

Nutrient Recovery from Paunch and Covered Anaerobic Lagoon Effluent

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Table of Contents

Executive Summary	3
1.0 Project Objectives	4
1.1 Background	4
1.2 Project Objectives	4
2.0 Overall Process Design	5
2.1 Process Flow Sheet	5
2.2 Pretreatment: Filtration and Settling	6
2.3 Aeration	7
2.4 Crystallisation Reactor	8
2.5 Product Collection	10
2.6 Process Operation and Control	10
3.0 Process Performance	12
3.1 Site A	12
3.1.1 Plant Installation	12
3.1.2 Pilot Plant Performance Data	12
3.2 Site B	13
3.2.1 Plant Installation	13
3.2.2 Batch Crystallisation Trials	14
3.2.3 Pilot Plant Performance Data	14
3.3 Fertiliser Growth Trials – GRDC Funded Activity	15
4.0 Cost Benefit	16
4.1 Basis Used in Assessment	16
4.2 Process Design and Analysis	16
5.0 Recommendations	17
Appendix A: Parameters used in CBA	19
Glossary	20

Executive Summary

This is the final report for project 2013/4007: Nutrient recovery from paunch and covered anaerobic lagoon effluent. The project was a collaboration between The University of Queensland (UQ), Meat and Livestock Australia (MLA) and Australian Meat Processor Corporation (AMPC). Existing research projects funded by the Grain Research and Development Council (GRDC) complement this project.

The nutrient recovery process includes three steps: aeration to increase pH prior to precipitation and reduce chemical consumption, crystallisation of nutrient products, and overflow tanks for product recovery. A nutrient recovery pilot plant was operated at two Australian red meat processing facilities. At Site A the plant treated filtered digestate from a paunch in-vessel anaerobic digestion (IVAD) unit and produced over 50 kg of struvite product. At Site B the plant treated effluent from a crusted anaerobic lagoon producing over 30 kg of crystallised fertiliser product. The crystallisation process has been highly effective with a soluble phosphorous (P) concentration of 6 mg.L⁻¹ in the process effluent, indicating that 80% of phosphorous is precipitated.

The plant treated 1,500L of wastewater per day and precipitated 26 mg.L⁻¹ of phosphorous. This corresponded to struvite production of 400 g.d⁻¹. However, only 300 g.d⁻¹ of struvite was being harvested from the process, indicating a portion of the precipitate was being lost in the effluent. This was identified as an area for subsequent optimisation. Based on the stoichiometric composition of struvite, the required magnesium (Mg) dose for complete P recovery is 37 g.d⁻¹. The actual dose rate of Mg to the process is approximately 40 g.d⁻¹, indicating chemical dosing is relatively efficient. However, process performance was variable at this dose rate. More detailed investigation into minimum Mg dosing for stable performance is recommended.

Cost–benefit analysis (CBA) demonstrated that the payback period for the struvite crystallisation plant could be approximately 7.8 years. This could reduce to 2.7 years if savings in trade waste fees from reduced nutrient discharge were considered. From the CBA it was clear that optimised P recovery should be a priority in continued process development. Considering the CBA of P recovery processes is highly dependent on both mitigation of waste disposal fees and the value of the nutrient product, market analysis for the fertiliser product is a critical step to validate CBA assumptions.

Fertiliser growth trials are not part of current AMPC/MLA projects; however, these activities are currently being supported by GRDC and the results will be available to assist in assessment and analysis of struvite technology in the 2014–15 financial year.

1.0 Project Objectives

1.1 Background

Red meat processing facilities can generate large volumes of wastewater rich in organic contaminants and nutrients, which can make them strong candidates for treatment processes aimed at recovery of both energy and nutrient resources. Previous pilot work funded by the Federal Government and AMPC as part of A.ENV.099 and A.ENV.0155 has shown that the digestate from paunch processing is highly suitable for phosphorous and ammonia recovery. Cost-benefit analyses in these previous projects indicated that nutrient recovery could add 20% revenue to a paunch digestion project (reducing payback by 20%). Based on existing pilot projects and recent wastewater analysis projects (A.ENV.131 and A.ENV.151) approximately 60 mgP L⁻¹, and 250 mgN L⁻¹ can be released during digestion of paunch wastewater and DAF sludge at a red meat processing facility. At these concentrations, phosphorous recovery through crystallisation is expected to be feasible with strong economic returns.

Crystallisation refers to technologies for recovery of nitrogen and phosphorus through precipitation of compounds such as struvite (MgNH₄PO₄·6H₂O). This is an emerging technology option, rather than an established process in the Australian red meat processing industry. Struvite precipitation is targeted towards P recovery, rather than N recovery. Struvite is a highly effective fertiliser that has a phosphorous content competitive with most commercial fertilisers, and it requires only magnesium dosing, which removes phosphorous at a net cost of \$1/kg P, compared to approximately \$11/kg P for iron or alum dosing. Given the fertiliser value of phosphorous at \$3.5/kg P, there is a substantial driver for phosphorous recovery.

Phosphorus is generally the limiting compound when considering struvite crystallisation from red meat processing wastewater. The ratio of nitrogen and phosphorus in Australian slaughterhouse wastewater is generally greater than 5:1, while the mass ratio of N to P in struvite is approximately 1:2. Therefore, complete removal of P would result in removal of approximately 10% of N from the wastewater. Struvite crystallisation is not suitable as a standard-alone technology for N removal, but may provide significant benefits to processing plants where P removal is required.

Crystallisation is a physico-chemical process and is generally governed by the solubility of compounds in the wastewater. The solubility of struvite decreases significantly at elevated pH (~8) and this generally allows for highly effective P removal (to less than 3 mg.L⁻¹ soluble P). However, slaughterhouse wastewater is a complex matrix of organic and inorganic components. Some of these components can bind to the P and inhibit crystallisation. Where the mechanism of inhibition is identified, chemical treatments can be applied (e.g. EDTA); however, this can significantly increase the cost of a struvite process.

1.2 Project Objectives

This is an extension of previous project 'A.ENV.0154: Nutrient recovery from paunch and dissolved-air floatation (DAF) sludge digestate', and it further examines the requirements for wastewater filtration, struvite precipitation and product recovery from the digester technology at a red meat processing facility (Site A). As part of the project extension, additional phosphorous recovery trials were conducted on a crusted anaerobic lagoon at a second site (Site B).

Stated objectives of the extension are to:

- develop technology for nutrient recovery from the main recirculation line in the pilot-scale in-vessel anaerobic digester unit at Site A (project A.ENV.0155)
- identify the lower limit for phosphorous removal (theoretical limit is approximately 5 mgp.L⁻¹)
- assess chemical consumption, provide scale-up data and complete cost–benefit analysis.

2.0 Overall Process Design

2.1 Process Flow Sheet

The overall process flow sheet for the crystallisation plant used for phosphorous recovery is shown in Figure 1. The set-up included an optional microfiltration unit, settling tank (2,000 L), aeration tank (200 L), crystalliser (150 L) and overflow tank to improve product recovery (100 L).

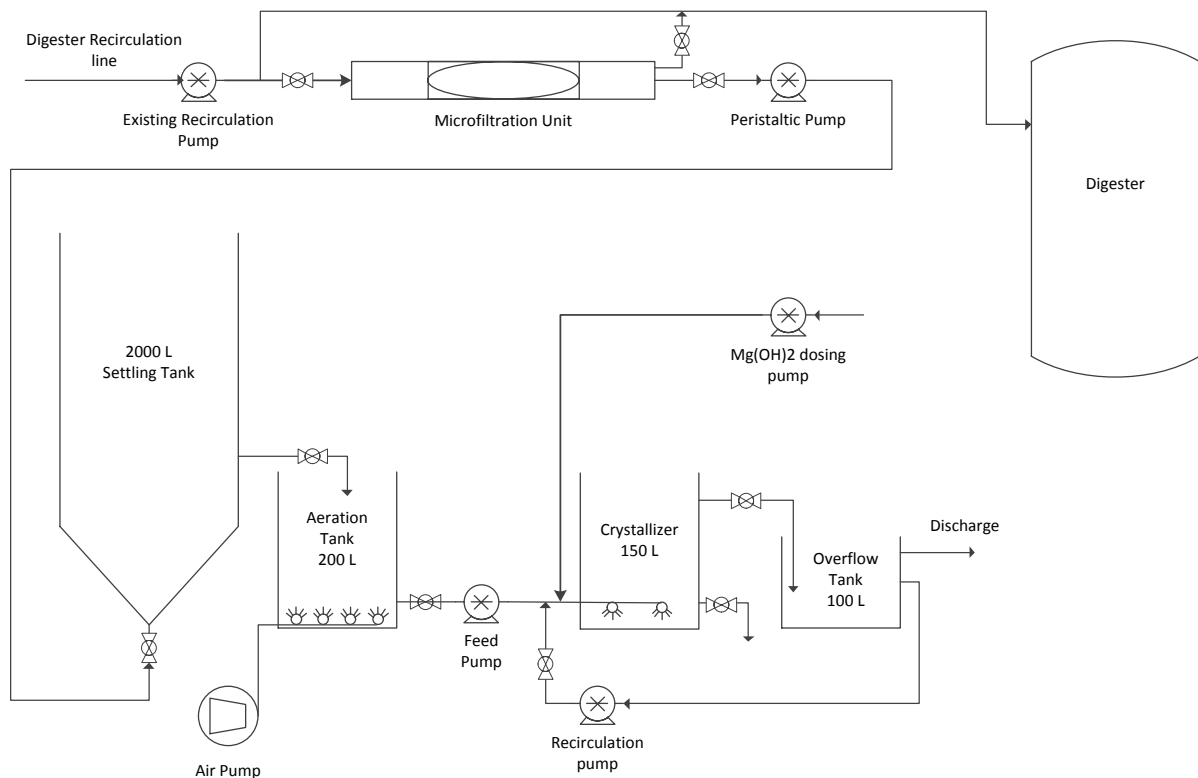


Figure 1: Process flow sheet for pilot scale struvite crystalliser for phosphorous recovery

2.2 Pretreatment: Filtration and Settling

The role of the microfiltration unit and settling tank was to produce a cleaner wastewater feed for struvite crystallisation. This is important as suspended solids can inhibit precipitation and/or reduce the purity of the fertiliser product.

Filtration was achieved using a custom filter module containing a stainless steel mesh (0.1 mm aperture size) as the filter media. The stainless steel module has two concentric cylinders. The internal cylinder is stainless mesh rolled into a 75 mm tube and it acts as the filter. The outer tube is 100 mm stainless steel pipe to collect permeate. The design of the stainless steel membrane module is shown in Figure 2 and Figure 3. Filtration was designed to remove coarse solids only, such as digested paunch. Coarse filtration is part of the original process design, but is not required on streams with lower solids or fines, such as lagoon effluent.

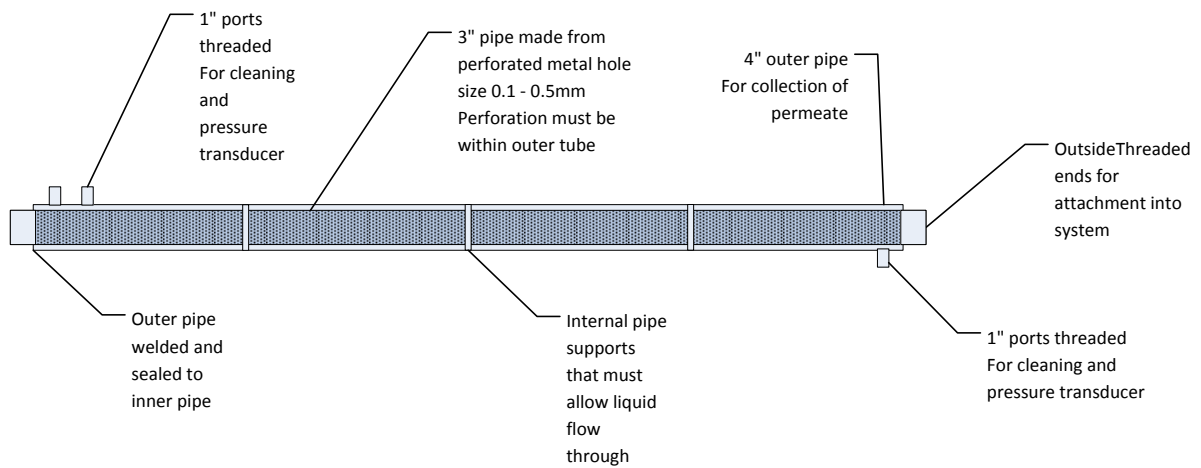


Figure 2: Schematic for custom-designed stainless steel filtration module



Figure 3: Custom-made stainless steel filtration module

The role of the settling tank was to further reduce the concentration of fine solids in the filtered feed stream prior to aeration and subsequent crystallisation. This step contributes to improved crystallisation and improved product quality.

During process design a settling test was conducted using a 1 L measuring cylinder on permeate from the stainless steel filter module. The solid settling behaviour was observed for 120 mins. As shown in Figure 4: Settling test on permeate recovered from the filtration unit, most solids in permeate settled in less than 45 mins. The clear supernatant was recovered and was tested in batch crystallisation experiments against a control without settling. The test confirmed that settling is required following filtration to produce suitable feed for the struvite crystallisation.

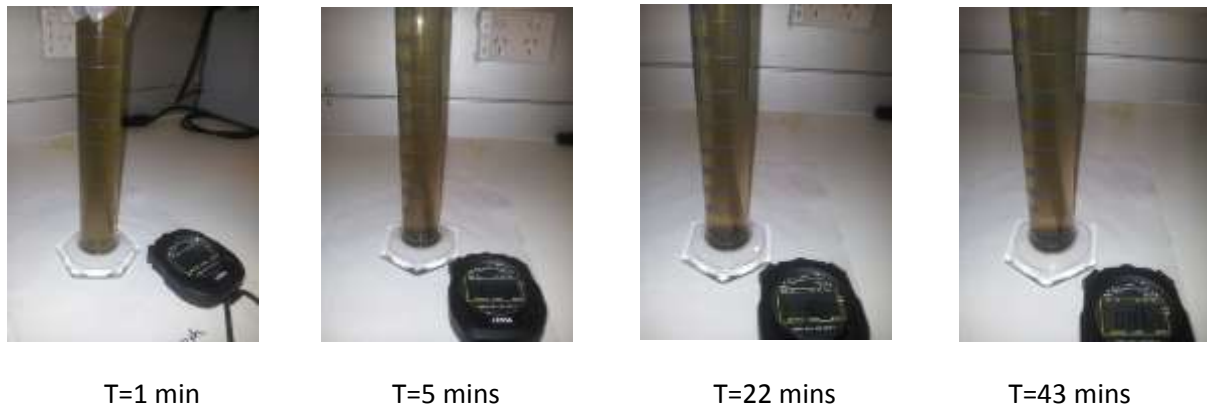


Figure 4: Settling test on permeate recovered from the filtration unit

As part of the original process design (Site A) a 2,000 L settling tank was installed to collect permeate from the custom-made stainless steel module. Permeate was fed at $1 \text{ L}\cdot\text{min}^{-1}$ and, therefore, the settling tank residence time is over 24 hours. The settled solids in the settling tank will be removed regularly. The settling tank was removed for the second trial (Site B) using lagoon effluent as a feed.

2.3 Aeration

Struvite crystallisation requires increased pH to significantly decrease the solubility of struvite. Increased pH can be achieved using aeration or chemical dosing (sodium hydroxide and/or magnesium liquid). Aeration increases pH by stripping CO_2 (a weak acid) from the solution and is considerably cheaper than chemical dosing. The addition of magnesium (typically in the form of $\text{Mg}(\text{OH})_2$) may also be required for precipitation; however, chemical addition will be lower following aeration.

An initial batch aeration test demonstrated that the pH increased from 6.4 to 7.8 after aeration for 30 minutes (shown in Figure 5). Based on this batch experiment an initial residence time of 60 minutes was selected for the aeration tank.

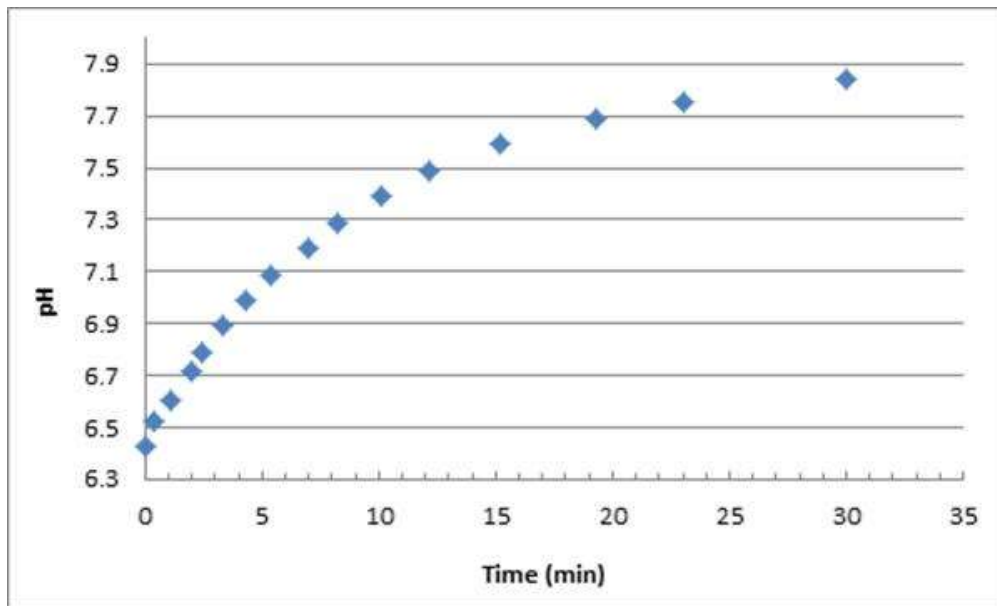


Figure 5: Increase in pH during batch aeration trials at a flow rate of 70 L.min⁻¹

Continuous aeration experiments were conducted to validate the results of the batch aeration trial. The continuous aeration experiments were performed without the addition of Mg in the crystalliser. Aeration was performed in a 200 L drum with a 100 L working volume. The air pump was operated with a flow rate of 20 L.min⁻¹ and six air stones (configured in strips) were used for sparging. Results of the continuous aeration trials were similar to the batch aeration trials. The pH of permeate increased with an increase in the residence time (Figure 6).

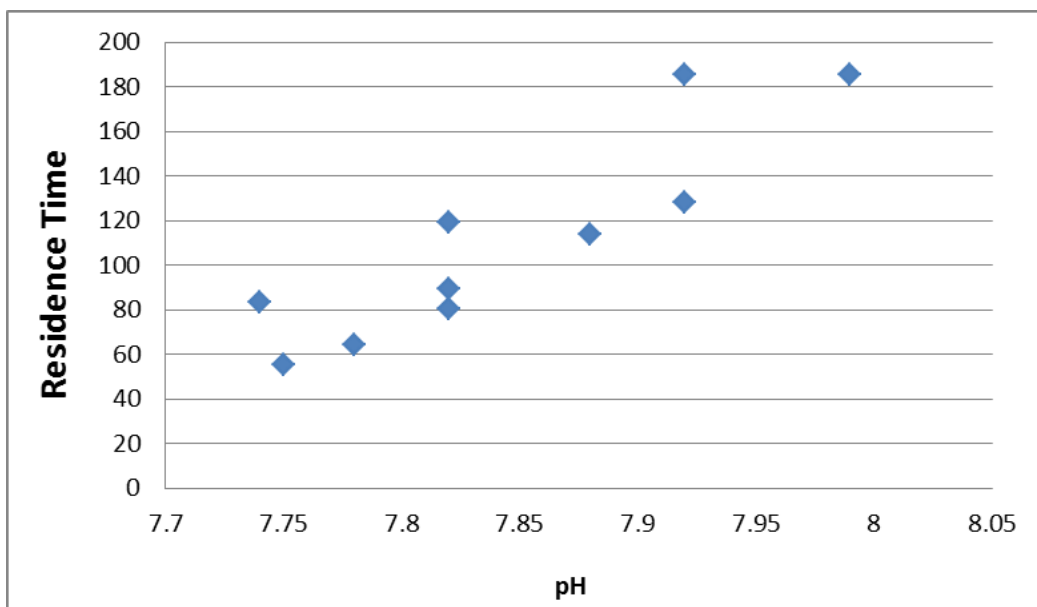


Figure 6: Residence time vs. pH in the aeration tank. The pH of the feed was constant at 6.55.

2.4 Crystallisation Reactor

The crystallisation reactor was custom designed at the University of Queensland. It is a 192 L square-bottom tank made of acrylic plates. The crystalliser has three zones with a total working

volume of 100 L (shown in Figure 7). The bottom zone includes a crystal accumulation zone, product discharge valve and two horizontal half-inch ($\frac{1}{2}$ ") diameter pipes to feed effluent from the aeration tank. Each $\frac{1}{2}$ " pipe has 3 mm holes each 50 mm apart facing the bottom of the crystalliser to create jet and mix settled crystals in the bottom zone. The middle zone is separated from the top and bottom zone via flat plates with a narrow opening (20 x 40 cm). The zone includes two flat plates and six lamella plates fixed using gaskets and screws, and can be completely removed for cleaning purposes. Six lamella plates are used inside the narrow opening, to reduce the upward velocity of the struvite crystals and retain maximum crystals in the bottom zone. The lamella plates are supported by 4 mm threaded stainless steel rods, placed perpendicular to the lamella plates. The lamella plates are spaced 25 mm apart using spacers and bolts. The top zone has a pH probe and overflow port for the effluent.

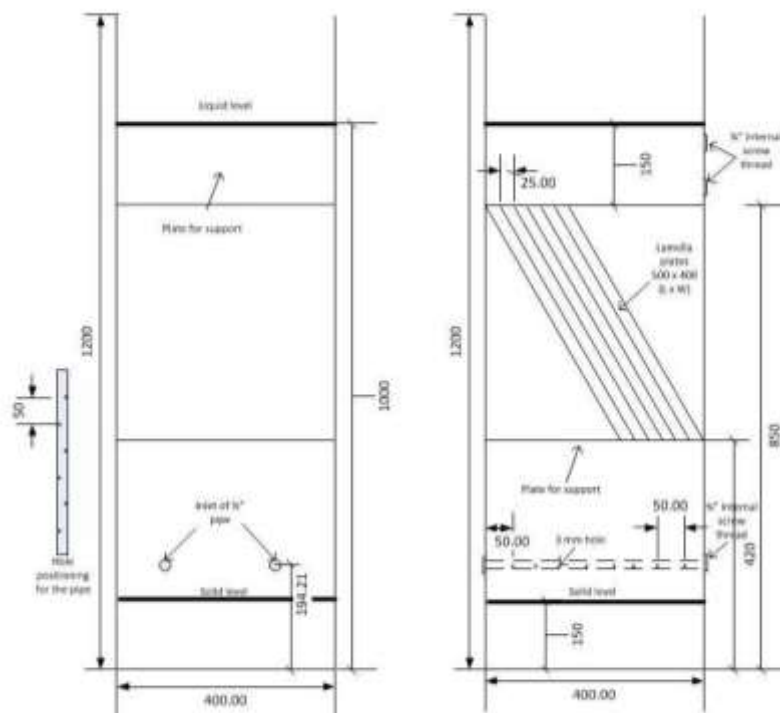


Figure 7: Design of struvite crystalliser used to extract phosphorus and nitrogen from paunch wastewater

During crystalliser operation, Mg dosing was used to further increase pH and assist in struvite precipitation. Magnesium was added as magnesium hydroxide liquid (MHL) containing 17.2% w/v magnesium and 10.1% w/v calcium. The full elemental composition of MHL is shown in Table 1. Typical Mg dose rates were 220 mL.d⁻¹ of solution. This equates to 40 g.day⁻¹ Mg.

Table 1: Elemental composition of magnesium hydroxide liquid (MHL) used for struvite crystallisation

Element	Unit	Concentration
Mg	%	17.2 ± 2.4
Na	%	15.0 ± 0.7
Ca	%	10.1 ± 0.5
K	%	1.0 ± 0.1
S	%	3.8 ± 0.2
Al	mg.L ⁻¹	762 ± 255
B	mg.L ⁻¹	125 ± 10
Ba	mg.L ⁻¹	86 ± 5
Cu	mg.L ⁻¹	1185 ± 68
Fe	mg.L ⁻¹	363 ± 177
Mn	mg.L ⁻¹	146 ± 33
Mo	mg.L ⁻¹	28 ± 39
Zn	mg.L ⁻¹	304 ± 55

Chemical dosing is a major cost associated with P recovery and is therefore an area for process optimisation.

2.5 Product Collection

Product collection consisted of 2 x 100 L settling tanks. Wastewater from the first settling tank overflowed into the second settling tank. Wastewater from the second settling tank overflowed and was discharged as process effluent. There was a recycle loop between the first settling tank and the crystallisation reactor; however, the settling tanks did not contain any other form of mixing or agitation and were designed to promote settling of the struvite product for collection.

2.6 Process Operation and Control

The nutrient recovery pilot plant was monitored and controlled using field sensors and a process logic control (PLC) system. A list of process sensors and measured variables is shown in Table 2. A piping and instrument diagram showing the location of sensors within the process is shown in Figure 8. The process control included alarms and automatic shutdown procedures to prevent equipment damage in the event of abnormal process conditions.

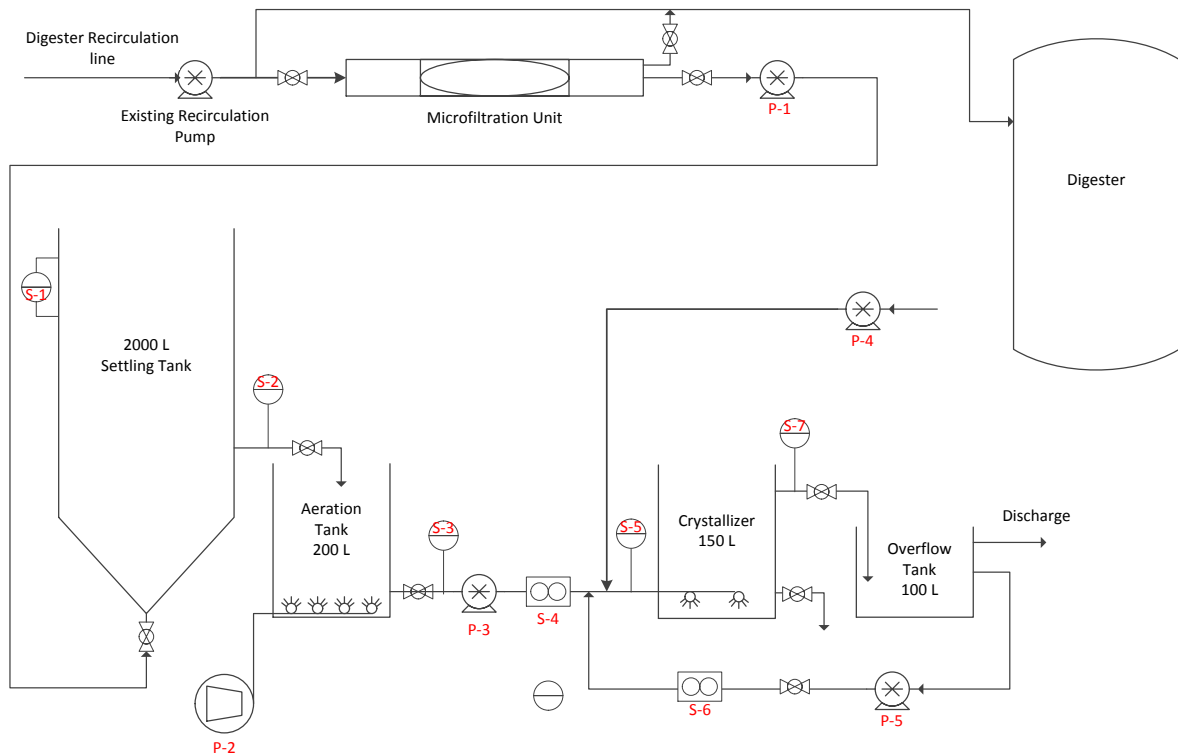


Figure 8: P and ID for the struvite crystallisation pilot plant

Table 2: Sensors and control loops used in nutrient recovery pilot plant

ID	Sensor	Measured variable	Purpose
S-1	Level controller	Level in the settling tank	Turns off peristaltic pump (P-1) if the liquid level in the settling tank is above set point
S-2	pH probe	pH prior to aeration	
S-3	pH probe	pH following aeration	The feed pump (P-3) is turned off if the pH following aeration is below set point (pH 8.2). If the pH is above set point (8.2), the aeration pump (P-2) is turned off.
S-4	Flow sensor	Flow rate of the feed pump (P-1)	Triggers alarm if the flow rate is below set point
S-5	Pressure transducer	Pressure in the crystalliser feed line	Turns off the entire system if the pressure is above set up (5 bar)
S-6	Flow sensor	Flow rate of the recirculation pump (P-5)	Triggers alarm if the flow rate is below set point
S-7	pH probe	pH in the crystalliser	Triggers Mg dosing pump (P-4) to 'on' position if the pH is below set point (8.4–8.6)

Process automation was achieved using a mobile process logic control system built to facilitate monitoring and control while maintaining operational flexibility. The PLC required a standard 230V GPO for power, and was capable of powering all pumps and sensors required for the pilot plant. The PLC logged process data, monitored process conditions/alarms and controlled all pump events. The PLC was designed to be portable and did not require specialist electrical installation.

This allowed the pilot plant to be located and installed with minimal infrastructure and minimal support from technical trades.

3.0 Process Performance

3.1 Site A

3.1.1 Plant installation

Site A is a cattle-only facility located in Queensland, Australia, and processes 1200–1400 head per day. The struvite crystallisation plant was commissioned at Site A in early 2013 to treat effluent from the biosolids demonstration plant, an IVAD process treating cattle paunch (Figure 9). The reactor was initially seeded with sand (0.5–1.0 mm) to assist granulation. The struvite deposited on the sand and granules were formed but the bulk of the product was in powdered form. The plant produced over 30 kg of crystallised product (struvite) from Site A and was decommissioned in December 2013.



Figure 9: Struvite crystallisation plant installed at Site A to recover phosphorous from anaerobically digested paunch

3.1.2 Pilot Plant Performance Data

Continuous crystallisation trials commenced in May 2013. A summary of pilot plant performance at Site A is shown in Table 3. The phosphorus concentration in the permeate exiting the filtration and settling stage was approximately 48 mg.L^{-1} and was similar to the phosphorus concentration in the digested paunch; therefore, the screening and clarification steps are effective and do not significantly impact P concentration. This is important for P recovery. However, during aeration, the P concentration reduced from 48 mg.L^{-1} to 29 mg.L^{-1} , suggesting a removal of 19 mg.L^{-1} of P (40%) during aeration. This was likely due to an increase in pH and precipitation of P as struvite or calcium phosphate. Both magnesium (e.g. component in struvite) and calcium also decreased in the aeration tank. Following struvite crystallisation the final concentration of P in the effluent was less than 3 mg.L^{-1} , indicating that 90% of P entering the crystalliser is recovered ($\sim 26 \text{ mg.L}^{-1}$). Final P recovery is in the range of $26 \text{ mg.L}^{-1} - 45 \text{ mg.L}^{-1}$.

Table 3: Concentration matrix at different sampling point

	pH	P mg.L ⁻¹	Mg mg.L ⁻¹	Na mg.L ⁻¹	Ca mg.L ⁻¹	K mg.L ⁻¹
Feed	6.7	52.7	12.4	215.5	38.5	65.5
Settling	7.3	47.6	16.6	210.8	37.2	59.6
Aeration	8.3	29.4	7.4	204.9	25.7	59.7
Effluent	8.7	2.6	37.3	203.3	13.5	58.7

At Site A, the pilot plant was treating 1,500 L.d⁻¹ of wastewater and total P recovery was in the range of 40 to 60 g.d⁻¹. This corresponds to struvite production of 400 g.d⁻¹ to 600 g.d⁻¹. The plant operated for approximately 100 days with approximately 50 kg of struvite produced.

3.2 Site B

3.2.1 Plant installation

Site B is a cattle-only facility in New South Wales, Australia, processing 1,200 head per day. The struvite crystallisation plant was relocated to Site B in early 2014 to recover P from treated effluent exiting a crusted anaerobic lagoon (Figure 9). Suspended solids in the effluent from a crusted lagoon is typically quite low and therefore the pilot plant was modified for use at Site B and did not include a coarse filtration step or a settling tank to remove solids prior to crystallisation. The reactor was initially seeded with sand (0.5–1.0 mm) to assist granulation. Struvite deposited on the sand and granules were formed, but the bulk of the product was in powdered form.



Figure 10: Struvite crystallisation plant installed at Site B to recover phosphorous from anaerobic lagoon effluent

3.2.2 Batch Crystallisation Trials

Batch crystallisation trials were conducted on effluent samples collected from Site B to estimate potential for struvite recovery. In the first set of batch experiments, the pH was increased by adding NaOH; however, seed crystals were not added. The results (presented in Table 4) demonstrate no change in soluble P during these trials, and this was likely the result of the inhibition of crystal nucleation that prevented the formation of new crystals. Additional batch crystallisation experiments were conducted using seed crystals to overcome potential inhibition of crystal nucleation; the results are presented in Table 5. The results from the second set of experiments demonstrate a decrease in soluble phosphorous, resulting from all tests with the addition of seed crystals. Phosphorous precipitation improved in tests as the pH was increased from 8.0 to 8.8.

Table 4: Soluble compounds in batch crystallisation trials without added seed crystals

pH	P mg.L ⁻¹	Mg mg.L ⁻¹	Na mg.L ⁻¹	Ca mg.L ⁻¹	K mg.L ⁻¹
7.1	29.8	18.2	154.2	21.6	64.8
7.1	29.6	39.3	153.4	20.6	64.5
7.4	29.6	42.4	183.0	20.7	64.7
7.9	29.8	42.8	216.2	20.5	65.6
8.3	30.0	42.5	248.9	20.6	65.2
8.6	29.3	41.4	277.0	20.0	64.1

Table 5: Soluble compounds in batch crystallisation trials with seed crystal addition

Event	pH	P mg.L ⁻¹	Mg mg.L ⁻¹	Na mg.L ⁻¹	Ca mg.L ⁻¹
Unfiltered – no seed	7.26	28.9	18.5	143.6	23.2
Filtered after aeration – no seed	8.00	28.2	18.3	140.6	23.1
Filtered after adding MgCl ₂ – no seed	7.98	27.1	51.3	137.0	23.0
Filtered – seeds	7.95	20.5	45.8	139.2	22.6
Filtered after raising pH – seed	8.36	12.7	39.7	177.3	22.5
Filtered after raising pH – seed	8.79	6.2	33.5	242.1	22.1
Filtered after waiting 2 hours – seed	8.76	5.4	32.8	237.8	22.4
Unfiltered	8.76	50.3	69.7	239.0	23.0

The results of batch crystallisation trials demonstrate the potential for the inhibition of new crystal formation; however, phosphorous recovery was still successful when smaller seed crystals were present. Recycling smaller crystals as seed crystals is part of conventional operating practice in commercial crystallisation processes and therefore these results are not expected to impact the viability of phosphorous recovery from slaughterhouse wastewater.

3.2.3 Pilot Plant Performance Data

A summary of pilot plant performance at Site B is shown in Table 6. The phosphorus concentration in the pond effluent (feed) was approximately 34 mg.L⁻¹ and was present almost entirely as soluble phosphate (PO₄). The phosphorous concentration in the pond effluent was significantly lower than concentrations previously measured in the raw wastewater produced at

this site (project A.ENV.151) and may indicate 40% of phosphorous discharged from the production areas accumulated in the crusted lagoon.

Table 6: Performance of phosphorous recovery process

		TKN mg N/L	NH ₄ mg P/L	TP mg P/L	PO ₄ mg P/L
Feed	Min	207	197	30	28
	Average	254	229	34	32
	Max	284	197	30	28
Aeration tank	Min	231	202	33	30
	Average	260	219	36	29
	Max	290	240	40	33
Effluent	Min	212	197	8	1
	Average	235	232	19	6
	Max	254	246	46	30

The P concentration in the wastewater showed no significant decrease during aeration, indicating that no P is lost during this step. This is a significant improvement from operation at Site A in the previous project (A.ENV.0154), where 40% of P accumulated in the aeration vessel. Following struvite crystallisation, the average final concentration of soluble P in the effluent was 6 mg.L⁻¹, indicating that 80% of P entering the crystalliser forms precipitate.

The average concentration of total P in the process effluent was influenced by several process disturbances and wash-out events; however, this value (19 mg.L⁻¹) does indicate that some of the precipitate was being lost in the effluent. This has been identified as an area for subsequent optimisation. The plant treated 1,500 L of wastewater per day and precipitated 26 mgL⁻¹ P. This corresponded to struvite production of 400 g.d⁻¹, approximately 300 g.d⁻¹ of solids was being harvested from the process, including struvite and digested sludge coming from the pond effluent. Therefore, product recovery was less than 75% and requires improvement.

Based on the stoichiometric composition of struvite, the required Mg dose for complete P recovery is 37 g.d⁻¹. The actual dose rate of Mg to the process was approximately 40 g.d⁻¹. This would suggest that Mg dosing was relatively efficient. However, the process had several days with poor crystallisation and soluble P removal. Examination of the process data indicated that soluble Mg was also low on these days and may have been a limiting factor. More work into the optimal Mg dose, considering cost minimising and stable process performance, is required.

3.3 Fertiliser Growth Trials – GRDC Funded Activity

As part of a GRDC project supporting the struvite recovery project, the struvite product was granulated using struvite as fine powder, seed granules (struvite or sand) of size 0.5–1 mm and binding solvent (10% citric acid). These granules were used for field trials on canola plants at Trangie, NSW, and on wheat plants at three different locations: Saddleworth (SA), Forbes (central NSW) and Curban (NSW near Gilgandra).

At Forbes and Curban, crop yields during the field trials were comparable for struvite and mono-ammonium phosphate (MAP) at similar application rates (8-P kg/ha). At Trangie and Saddleworth, the results were inconclusive, due to no/limited response of the fertiliser. There was no

significant difference in crop yield for plots with and without any added fertiliser at these sites. Additional field trials are recommended, in conjunction with GRDC projects, to assess struvite as a renewal fertiliser, establish market value and market confidence.

4.0 Cost Benefit

4.1 Basis Used In Assessment

A cost–benefit analysis was conducted based on an Australian plant processing 600 head per day, 250 days per year, with total effluent flow of 1.8 ML per day. Basic inputs were as presented in Table 7.

Table 7: Wastewater flow, concentration and load for cost–benefit analysis

	Concentration mg·L ⁻¹	Load
Flow		1.8 ML d ⁻¹
COD	10,200 mg L ⁻¹	18.4 tonnes d ⁻¹
Solids	8,400 mg L ⁻¹	15.1 tonnes d ⁻¹
O&G	2,300 mg L ⁻¹	4.2 tonnes d ⁻¹
Nitrogen	405 mg L ⁻¹	730 kg d ⁻¹
Phosphorous	56 mg L ⁻¹	100 kg d ⁻¹

4.2 Process Design and Analysis

The crystallisation plant used in the CBA combines the aeration stage and crystallisation reactor in a single process vessel (HRT 2 hours). Capital costing is estimated at \$1,000 per kL tank volume (similar to the cost of the anaerobic digestion demonstration facility in project A.ENV.099/A.ENV.155). This is a relatively high installed cost for full-scale process vessels, but it was selected to provide a conservative cost–benefit analysis and allow some margin for baffling and other inclusions within the vessels. Estimated capital costs are shown in Table 8.

Table 8: Capital costs for 600 head per day example

Capital Costing		
Aeration tank	0kL	\$0
Crystallisation reactor	150kL	\$150,000
Pumps and aeration	10kL	\$28,026
Piping	5% tank cost	\$14,013
Foundation	10% tank cost	\$28,026
Electrical and installation	5% tank cost	\$14,013
Process control		\$40,000
Total installed capital		\$248,026
Engineering		\$24,802
TOTAL COST		\$272,829

This indicates that the crystallisation tank contributes approximately 55% to capital cost. The addition of the aeration stage may add an additional 20–25% to capital requirements and will be investigated during sensitivity testing. A membrane filtration module was added in the pilot plant to remove solids prior to crystallisation, and this contributed approximately 20% of the capital cost. Dewatering and/or filtration have not been included in the cost of a full-scale nutrient recovery plant as this is likely not required on anaerobic lagoon effluent; however, dewatering could be added to the CBA and could increase capital by 20%.

Operating costs have been estimated based on current pricing, including electricity at \$0.15/kWh, personnel at \$80,000 per full-time equivalent, maintenance of 5% per annum capital and normal chemical costs for magnesium oxide, etc. Process performance is based on anaerobic biodegradability of 85% (taken from project A.ENV.151), phosphorus release and availability of 74%, and nitrogen release and availability of 32%. Under these conditions, phosphorus is the limiting nutrient for recovery through struvite precipitation. Fertiliser product value is based on recovered phosphorous at \$3.48/kg P and recovered nitrogen at \$1.33/kg N.

Table 9: Annual operating costs for 600 head per day example

Item		Cost
Operator salaries	0.2 FTE	\$16,000
Vessel and piping maintenance	4% capital	\$13,641
Mixing and aeration	0.5 kWh per m ³ per day	\$4,106
Chemical MgO		\$40,134
Total Operating Costs		\$73,882
Nitrogen recovered	(\$1.33/kg N) inc. chemicals	-\$17,565
Phosphorous recovered	(\$3.48/kg P) inc. chemicals	-\$91,454
Total product value		-\$109,020
Net annual benefit		-\$35,138

Based on the scenario described, the payback period for the crystallisation plant would be approximately 7.8 years; however, this CBA does not consider the reductions in disposal costs for N and P that are captured during crystallisation. Trade waste fees could be reduced by \$67,000 (\$43,000/yr P and \$24,000/yr N) for a plant discharging to the sewer in the Brisbane region, and this could reduce the payback to 2.7 years. However, disposal costs are highly dependent on the mode of final disposal (irrigation or sewer) and council trade waste fees.

5.0 Recommendations

While process vessels are the major component of capital expenditure, mitigation of trade waste fees and revenue from the struvite fertiliser product will have the biggest impact on the CBA and payback calculations. Based on relative concentrations of nutrients in the feed and the chemical composition of the desired struvite product, phosphorus has been identified as the limiting nutrient in struvite precipitation and the limiting factor impacting the quantity of recovered product. Therefore, it is clear that optimised P recovery should be a priority in continued process development.

The average concentration of total P in the process effluent was greater than the soluble P, which indicates that some of the precipitate was being lost in the effluent. This reduces the quantity of the product recovered and increases the discharge costs of the nutrients. At Site B, the pilot plant performance was also influenced by several process disturbances where digested sludge was washed out with the AL effluent and fed to the struvite crystallisation pilot plant. These disturbances have the potential to significantly impact the crystallisation process by reducing precipitation performance through several mechanisms such as a buffering effect that reduces pH and increases P solubility. Sludge in the reactor may reduce settling of the struvite product and/or lead to accumulation of organic residues in the product. This decreases the P concentration and potentially decrease the value of the product. The frequency and impact of these sludge wash-out events is an area for further investigation. A better understanding of this operating risk would assist in decision making, particularly around strategies to prevent solids addition to the process, such as microfiltration modules.

Further to this, current research being undertaken by UQ demonstrates that nutrient release from in-vessel anaerobic digestion processes is approximately 90% of N (as NH_3) and only 74% of P (as PO_4). Similar trends were observed when examining CAL influents and CAL effluents, where up to 50% of P in the slaughterhouse wastewater was accumulating in the CAL. This data demonstrates that anaerobic treatment steps have not been optimised for nutrient recovery. Again, this reduces the quantity and value of product recovery and increases the costs associated with waste discharge. Further research is recommended to re-tool anaerobic treatment and nutrient recovery processes and to integrate them as an optimised treatment train. Optimisation of the integrated process should focus on maximising the release of nutrients in the anaerobic step to facilitate recovery in the crystalliser. Operation of the anaerobic step at a slightly depressed pH is a potential strategy to prevent the loss of nutrients; however, this may impact process rates and/or stability and therefore must be investigated rigorously.

Considering the CBA of P recovery processes is highly dependent on both mitigation of waste disposal fees and the value of the nutrient product. Market development analysis for the recovered nutrient product is a critical step to ensure the fertiliser market exists and the value is accurate. This will allow a complete and detailed cost–benefit analysis of the technology. Additional field trials are recommended to assess struvite as a renewal fertiliser, confirm market value and establish market confidence. While crop growth trials are not expected as part of the AMPC projects, these activities are currently being supported by GRDC, and the results will be available to assist in the assessment and analysis of the technology in the 2014–15 financial year.

Appendix A: Parameters Used in CBA

The following data and assumptions were utilised as the basis of the CBA calculations.

Description of case study:

- 1,800,000 litres of effluent per day
- Five days per week operation
- 24 hours per day
- 50 weeks per year
- 405 mg.l⁻¹ nitrogen as ammonia
- 56 mg.l⁻¹ phosphorus as phosphate.

Basis of capital costs:

- HRT of two hours for crystallisation vessels
- Installed capital cost of \$1,000 per m³ for process vessels
- Piping cost based on 5% of vessel cost
- Foundation cost based on 10% of vessel cost
- Electrical ancillaries based on 5% of vessel cost
- Control system fixed at \$40,000.

Basis of operating costs and revenue:

- General maintenance cost at 5% of capital
- Aeration energy required at 0.5 kwh per m³ per day
- Electricity cost of \$0.15 per kwh
- Operational staff cost of \$80,000 per year for one full-time equivalent
- Plant requires maintenance staff at a rate of 0.2 fte
- Magnesium cost of \$800/tonne of mhl
- Fertiliser value of nitrogen recovered is \$1.33 per kg n
- Fertiliser value of phosphorus recovered is \$3.48 per kg p
- Trade waste fee saving for nitrogen of \$2.03 per kg n
- Trade waste fee saving for phosphorous of \$1.63 per kg p.

Process performance assumptions:

- Phosphorous recovery is 74% or 40 mg.l⁻¹
- Nitrogen recovery is 5% or 20 mg.l⁻¹
- Magnesium dose rate at 2x stoichiometric requirement

Glossary

AD	Anaerobic Digestion
AL	Anaerobic Lagoon
AMPC	Australian Meat Processor Corporation
CAL	Covered Anaerobic Lagoon
CBA	Cost–Benefit Analysis
CO ₂	Carbon Dioxide
COD	Chemical Oxygen Demand
DAF	Dissolved-Air Flotation (Tank)
EDTA	Ethylenediaminetetraacetic Acid
FOG	Fat, Oils and Grease
GRDC	Grain Research and Development Corporation
HRAT	High-Rate Anaerobic Technology
HRT	Hydraulic Residence Time
IVAD	In-Vessel Anaerobic Digestion
N	Nitrogen
MG	Magnesium
MHL	Magnesium Hydroxide Liquid
MLA	Meat and Livestock Australia
NH ₄ -N	Ammonium Nitrogen
P	Phosphorus
PLC	Process Logic Control
Po ₄ -P	Phosphate Phosphorus
SRT	Sludge Retention Time
UQ	The University Of Queensland