulate matter formed during generation of electricity with minor contributions attributed to chemical production.

Terrestrial acidification potential quantifies the creation of precursors of acid rain. The unit of measurement is kilograms of sulfur dioxide equivalent per litre of potable water produced (kg SO_2 eq/L). Similar to particulate matter formation potential, the increase in terrestrial acidification potential was due to electricity generation resulting in the internal and EoP recycling scenarios having a higher impact indicator score of 2.51×10^{-5} (+10%) and 2.38×10^{-5} (+4%) kg SO2 eq/L when compared to the base case.

Photochemical Ozone Formation

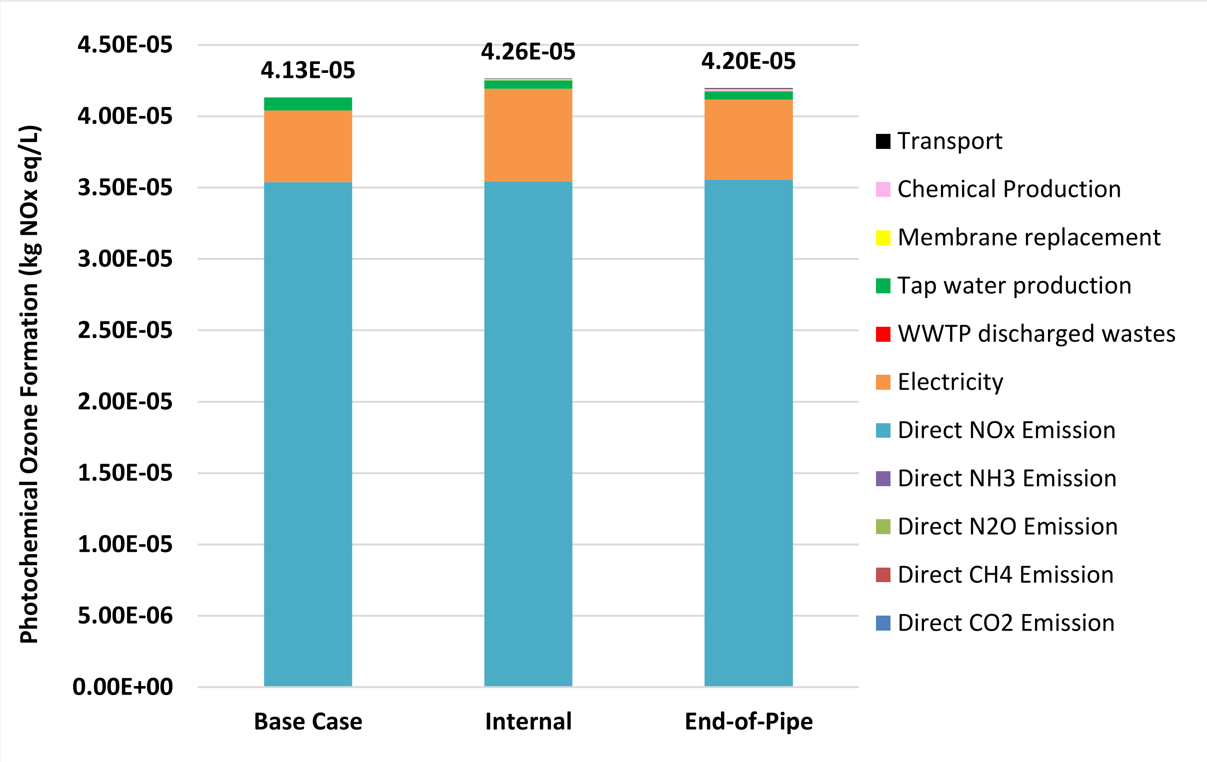

Figure 5: Breakdown of Factors Contributing to Photochemical Ozone Formation for Base and Recycling Scenarios

The photochemical ozone formation potential quantifies the creation of the chemicals responsible for photochemical ozone and is measured with the unit of kg NO_x eq/L. From Figure 5, it was clear that 80% of the photochemical ozone formation potential was due to direct NO_x gases emitted from the nutrient removal process with electricity generation being the next major contributor. Despite the used of energy-intensive RO systems in both the internal and EoP recycling scenarios, an insignificant increase in photochemical ozone formation potential was observed with a 3% and 2% increase in environmental burden respectively.

Freshwater Eutrophication and Ecotoxicity

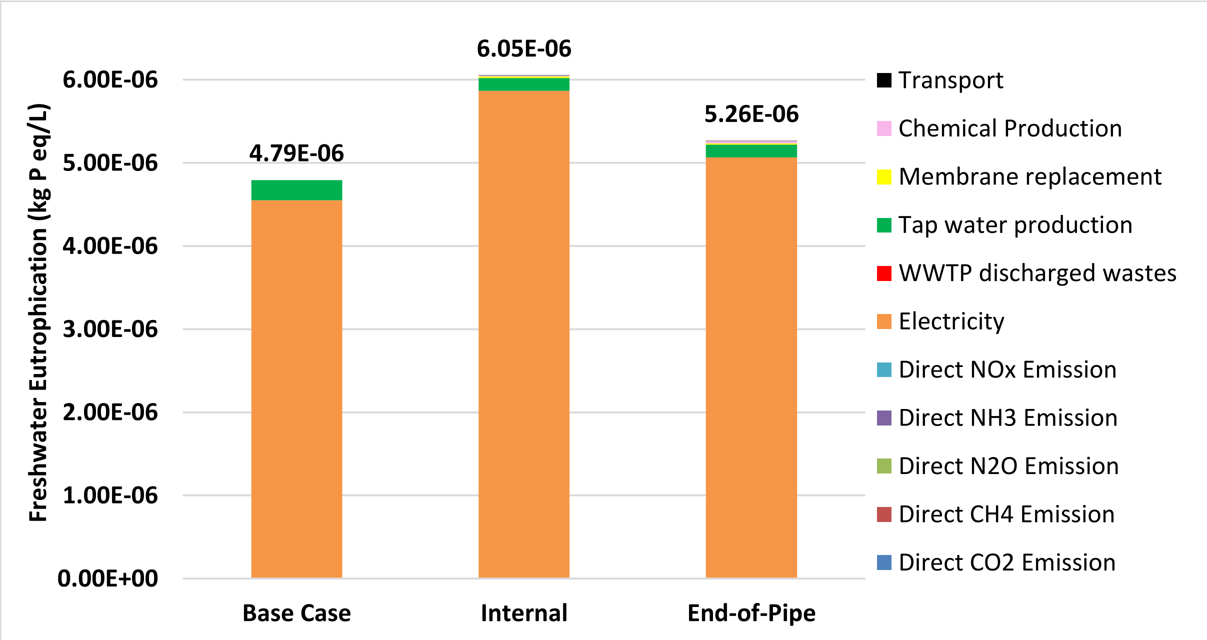

Figure 6: Breakdown of Factors Contributing to Freshwater Eutrophication for Base and Recycling Scenarios

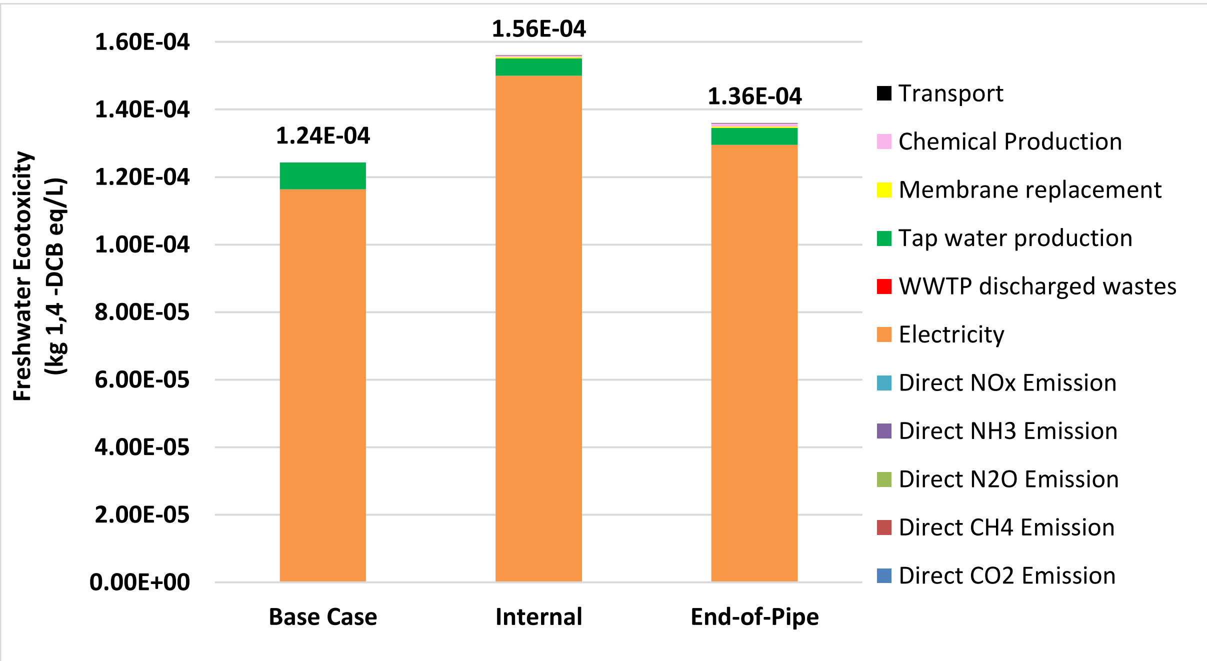

Figure 7: Breakdown of Factors Contributing to Freshwater Ecotoxicity for Base and Recycling Scenarios

The freshwater eutrophication potential quantifies the potential for increased aquatic plant growth in freshwater bodies due over fertilisation of soil and water. The unit of measurement for this indicator is kilograms of phosphorus equivalent per litre of potable water produced (kg P eq/L).

Freshwater ecotoxicity accounts for the impact on freshwater ecosystems, as a result of emissions of toxic substances to air, water and soil and is measured in the unit of 1kg of 1,4-dichlorobenzene-equivalents (kg 1,4-DCB eq). Given that wastewater is treated to meet stringent discharge limits, the freshwater eutrophication and ecotoxicity potential were not affected with electricity generation being the major contributor to both environmental indicators due to the increased energy consumption required for operation of water recycling technologies.

Fossil Resource Scarcity

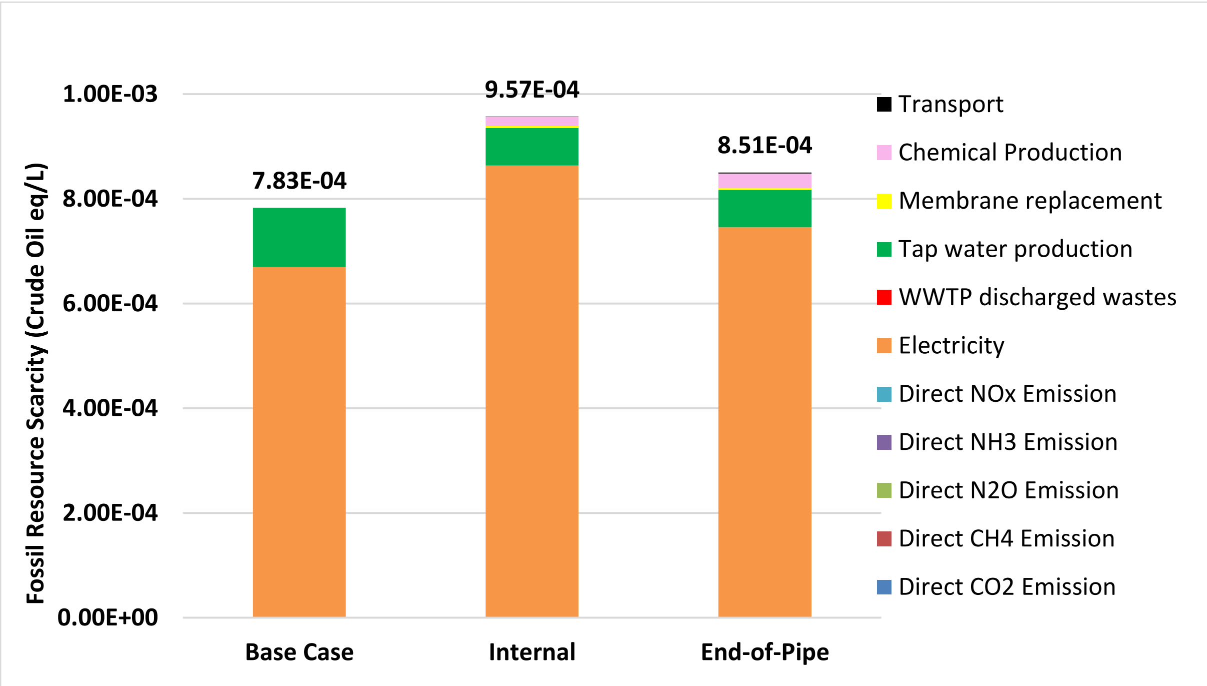

Figure 8: Breakdown of Factors Contributing to Fossil Resource Scarcity for Base and Recycling Scenarios

The abiotic depletion of fossil fuels quantifies the consumption of non-renewable fossil fuels. The measurement unit of this indicator is kilogram of crude oil equivalent per litre of potable water produced (kg crude oil eq/L). As expected, the additional energy required to operate water recycling technologies resulted in an increase in fossil fuel scarcity for both potable recycling scenarios. Comparison with the base case, internal and EoP recycling accounted for a 22% and 9% increase in fossil resource's environmental burden. Supplementation of potable town tap water with recycled potable water resulted in a slight decrease in fossil resource scarcity, however, this decrease was offset by increased fossil resource consumed for chemical production.

Mineral Resource Scarcity

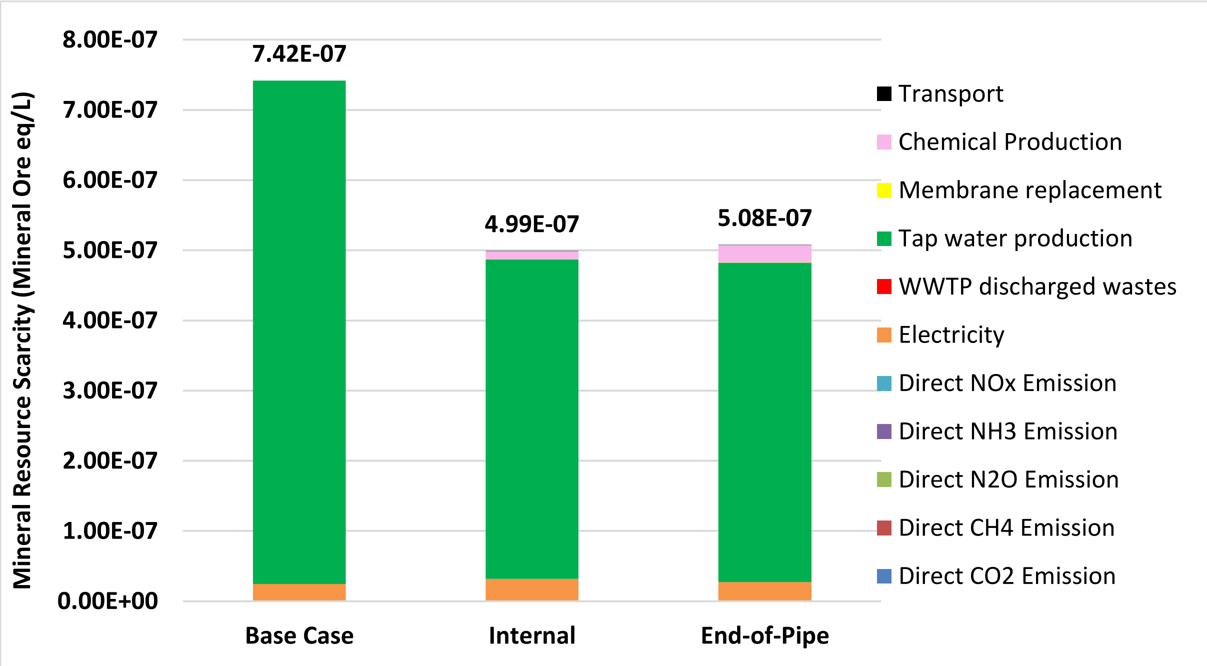

Figure 9: Breakdown of Factors Contributing to Mineral Resource Scarcity for Base and Recycling Scenarios

The abiotic depletion of mineral resource quantifies the consumption of non-renewable mineral resources (not fossil fuels). The measurement unit of this indicator is a kilogram of mineral ore equivalent per litre of potable water produced (kg mineral ore eq/L). The increase in abiotic mineral depletion is expected due to the increased mineral use in production of chemicals for the treatment process and polymeric membrane replacement. For all three scenarios, the potable tap water production contributes the highest reading due to the usage of mineral chemicals used to conventionally produce potable tap water. Therefore, adoption of potable water recycling decreased the amount of potable tap water required to be produced.

Freshwater Consumption

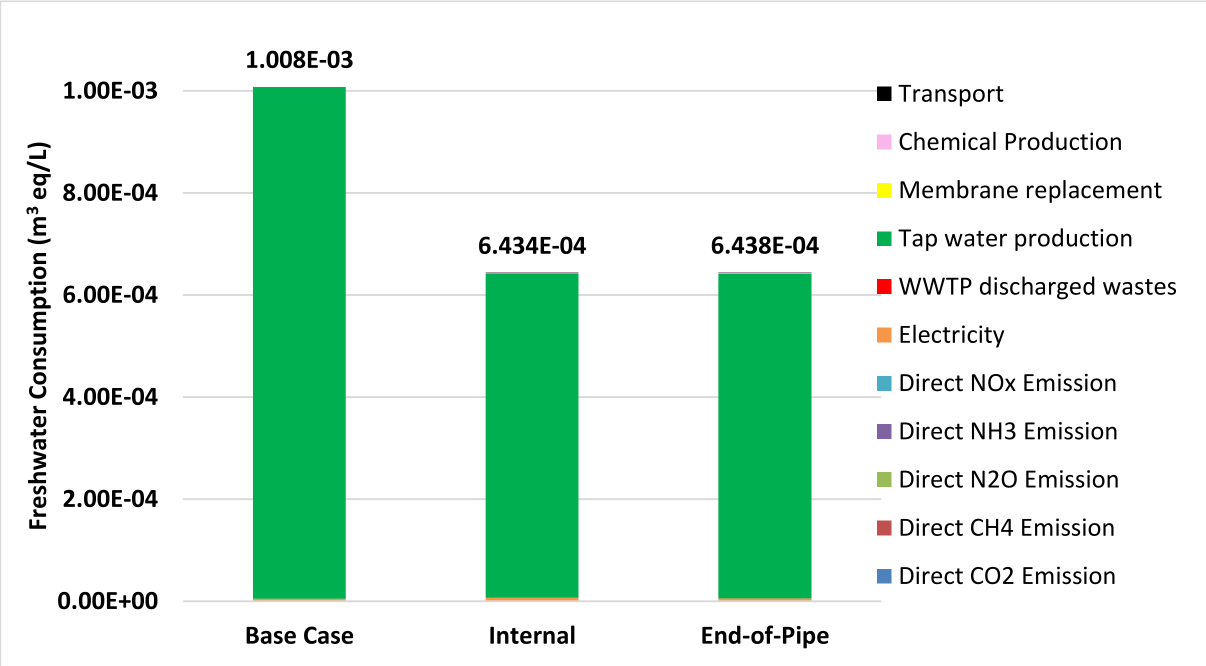

Figure 10: Breakdown of Factors Contributing to Freshwater Consumption for Base and Recycling Scenarios

The water consumption results in the reduction of the freshwater availability, this will further increase the strain on existing potable water supplies further exacerbating potable water competition between irrigation/food processing and human consumption. As both internal and EoP recycling scenarios recover potable water for supplementation of potable water used in the abattoir, the freshwater consumption impact indicator scores for both recycling scenarios were significantly lower than the base case scenario. Given that both recycling scenarios recovered the same volume of potable water, the impact indicator scores both decreased by 36% indicating an overall environmental benefit with respect to freshwater consumption.