AMPC

FINAL REPORT

Struvite or Traditional Chemical Phosphorus Precipitation – What Option Rocks?

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1.0 EXECUTIVE SUMMARY

Phosphorus removal from red meat industry wastewater is currently performed by chemical precipitation, but there is increasing interest in struvite crystallization, as it produces a useable fertilizer product rather than waste solids. This research project aimed to review some commercially available and proven full-scale struvite crystallization systems and perform a technical and economic assessment of the potential for struvite crystallization as a phosphorus removal process against conventional phosphorus precipitation by chemicals.

Struvite crystallization is a significantly more sophisticated process than chemical precipitation. Struvite comprises a magnesium, phosphate and ammonium compound and crystallises from water solutions at elevated pH when there is sufficient supersaturation. The similarity between conventional chemical precipitation and struvite crystallization is that both require chemical addition to facilitate solids precipitation. Struvite crystallization requires a more controlled environment with reactor design focused on fine solids retention, chemical addition and mixing techniques to promote large crystal/agglomerate formation to permit their separation from the effluent. This results in a higher up-front capital cost.

There are no reports of full-scale struvite processes implemented on meat processing facilities. However, pilot scale studies in Australia with the meat processing wastewater has proven its technical feasibility. However washout of struvite fines, reducing the overall phosphorus removal efficiency, was an issue.

Struvite crystallization is a commercially viable, operationally practicable phosphorus removal process with over 50 full-scale installations world-wide provided by numerous vendors. While the successful adoption of struvite crystallization technology and longer than 10 year operating history is reassuring, the number of competing vendors with radically different designs is challenging for industry decision makers.

The major design considerations determining the most appropriate struvite crystallization technology for red meat processors include: the initial and final phosphorus discharge concentrations, integration of the struvite process with the wastewater treatment plant without impacting negatively on downstream operations, and its cost competitiveness with alternate phosphorus removal technologies and especially precipitation. The appropriate choice is likely to differ for individual meat processing facilities given different existing infrastructure, location and facility size. It is critical to understand that struvite technology will achieve only moderate final effluent levels (typically 15 – 20 mgP/L) more suitable for discharge to irrigation than sewer or surface waters.

Johns Environmental approached four vendors, selected on the basis of market share and different process designs, to ascertain capital and operating cost estimates for a struvite process suited to a medium-sized red meat processing facility with anaerobically-treated effluent. Phosphorus removal performance and some process detail were also requested. The results indicate that such a treatment plant would cost of the order of between A$4.75 – 6.25 million to purchase and install with annual operating costs of A$400,000 – 800,000. The capital costs are much higher than for competing processes, but with the benefit that the struvite solid is far more environmentally useful than chemical sludges.

To better understand how the struvite process stacks up against competing chemical precipitation processes – both a standalone chemical phosphorus precipitation (CPP) plant and a co-precipitation with a biological nitrogen removal activated sludge plant (BNR) – a series of cost benefit analyses were performed. Despite the high upfront costs, the struvite process is still economically better than a stand-alone chemical phosphorus precipitation unit in most scenarios over 20 years. To the contrary, however, struvite is usually not competitive if the processing site has the option to chemically dose into an existing BNR system. This is often the case for the larger meat processing facilities in Australia.

Only under more optimistic scenarios is struvite crystallization the most economical phosphorus treatment option. Under this scenario the requirements are for large processing plants (5 ML/d or more wastewater flow) with high sludge disposal costs (> $220/tonne), a high initial phosphorus concentration (80 mg/L) and low-end struvite equipment and installation costs (< $AUD 6,500,000).

The cost benefit analysis highlighted variables with the most impact on economic feasibility over a 20 year life. Interestingly, the value of the struvite had relatively little effect on the economic competitiveness of a struvite installation with only a 10% difference in Net Present Value (NPV) between a struvite value of $0 and $400 per tonne. The factors with greatest impact were the cost of chemical sludge disposal, meat processing facility size (larger is best) and feed phosphorus concentration (higher is better).

The intangible significant advantages in terms of environmental credentials attributed to the installation of struvite crystallization phosphorus recovery has not been accounted for in the economic viability but should also be considered.

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2.0 INTRODUCTION

Phosphorus removal from wastewater is an expensive but necessary requirement to meet discharge conditions at many Australian red meat processing plants. The three technical options that are commercially proven for phosphorus removal from wastewater are:

- enhanced biological phosphorus removal (EBPR), or "Bio-P" uptake typically in purpose-built activated sludge plants,
- phosphorus uptake by bacterial growth in a wider variety of biological systems (activated sludge, aerated ponds, etc), and
- chemical precipitation.

Phosphorus removal using EBPR is common in large sewage treatment plants, but has proven challenging for meat processing operations due to the elevated nitrogen levels and the requirement for high levels of readily biodegradable carbon, which is lacking in meat processing wastewater for the level of phosphorus reduction required (EBCRC, 2008). On the contrary, the removal by bacterial phosphorus uptake is much simpler, but typically removes only a small proportion of the reduction required. This leaves meat processing plants with little option but to install the most proven option - chemical precipitation systems - despite the significant and costly downsides of high chemical consumption and the need to dispose of unstable chemical sludges with little beneficial outcome.

There is much interest in the industry as to whether struvite crystallization is a more cost effective and environmentally friendly alternative to current chemical precipitation. This report seeks to address this question through a review of the background of struvite crystallization, an assessment of the currently available and proven struvite crystallization technologies and a comparison of the economics, using cost benefit analysis, of a dedicated struvite crystallization facility versus a traditional chemical phosphorus precipitation (CPP) plant treating meat processing effluent at three different scales.

The research described in this report is based on technical and cost data obtained directly from the selected vendors of struvite technology. It has been reviewed by Johns Environmental to ensure that it meets engineering requirements such as a valid mass balance over the process, is in line with basic crystallization theory and is consistent with the existing scientific understanding of the process. However, the reader should understand that most of the vendors are based in the USA and that cost data is based on US conditions, which may not translate directly to those in Australia. Care should be exercised in applying the outcomes of the research to a specific meat plant in Australia.

3.0 PROJECT OBJECTIVES

This project aimed to investigate a number of the most promising proprietary full scale struvite crystallization technologies and assess their costs and suitability to the meat industry. The objectives were as follows:

a) Identify the major struvite crystallization technologies available in the current market. For each of these designs assess:

- Application and location of current installations;
- Phosphorus removal capability of current installations;
- Identify method of chemical addition, precipitating agent, process conditions, particle growth, solid separation and solid processing as available;
- Ancillary equipment required;
- Estimated CAPEX of installation including ancillary equipment;
- Estimated OPEX including electricity and chemical addition for the full installation including ancillary equipment; and
- Suitability to the Australian meat industry.

b) Compare chemical precipitation versus struvite processes using a cost benefit analysis (CBA) approach on the installation of relevant technologies.

c) Identify clearly the factors that most influence the selection of a struvite process over traditional chemical precipitation.

4.0 CHEMICAL PHOSPHORUS PRECIPITATION THEORY

This section lays out some helpful background on both the traditional chemical precipitation and struvite crystallization processes and their application to the meat processing industry. This is useful is useful to understand the struvite technology design options.

4.1 Chemical Precipitation Processes

Most chemical precipitation processes to remove phosphorus work on the basis of adding a trivalent ion [the precipitant] – typically aluminium, iron or an organic variant of these – which reacts with the soluble phosphorus ion (usually HPO_4^- at the neutral pH of the wastewater) to form a solid which can be separated from the liquid wastewater. The reaction is typically very rapid. The precipitant is usually added as a concentrated solution, although electrocoagulation processes [EC] can be considered as a process variant in which the trivalent ion is dosed electrically into solution from a sacrificial anode. The reaction works mainly with soluble phosphorus. Insoluble organic and/or solid forms of phosphorus must be removed by other means.

Photo 1: Typical dosed DAF and belt filter press for DAF float dewatering

The solid phosphorus must then be separated from the effluent. This can be performed in a number of ways depending where the precipitation process occurs. For meat processing facilities discharging to sewer, phosphorus precipitation is most frequently conducted in a chemically dosed Dissolved Air Flotation [DAF] unit which also is used to reduce oil & grease, BOD and TSS levels in the wastewater prior to discharge. In this case, the precipitated phosphorus is removed in the DAF float/sludge. In this instance, insoluble phosphorus present in the fine solid material is removed with the organic TSS portion of the DAF float, while solubilized phosphorus is precipitated by the precipitant and removed as an inorganic solid in the float. Other options are available. Rather than a DAF, a lamella settler may be used instead, but the principle and the outputs are the same.

For these systems the operating costs are high. The main contributors are:

- the consumption of the precipitant chemical;
- dewatering the DAF float or sludge, which usually requires polymer, and
- disposal of the unstable sludge containing the precipitated phosphorus.

For meat processing plants with activated sludge BNR systems, an alternate approach is to dose the chemical precipitant into the activated sludge basin. This is useful since virtually all of the phosphorus is present in a soluble phosphorus form which reacts quickly with the precipitant. The precipitated phosphorus then enmeshes in the activated sludge floc and is removed regularly removed during wasting of the excess sludge. While chemical consumption is still largely similar, a separate dewatering device is not required and the mixture of biological and inorganic phosphorus sludge is potentially easier to dispose of.

Nevertheless, in either instance, large quantities of sludge containing the precipitated phosphorus is produced with little beneficial value. Its disposal will only become ever more difficult and expensive.

4.2 Struvite chemistry

Struvite is a solid crystalline product containing equimolar amounts of magnesium, ammonium (NH_4^+), and phosphate (PO_4^{3-}) and 6 moles of water. The struvite process ensures that these components ions are available in the correct proportion and manipulates the pH of the solution to generate a solid crystal product that can be separated from the wastewater. Unlike traditional chemical precipitation processes the struvite solid has some environmental benefit in that it has been proven to be an excellent slow release fertilizer rich in nitrogen and phosphorus.

Its application to red meat processing wastewater is of interest because:

- meat processing wastewater contains high levels of ammonium and phosphorus conducive to forming struvite without the need to add more of these components. Hence only magnesium dosing is required;
- the struvite process can be performed at mildly alkaline pH eliminating the need to add large amounts of alkali for pH adjustment;
- the struvite solid can be readily separated from the liquid wastewater. This is a key aspect of proprietary designs since poorly designed struvite processes may find it difficult to achieve the required particle size; and
- an environmentally beneficial product is more easily disposed of.

Struvite is a crystallization process rather than a precipitation process, which defines traditional chemical processes. The key factors in the design and operational control of a crystallization process are solubility, supersaturation, nucleation and growth.

4.2.1 Solubility

Solubility is the concentration at which no further solid can dissolve into the liquid. If the concentrations of ammonium, phosphate and magnesium are too low, struvite solid will not form. The solubility also defines the lowest theoretical concentration of phosphorus in the treated effluent that can be achieved by the process.

The solubility of struvite in water is strongly affected by the pH of the solution while the temperature has relatively little effect. Figure 1 shows the solubility of struvite as a function of pH. At pH 7 the solubility of struvite is 160 mg/L while at pH 8 it is 50 mg/L. This is equivalent to 20mg/L and 6 mg/L of total phosphorus respectively. The pH is manipulated by struvite processes to persuade solid struvite to form.

Due to the relatively high solubility of struvite in water at near neutral pH, struvite processes can generally only achieve discharge concentrations of 15 to 20 mg/L. This is unlike chemical precipitation processes that can reduce TP levels to as low as 1 mg/L in the treated effluent. This is not necessarily a concern where the discharge is to irrigation, but it may make it unsuitable where lower discharge limits are set, such as to surface water or sewer discharge.

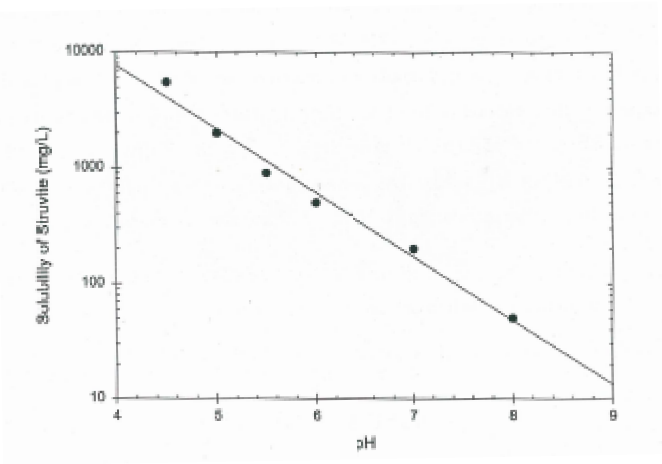

Figure 1: Solubility of struvite versus pH (Harrison, 1999)

4.2.2 Supersaturation

Supersaturation describes the difference between the solution concentration and the solubility concentration for a given pH and temperature. Crystallization can only occur when the solution supersaturation has a positive value. The degree of supersaturation defines the amount of phosphorus that can be removed by the struvite process. For example, if the start TP concentration is 60 mg/L, approximately 40 mg/L can be removed as struvite, if the solubility limit is 20 mg/L (e.g. 67% removal).

Supersaturation is controlled by either raising the solution concentration or lowering the solubility. In the case of struvite, magnesium addition is used to raise the combined solution concentration in the phosphate and ammonium rich wastewater and the pH is increased to lower the solubility. The maximum supersaturation is determined by the initial TP concentration in the wastewater (since phosphorus is typically the limiting ionic component of struvite).

The degree of supersaturation also defines the rate at which crystals grow and new crystals form. Ideally the supersaturation remains at a moderate level that encourages the growth of existing crystals and producing a population of large sized crystals. When the supersaturation is too high many new crystals form spontaneously creating a population of very small sized crystals that are difficult to separate from the treated effluent.

4.2.3 Nucleation

Nucleation is the spontaneous birth of new crystals that occurs in high supersaturation solutions. Uncontrolled nucleation results in a small sized crystal population that do not settle and thus exit with the effluent and reduce struvite removal efficiency. Strategies such as high mixing energy are used to rapidly disperse high concentrations or low solubility zones so as to control nucleation.

4.2.4 Crystal Growth, Agglomeration and Ageing

Crystal growth occurs in supersaturated solutions. The higher the supersaturation, the higher the rate of growth. Successful crystallization requires tight process control to maintain the supersaturation at concentrations that preference optimal crystal growth. Harrison *et al*. (2011) have quantified the growth rates of struvite crystallization in water.

Struvite crystallization is often described as precipitation as it is rapid crystallization initiated by a chemical reaction whose product is sparingly soluble. These conditions often result in high supersaturations that produce large numbers of fine crystals. Crystallization includes two additional processes that affect the final crystalline product - agglomeration and ageing. Agglomeration is the coalescence of individual crystals to form a larger particle. This is favoured in densely packed crystal solutions with high mixing energy. Ageing describes all other irreversible processes that occur after the precipitate formation and help increase the particle size of the crystal and/or agglomerates.

4.3 Removal of Struvite Product from Wastewater

Struvite particles are separated from the wastewater stream as either single large crystals, an agglomeration of smaller crystals or small particles entrapped in floccular sludge.

- Large crystals produce the most pure solid form of struvite (Photo 2). This is difficult to achieve industrially as singular crystal formation requires extremely precise process control to enable struvite crystal growth, while preventing new particle formation (or nucleation).
- Production of agglomerates (Photo 3) is a more common approach but produces a less pure product. Agglomerates form in a high solids density solution that allows small crystals to grow

together to form larger particle. Process conditions are less stringent than for the large crystals as both nucleation and growth are required.

- The entrapment of small struvite crystals in a floccular sludge produces the most impure product but it is the easiest to control. Process conditions only need to ensure a supersaturated solution. Significant crystal growth is not necessary as the ultrafine particles are entrapped in the flocculent sludge which facilities their removal.

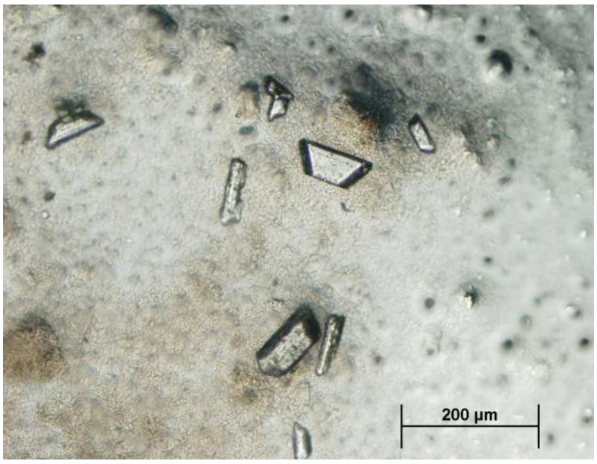

Photo 2: Individual Struvite Crystals

Photo 3: Struvite Agglomerates

4.5 Application of Struvite to Meat Processing Wastewater

Struvite crystallization for phosphorus removal is a possible treatment technology option for the Australian red meat industry wastewater given its high phosphorus concentration and high flows. Struvite crystallization, as a method of treating wastewater, was first reported in 1984 (Dijk, 1984). No full scale struvite plants have been installed in Australia by the vendors identified in this report, but some home-grown plants have been trialled. The most significant of these, was the large scale struvite crystallization system treating the anaerobic digestor sidestream at the Oxley Creek sewage plant designed and installed by Brisbane Water and described by Muench & Barr (2001). Despite success at pilot scale, the full-scale unit had recurring issues, mainly with the magnesium oxide dosing system followed by major damage in the 2011 Brisbane floods and was subsequently it was decommissioned.

The first research project on struvite crystallization from meat processing wastewater occurred in 1998 at the JBS Dinmore facility and successfully demonstrated 50% phosphorus reduction in a pilot scale vessel treating segregated combined trommel screen and raw material bin wastewater. The pH was initially adjusted to 8.5 to 9.0, seed crystals added and then magnesium chloride solution added to stoichiometric quantities. The magnesium and phosphate concentration decreased over the 3 hour investigation resulted in a 50% phosphate removal and 17% ammonium removal. This study helped spark the beginning of the interest in struvite crystallization as a phosphorus removal technology for the Australian red meat industry.

Subsequently further investment in struvite R&D studies has occurred. A continuous struvite crystallization process using filtered digestate from paunch processing as the feed successfully produced 20kg of struvite material over a 3 month project at the Teys Beenleigh facility in 2013 (Jensen et al, 2013). This system involved an aeration tank for pH adjustment to 7.8, a 100L crystallizer with magnesium feed, an overflow tank for fines separation and a recirculation loop. Magnesium hydroxide was dosed into the crystallizer to achieve a pH of 8.2. The project successfully produced effluent with only 5mg/L total soluble phosphorus but an issue with fines wash out increased the overall total phosphorus to 50mg/L. This has been a recurring issue with many struvite (and general crystallization) systems and requires good crystallization vessel and process design to avoid.

Jensen relocated the system to investigate struvite crystallization from red meat industry anaerobic pond effluent (Jensen, 2015). Struvite crystallization reduced the total phosphorus concentration from 34 mg/L to an average of 19 mgP/L. Wash out of fines struvite precipitates was again an issue with the average soluble phosphorus concentration being 6 mg/L.

There appear to be no non-Australian studies publically available regarding the application of the technology to meat processing and discussions with vendors as part of this project found that none had implemented their technology in any meat processing industry previously.

It is our opinion that given the technical challenges associated with adopting struvite crystallization technology without specific expertise and experience in crystallization field, the use of a proven proprietary struvite reactor designs will be the fastest, and probably most economic, route to implementation of struvite crystallization in the treatment of red meat industry wastewater.

4.6 Struvite uses

The most common use for struvite produced from waste streams is as a slow release fertilizer (Bridger et al, 1962). Recovering struvite from wastewater is a method of closing the phosphorus loop so as to promote its recycling back to agricultural application. Struvite has a number of advantages for its use as a fertilizer:

- The elements found in struvite (N, P, Mg) are important plant nutrients;
- Struvite crystals have relatively low solubility at neutral pH and thus dissolve slowly. This makes it a slow release fertilizer. The rate of release can be controlled by the size of the struvite particle.
- The low ammonia concentration allows its application at high doses without burning plant roots or leaves.
- The crystal purity means that it fulfils typical legal requirements for heavy metals, such as cadmium, lead and mercury.

Other less common uses for struvite include inclusion in mortars for building products (Abdelrazig et al, 1989).

5.0 STRUVITE TECHNOLOGY DESIGN CONSIDERATIONS

The struvite crystallization proprietary technologies implemented over the past 10 years are successfully producing struvite with a market value. This section discusses the different design considerations for struvite crystallization processes

5.1 Reactor Mixing

Adequate mixing is vital to successful struvite crystallization. The mixing will quickly distribute chemical additions and keep struvite particles suspended.

Rapid distribution of chemicals reduces the risk of localized high concentration zones which can lead to:

- Scaling on equipment surfaces adjacent to the chemical addition. Successful design encourages struvite growth on the struvite particulate surface area so that it can be continuously removed as product from the reactor. Scaling increases maintenance costs and reactor downtime.
- Excessive nucleation which results in a high population of extremely small particles that are difficult to separate from the liquid discharge. Successful design requires the formation of carefully sized struvite particles, either due to growth on the crystal surface and/or small particle agglomeration. The larger the particles the easier they are to separate from the liquid.

Three mixing methods are used in struvite reactor designs with most using a combination of two:

1. Air fluidisation;
2. Water fluidisation;
3. Mechanical agitation.

Air fluidization is popular in struvite reactor designs as it serves two purposes; bulk mixing of the reactor contents and pH adjustment (discussed in Section 5.3). A blower typically injects air through a diffuser at the base of the reactor. The movement of the air as it rises through the reactor provides reasonable mixing energy. As high mixing energy is paramount to successful struvite reactor design, air fluidization is often supplemented with water fluidization or mechanical agitation.

Water fluidization is also popular and is applied where the struvite crystal mass is suspended by an upward flow of wastewater in the reactor. Since the flowrate required exceeds that of the incoming raw wastewater stream, it is common to recirculate a portion of the reactor contents. The advantage of this method of mixing is increased phosphorus removal efficiency since there is a higher probability of small particles present in the reactor discharge stream agglomerating to a large particle size as they recirculate through the reaction zone. The disadvantage of water fluidization is the pumping cost.

Mechanical agitation with a low shear impellor is the third method of mixing in struvite crystallization reactors. The low shear impellor reduces particles breakage. The main advantage of mechanical mixing is its low operational cost. A disadvantage is that the mixer provides additional surface area for possible unwanted scaling.

5.2 Magnesium Dosing

Magnesium dosing is required to achieve struvite production, since the magnesium concentration is below the solubility limit for struvite formation in meat industry wastewaters. Magnesium is dosed at greater than stoichiometric quantities to ensure that phosphorus is the limiting component. The two commonly used magnesium sources are magnesium chloride and magnesium oxide.

Magnesium oxide (often called mag oxide) is the less common magnesium source, despite its advantageous properties. Magnesium oxide forms magnesium hydroxide in the presence of water. Its dissolution provides not only magnesium ions but also 2 hydroxyl ions (OH-) that raise the pH. All ions improve struvite removal efficiency. However magnesium oxide is usually supplied in a slurry form that is notoriously difficult to handle and requires considerable time to dissolve. Struvite crystallization can occur on the fine solid particles of magnesium oxide which means a significant amount of the mag oxide is unavailable to react. This increases the chemical cost of the process markedly.

Magnesium chloride is the magnesium source of choice for most overseas large scale struvite reactors processing wastewater. It is readily available from chemical supply companies in liquid form. The benefit of this magnesium salt is that it is readily soluble in wastewater so that all the magnesium is available for the reaction to produce struvite. The contribution of chloride to the wastewater must be considered when pasture irrigation is the ultimate disposal.

5.3 pH Control

The control of pH is the means by which conditions are manipulated to reduce struvite solubility and drive its crystallization as a solid. Within the pH range 8 to 9.5 (Battistoni *et al*, 2001), struvite solubility is at its lowest resulting in greater struvite removal efficiency. Figure 2 shows removal efficiencies of phosphate and ammonia from anaerobically treated swine wastewater (Kim, et al., 2017). Whilst reasonable removal efficiency with respect to phosphate occurred between pH 7 and 12, the highest values were from pH 8 to 10.

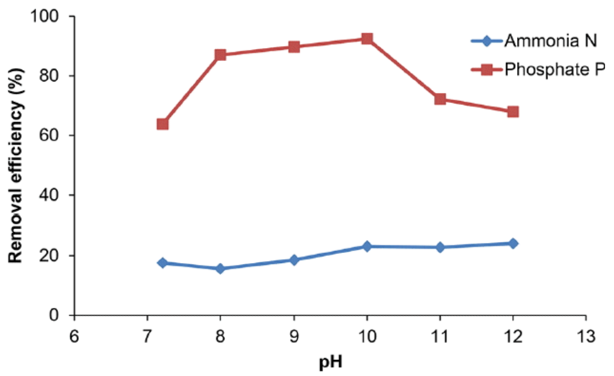

Figure 2: Ammonia N and phosphate P removal according to pH for real wastewater.

There are three commonly used methods for increasing the pH, namely carbon dioxide stripping, sodium hydroxide dosing and magnesium hydroxide dosing. In most cases sodium hydroxide is used for the final pH adjustment.

Carbon dioxide stripping via aeration can significantly increase the pH especially when directly downstream of an anaerobic system. Air stripping may not, however, achieve the desired pH 8.0.

Magnesium hydroxide dosing will not only provide the magnesium source, but will also increase solution pH. Whilst significant cost benefits are possible, it is not commonly used due to handling difficulties on an industrial scale. Sodium hydroxide (NaOH) is by far the most common method for pH control. Even systems with CO_2 stripping or magnesium hydroxide addition usually dose sodium hydroxide to increase the pH.

5.4 Solid/Liquid Separation

There is little gain in crystallizing the struvite if it cannot be separated from the effluent. The overall removal efficiency is poor if a significant portion of the struvite crystals are entrained in the liquid effluent stream.

Successful struvite processes either generate large struvite particles or entrain smaller struvite particles in sludge flocs as discussed in Section 4.3. The large struvite particle in the form of single crystals or crystal agglomerates are readily removed from the base of the reactor where they naturally settle and are screened from the liquid stream. In co- crystallization systems, the struvite entrapped in bacterial flocs are removed with the waste activated sludge from the mixed reactor contents. In all cases, the solids exit the system as the struvite product while the liquid is returned to the reactor for further growth of the remaining smaller struvite particles.

Most proprietary struvite reactor designs include a settling zone and a weir that reduces the carryover of fine struvite particles into the final effluent. The settling zone can be operated in batch or continuous mode and is usually integrated into the crystallization vessel.

5.5 Ancillary Processing

Ancillary processing includes product drying and palletization. Both are not essential to the struvite crystallization process but increase its overall value.

6.0 METHODOLOGY OF STRUVITE TECHNOLOGIES REVIEW

Sixteen different industrial scale struvite recovery technologies, as listed in Table 1, currently operate at over 50 sites across the world (Kabbe, 2017). The majority of installations are located in Western Europe and North America, as shown in Figure 3, and the majority with domestic wastewater application. Australia currently has no operating installations despite our tightly regulated environmental discharge limits and high demand for agricultural fertilisers.

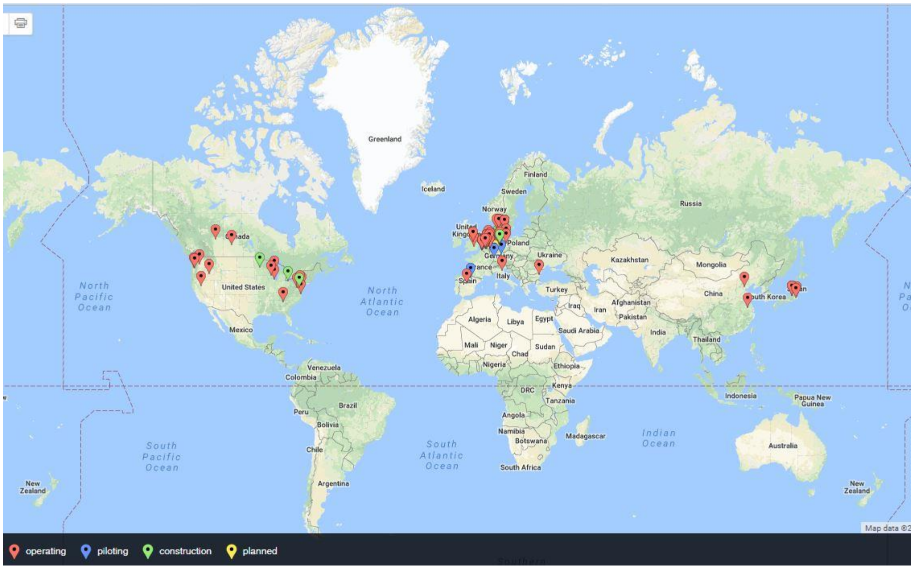

Figure 3: World distribution of Industrial Scale Struvite Crystallization Installations

Table 1: Current Struvite Crystallization Industrial Scale Technologies (Kabbe, 2017)

Technology	Parent Company	Country of Origin	# Full Scale installations	Operational since
AirPrex	CNP	USA	8	2009
ANPHOS	Colsen	Netherlands	1	2011
Crystalactor	DHV	Netherlands	1	2010
EloPhos	Eliquo Stulz	Germany	1	2016
Gifhorn		Germany	1	2007
Phosnix	Unitika	Japan	1	1998
KURITA	Kurita	Japan	1	1997
Multiform	Multiform Harvest	USA	4	2012
NASKEO		France	1	2015
NuReSys	Nutrients Recovery Systems	Belgium	8	2008
PEARL	OSTARA	Canada	14	2009
PHOSPAQ	Paques	Netherlands	4	2006
PhosphoGREEN	SUEZ	France	3	2013
REPHOS	Akwadok	Belgium	1	2006
STRUVIA	Veolia	France	1	2015
Swing	Swing Corporation	Japan	1	2012

Four proprietary struvite technologies were selected from the international vendors listed above. These four technologies covered the range of unique struvite crystallization designs and each had multiple industrial scale installations and a long operational history. The selected technologies were:

- Multiform
- Ostara Pearl
- NuReSys, and
- PhospaQ

These are described in detail in Section 7. Other technologies, such as CNP's Airprex and Suez' PhosphoGREEN, also have several installations, but were discounted since their processes were similar in design to the 4 chosen technologies. Johns Environmental does not have an opinion that the chosen suppliers are necessarily better than the others.

Johns Environmental corresponded with each of the four selected suppliers to gain an understanding of the individual design, phosphorus removal capabilities and estimates of capital and operational expenses for the design specification. In order to have a clear comparison, each supplier was provided with the same design specification details as outlined in Section 6.1.

6.1 Design Specifications

The struvite technology design specifications submitted to the selected vendors were based on the composition and flow of anaerobic treatment wastewater from a theoretical, integrated, medium-large sized Australian red meat processing facility. The specification is listed in Table 2. A total phosphorus level in the mid-range of values commonly measured in the Australian industry was used.

Table 2: Composition and Flow Basis

Parameter	Units	Value
Production	day/week	5
Flowrate	kL/day	3,000
pH		6.8
Temperature	°C	30
Conductivity	µS/cm	4,000
Total Alkalinity	mg/L	1,600
COD	mg/L	900
BOD_5	mg/L	460
Oil and Grease	mg/L	<50
Total Suspended Solids	mg/L	400
Ammonia as N	mg/L	300
Total Nitrogen	mg/L	350
Total Phosphorus	mg/L	60
Phosphate as P	mg/L	55
Magnesium	mg/L	17
Iron	mg/L	1
Calcium	mg/L	27

The struvite crystallization unit was specified to be post anaerobic treatment but upstream of biological nutrient removal as shown in Figure 4. All struvite technologies CAPEX and OPEX estimates were based on this information.

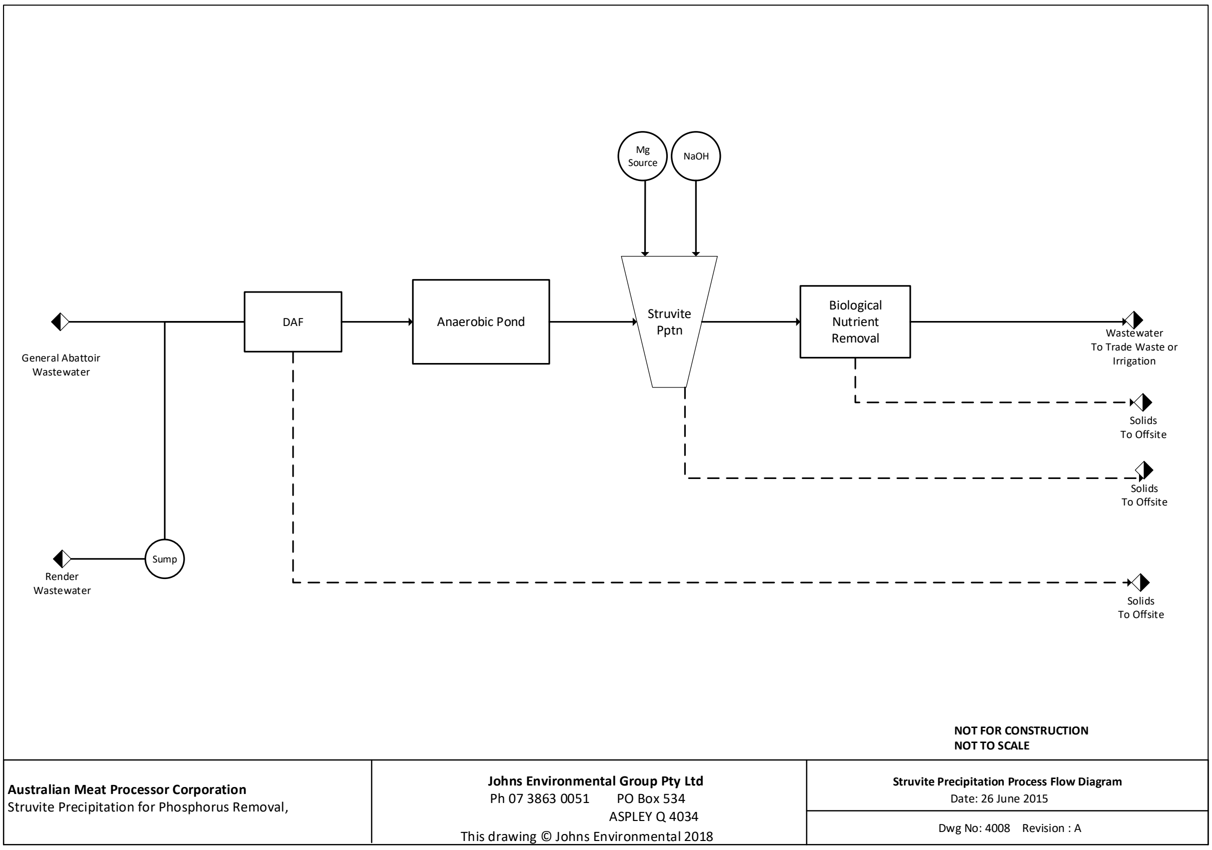

Figure 4: Process Flow Diagram specifying struvite crystallization placement in WWTP

6.2 Information Request

The selected vendors were contacted via email and some followed by telephone communication. The information requested aimed to collate design details, capital and operational expenses, full scale installation application and locality, final struvite product description and pertinent diagrams and photos. The following list details the information requested:

- P&ID or technical drawing of process;
- CAPEX estimate based on wastewater composition and flow;
- Inclusion and exclusions in estimate, clearly stated;
- Estimate of chemical requirements;
- Estimate of electrical requirement;
- Photo of final struvite product;
- List of current full scale installations;
- Other pertinent information.

7.0 STRUVITE TECHNOLOGIES REVIEW

This section provides a review of the four proprietary vendors.

Operational expense estimates for all systems assume the following:

- 12c/kWh,
- 24 h/d and 240 days/year operation,
- \$2.50/kg 50% NaOH,
- \$610/t 32 wt/wt% $MgCl_2$,
- \$200/t struvite product.

7.1 Multiform Harvest

The information from Multiform Harvest Incorporated presented in this section is based on email and phone communication during February and March 2018 and a Multiform Harvest document prepared for Johns Environmental and the Australian Meat Processor Corporation.

Multiform Harvest Inc., based in the USA and Canada, specialize in nutrient recovery systems and markets the Multiform™ technology developed by its founder Dr. Keith Bowers. Multiform was the first company to patent and use a fluidized bed technology for nutrient recovery. They have several operating full scale nutrient recovery systems in North America in both municipal and intensive agricultural applications (dairy). The technology was originally developed for use on effluent from swine farms.

The Multiform™ technology is a single pass fluidized bed struvite reactor as shown in Photo 4 and Figure 5. The design philosophy enables Multiform to offer the smallest and fastest systems with high nutrient recovery rates and minimal operational problems. They state that their systems are "fully automated and yet simple and robust to operate". They will also work closely with clients to maximize secondary benefits from the utilization of the recovered nutrients. Multiform also recommend its application in nutrient rich side-stream where biggest impact can be made with the minimal expense.

Photo 4: Multiform Harvest Installation

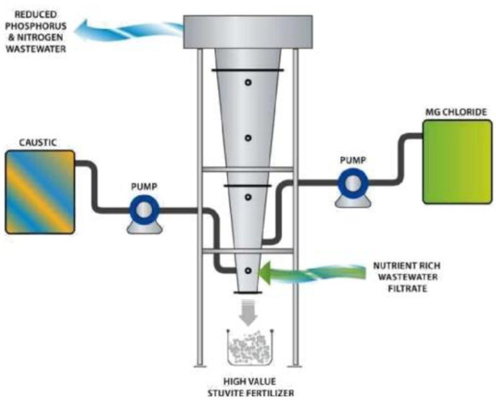

Figure 5: Multiform Harvest Schematic

7.1.1 Multiform general process description & performance

Struvite crystallization and solids-liquid separation all occur within the one Multiform reactor as illustrated in Figure 6. Phosphorus-rich wastewater is pumped into the base of the conical stainless steel reactor. As the liquid travels up through the column it is initially mixed with sodium hydroxide to raise the pH and then magnesium chloride to maintain the required degree of supersaturation. As a consequence, struvite forms on the surface area provided by the struvite crystal mass in the reactor and the crystals grow in size.

The flowrate and the shape of the reactor allows the suspension of the smaller particles by the incoming wastewater within the agglomeration (conical) zone. Large struvite pellets sink gradually towards the reactor base as they increase in size from crystal growth and agglomeration of smaller particles into larger ones. These are removed from the reactor by periodic discharge. The treated water exits at the top of the reactor, which has a wide cross-section to ensure that all but the finest struvite particles settle back into the agglomeration zone.

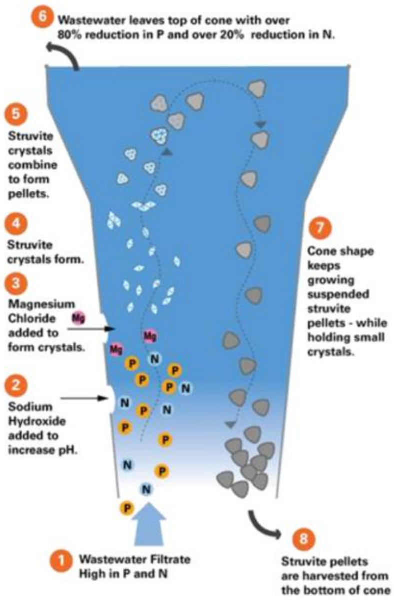

Figure 6: Multiform Harvest Process Schematic

The absence of air stripping in the Multiform™ technology is beneficial to installations with downstream conventional biological nutrient removal that require organic content for denitrification. Addition of oxygen to the wastewater would result in the formation of aerobic biological floc that readily consume COD even within the short hydraulic residence time of the struvite reactor.

The wastewater composition and flows provided for a typical Australian meat processing plant are all within the normal operating ranges for Multiform systems. The specified orthophosphate concentration in the design specifications is acceptable but at the lower end of the preferred range. The minimum design orthophosphate recovery efficiency of 88% estimates an effluent total phosphorus concentration of 12mg/L. The total solids content and temperature of meat processing wastewater are also within the design range required for effective struvite crystallization. Multiform note that industrial wastewater streams can have higher non-trace aluminium, iron and calcium concentrations that may impact the performance and effectiveness of the struvite recovery. They recommend that these ions are evaluated for each individual plant prior to installation.

The flowrate and orthophosphate concentration govern the size, design and cost of the Multiform system. The standard sized reactor processes a feed flowrate of 600 to 700 kL per day. For larger flows, multiple standard units may be used, however custom designed reactors may be more economical.

The fully automated control system Multiform enables operation with less than ¼ FTE for system monitoring only. Multiform also claim that system is easy to shutdown and restart.

The final struvite product from the Multiform installation has a sand-like texture and appearance as shown in Photo 5. Multiform Harvest also have the technology to further process the struvite product if desired and can offer to explore the option of entering an agreement to purchase and market the struvite if desired by the client.

Photo 5: Multiform Harvest Final Struvite Product

7.1.2 Recommended Multiform installation for red meat plants

For the effluent flow and load specified in Section 6.1, Multiform Harvest calculate the need for 4 standard reactors at a capital estimate of $US 2.5 million (-10/+25%) (equivalent to $AUD 3,350,000) including reactor, pumps, dosing facilities, dewatering equipment and operator training. This estimate does not include shipping (estimated to be $US 5,000 per container) or electrical and mechanical installation including structural facilities, walkways and platforms. Multiform advised that the capital costs could be significantly reduced with the construction of a single unit and that manufacturing in Australia could be explored if multiple systems are required. Multiform also provided an estimate of $US 420,000 ($AUD 560,000) for additional struvite dryer and $US 50,000 spares inventory. Other pertinent information is the overall height of 10.2m and total system footprint of 93 m^2.

The Multiform estimates for operational expense, including electrical and chemical demand, are summarised in Table 3 below.

Table 3: Multiform™ Operational Estimate

Item	Chemical input	Quantity	Annual OPEX
Magnesium dosing	$MgCl_2$ (32 %w/w)	2.0 tonne/d	$290,000
pH adjustment	NaOH	1.0 tonne/d	$570,000
Electrical demand		23 kW	$15,800
Struvite production		1.2 tonne/d	-$57,600
Total			**$818,200**

Notes: Electrical demand excludes dryer.

Johns Environmental recommend that the suitability of the Multiform Harvest system for Australian red meat industry wastewater treatment plant would need to consider the following:

- The Multiform system is a simple process that is highly automated and requires only minimal operator attention.
- The system is usually supplied in standard units that treat 30 to 35 kL/hour but custom built units may be more economical for larger installations.
- There are units installed at a dairy feedlot in North America and the directors have experience in the meat processing industry.
- The Multiform system is suitable for use upstream of a conventional biological nutrient removal system as the absence of air stripping guarantees minimal organic contaminant removal.
- The single pass design reduces the pumping power required compared to other designs with recirculating flows.
- The simplicity of design allows the flexibility of daily shutdowns.
- The final struvite product could either be passed to a composting facility or further processed to increase its direct marketability.

7.2 NuReSys

The information on the NuReSys® system presented in this section is based on email communication during January to March 2018 and from the NuReSys website.

Nutrients Recovery Systems is a Belgium company that solely markets the NuReSys® technology. There are ten industrial scale NuReSys systems (2 under construction) installed in Western Europe with both industrial and domestic applications. The oldest has been operational since 2008. NuReSys has both municipal and industrial (potato processing) applications some described in Moerman *et al* (2009).

7.2.1 NuResSys general process description & performance

The NuReSys struvite system is a multi-step process comprising a stripping vessel, a crystallizer and a settler to separate product struvite from the effluent as shown in Figure 7 and Photo 6

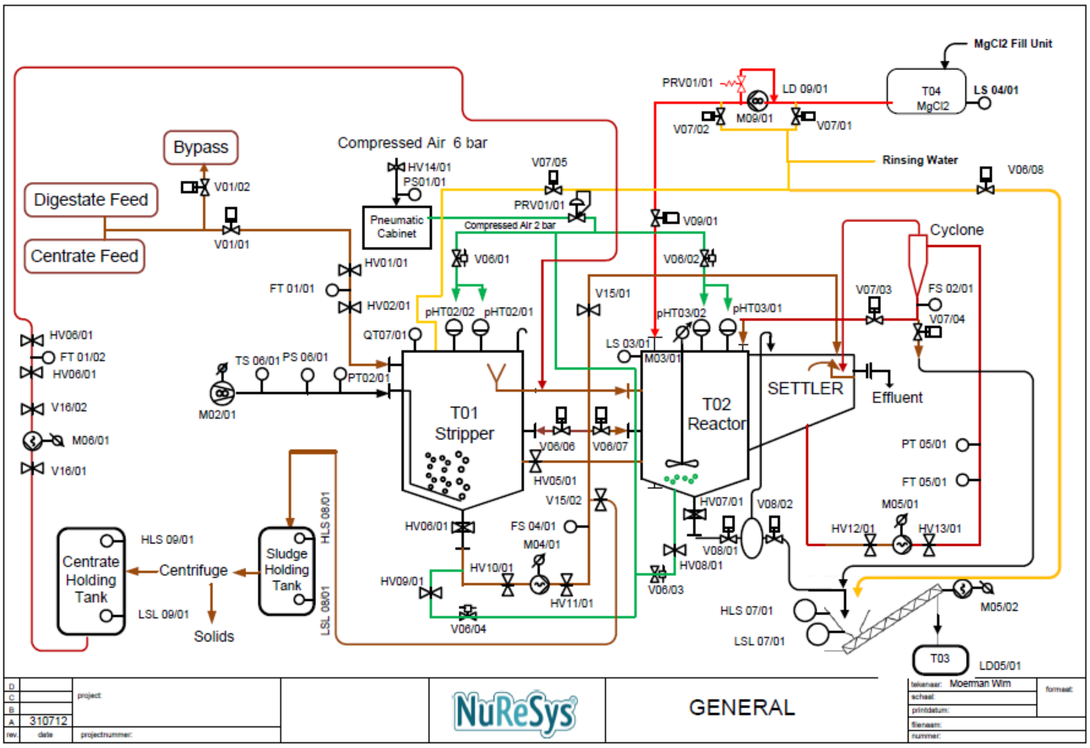

Figure 7: NuReSys P&ID Example

The first step in the NuReSys process is the Stripper where a blower injects air into the anaerobically treated wastewater. This allows two functions, stripping of the dissolved carbon dioxide to increase the pH and aerobic biological organic removal. Waste activated sludge is removed from the system through the base of the Stripper. Clarified wastewater discharges from the top of the Stripper to the downstream Crystallizer. The Stripper pretreatment improves the overall struvite purity because it reduces the organic concentration in the liquor that will be enmeshed in the crystal agglomerates in the next step.

Photo 6: NuReSys Clarbout Installation

The second step in the NuReSys process is the crystallizer where magnesium chloride is added to a mechanically stirred tank. If necessary, further pH adjustment with sodium hydroxide also occurs. Struvite nucleation, growth and agglomeration occurs in this supersaturated, high crystal density environment. The larger struvite particles are extracted intermittently from the base of the Crystallizer and passed over a dewatering screen to form the final struvite product. A low shear impellor is used for mixing to minimize breakage of the struvite crystals. The wastewater gently passes from the Crystallizer into the adjoining Settler.

The third step in the NuReSys process is the settler and hydrocyclone that separate the small struvite particles from the final discharge. The Settler provides a stilling zone allowing the small struvite particles to settle from the wastewater. The small struvite particles reenter the Crystallizer via a hydrocyclone. The wastewater discharge from the settler contains a low solids concentration that ensures a high overall phosphorus removal efficiency.

The technology design is simple but reportedly effective. The separation of the pH control unit, the crystallization unit and the solids separation in the settler and then the hydrocyclone provides considerable process control options.

Process feed flowrates to NuReSys systems vary from 0.12 to 3.4 ML per day at phosphorus concentrations of 60 to 650 mg PO_4-P per liter. The lower flows are usually associated with the higher phosphate concentrations. Installations can achieve discharge phosphate concentrations of 15 to 20 mg PO_4-P per liter however concentrations lower than 30mg/L come at the cost of additional chemical dosage. The removal efficiency is highly dependent on the influent phosphorus concentration. The design specification for the typical Australian meat processing plant fits within these process typical process ranges although at the very bottom end of viable phosphate concentrations.

The final struvite product is a high purity, pellet type product, as shown in Photo 7, marketed as Bio-Stru®.

Photo 7: NuReSys Final Struvite Product

Photo 8: NuReSys Struvite Product

7.2.2 Recommended installation for red meat plants

NuReSys provided a direct equipment capital expenses estimate for a system capable of processing the wastewater stream specified in Section 6.1 of k€1,200,000 (equivalent to $AUD 1,850,000). This price includes all reactors, blowers, solids dewatering, dosing pumps etc. This estimate does not include shipping, civil structures or electrical and mechanical installation.

The NuReSys estimates for operational expense, including electrical and chemical demand, are summarised in Table 4 below. NuReSys estimate that the stripping of CO_2 from the anaerobic effluent will increase the pH to the desired value and no further caustic addition will be necessary.

Table 4: NuReSys Operational Estimate

Expense	Consumables	Quantity	Annual OPEX
Magnesium dosing	$MgCl_2$ (32 w/w%)	2 tonne/d	$290,000
pH adjustment	NaOH	Not needed	$0
Electrical demand	kW	60	$40,000
Struvite		Not stated	
Total (with no rebate for struvite value)			**$330,000**

Johns Environmental recommend that the suitability of the NuReSys system for the Australian red meat industry wastewater treatment system needs to consider the following:

- One system has been applied successfully in intensive livestock industry. A NuReSys installation has been successfully operating since 2006 at a German dairy sit. It processes phosphate feed (60 to 65 mg PO_4-P/L), at a nominal flow of 125 kL/h wastewater to produce 600 kg/d of struvite product. These process flows and phosphate feed conditions are similar to process conditions of this typical meat industry wastewater streams however is likely to be differences in oils and grease and micronutrient composition.
- Significant organic removal (COD) in the stripper will not be desirable if upstream wastewater treatment involves conventional biological nutrient removal that requires a carbon source. However the degree of removal is unknown and will depend on the hydraulic residence time. If there is significant organic removal, then this process would be beneficial in conjunction with emerging anammox technology that demands wastewater feed with low organic content.
- The separate unit processes will allow more process control options to optimise phosphate removal efficiency.
- The final saleable product is particularly suited for when the market demand for high quality struvite forms in Australia.

7.3 Ostara Pearl

The information from Ostara Nutrient Recovery Technology Inc. on the Ostara Pearl Process presented in this section is based on email communication in April 2018, a document prepared by Ostara for AMPC and Johns Environmental and information from the Ostara website.

Ostara, founded in 2005, is a Canadian company based in Vancouver that specialises in nutrient recovery through their Ostara Pearl® and Wasstrip® processes and the marketing of the struvite fertilizer product sold as Crystal Green®. Ostara has the largest number of full scale struvite installations world-wide with 14 currently operating across North America and Europe. The first facility commenced operation in 2007. The Ostara Pearl process is currently applied to wastewater treatment from municipal sludge anaerobic digestors only. Unlike most other vendors, Ostara seek to retain ownership and marketing of the struvite product with the client responsible for the facility operations and Ostara continuing to provide high level production and operational support though the life of the offtake agreement.

7.3.1 Ostara general process description & performance

The Ostara Pearl struvite system is a continuous process in a single struvite reactor as shown in Figure 8 and Photo 9. The struvite reactor is an upflow fluidized crystalliser with increasing diameter with height. Mixing is achieved by a large liquid recirculation loop originating from close to the top of the vessel and entering at the base to provide sufficient superficial velocity in the column to suspend the crystal mass. The process is controlled through chemical addition rates. Magnesium is dosed as magnesium chloride and sodium hydroxide to adjust the pH. Chemicals are injected with the recirculated flow at the narrow base of the column. The chemical addition facilitates the controlled growth of the small struvite seed crystals to the desired size. The increasing diameter with height allows reduced mixing and uplift velocities as the liquid rises allowing retention of fine crystal seed particles in the column. Large struvite particles settle towards the base of the crystallizer from where they are periodically withdrawn.

The flow rate and feed phosphorus concentration varies widely between installations, but the typical phosphorus effluent concentrations are between 15 and 30 mg/L PO_4 as P. The size of the final pellet product is controlled between 1.0 and 4.5 mm. This system produces a high purity struvite product that Ostara market as Crystal Green® (Photo 10).

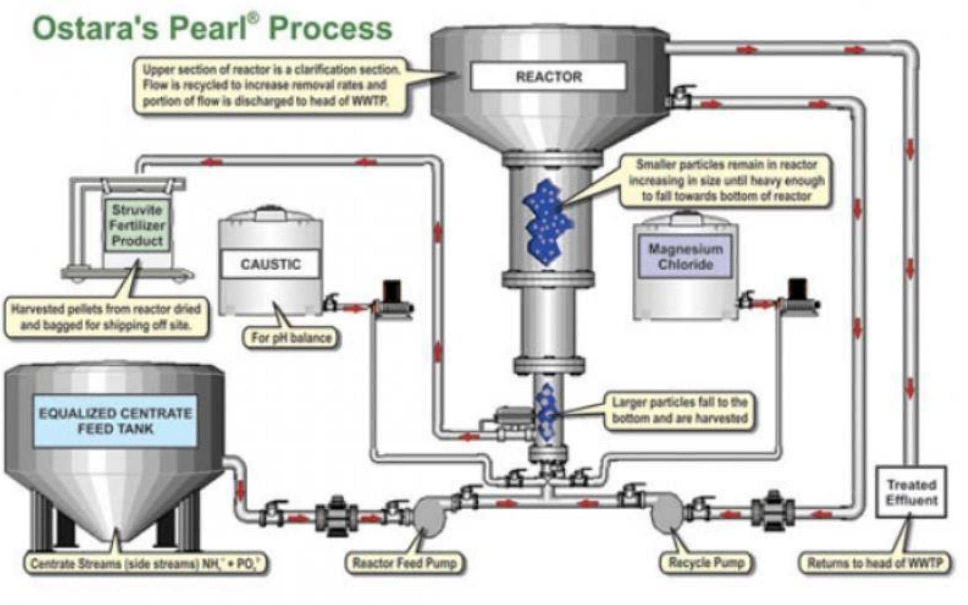

Figure 8: Schematic of Ostara Pearl Process (Hazen and Sawyer)

Photo 9: Ostara Pearl installed at Amersfoort, The Netherlands

Photo 10: Ostara Pearl Struvite Product

7.3.2 Recommended installation for red meat plants

Ostara recommends one Pearl 2K (P2K) reactor for the treatment of the design specifications (in Section 6.1). The reactor is not hydraulically limited but based on the phosphate mass loading rate. The P2K has the capacity to treat 250 kg PO_4-P/d under continuous operation. The design specifications are for 118 kg PO_4-P/d so there is double the capacity for the same Ostara CAPEX. The capital cost estimate for the direct equipment costs is $US 2.5 to 3.5 million (A$ 3.4 to 4.7 million) including reactor, chemical storage tanks and dosing systems, dewatering screen, product dryer and product storage dryer. The CAPEX also includes instrumentation and control system, construction support, commissioning and technology licenses. Installation, including civil buildings, plumbing and electrical are additional to be arranged by the client. Ostara experience estimate an overall cost of installing a single P2K reactor of between $US4.75 to 6.25 million ($AUD 6.4 to 8.4 million).

Note that the high cost of the Ostara system (both CAPEX and OPEX) is in part due to inclusion of a product drier, which is not a feature of most other vendor offers. Ostara estimates for operational expense, including electrical and chemical demand are summarized in Table 5. The actual chemical costs will depend on many factors such as wastewater alkalinity and conductivity.

Table 5: Ostara Pearl Operational Estimate

Expense	Consumables/Units	Quantity	Annual OPEX
Magnesium dosing	$MgCl_2$ (32 w/w%) (kg/d)	1,800	$265,000
pH adjustment	NaOH (kg/d)	210	$126,000
Electrical Demand	kW	220	$6,400
Struvite Production	tonne/yr	200	
Total			**$AUS 400,000**

Other operating costs include maintenance, labour and hot water for drying. Ostara has assumed that there is hot water available for use and this is not included in the energy requirement. Approximately 40L of 90°C hot water is required per tonne of crystal green product.

Johns Environmental recommend that the suitability of the Ostara Pearl system for Australian red meat industry wastewater treatment plant would need to consider the following:

- The Ostara Pearl process has not been demonstrated in industrial effluent settings, unlike the other suppliers above.
- This system does not use air stripping for mixing or pH control thus minimising organic removal. This favours a conventional biological nutrient removal system that requires a carbon source.
- The energy demand is relatively small considering the large recirculation loop requiring pumping energy.
- The recirculation loop will increase the removal efficiency by reinjecting small particles back into the reaction zone.
- The addition of the chemicals to the recirculation loop helps avoid high supersaturated zones that cause nucleation. This would be a significant advantage to the development of large pellet sized crystal agglomerates.
- Ostara have a long history marketing the Crystal Green® struvite product and may be successful in finding an Australian market.
- The Ostara proprietary reactor may only be suitable for the larger meat industry facilities due to its reactors being suited to larger phosphate loadings.

7.4 PhosPAQ

The information from Paques on the PhoPAQ system is based on a Paques presentation, a conference paper (M. Remy, 2013) and the Paques website. Paques did not agree to supply capital cost or operational cost estimates.

Paques is a large multinational company specialising in biological wastewater and gas treatment technologies based in the Netherlands. Phospaq™ is the struvite crystallization unit process offered by Paques and is often marketed in unison with their Anammox® technology. There are 12 Phospaq installations across Europe, China and the USA treating both municipal and industrial anaerobic effluents. The first installation in the Netherlands has been operating on a municipal and food waste stream since 2006.

7.4.1 Paques general process description & performance

The Paques Phospaq system is a mechanically mixed, batch struvite crystallization and aerobic biological treatment reactor as illustrated in Photo 11 and Figure 9.

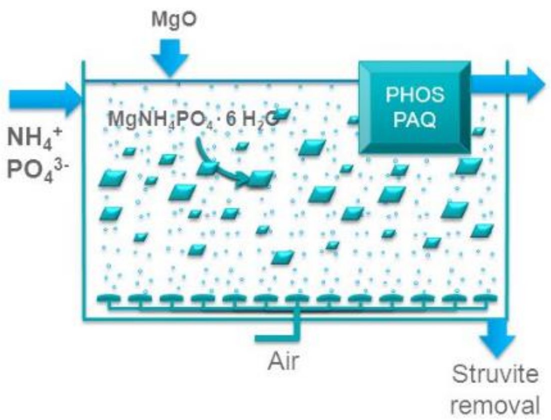

Figure 9: PhosPAQ Schematic

Photo 11: PhosPAQ Installation

The Phospaq method of phosphorus removal via struvite crystallization is facilitated by the addition of magnesium oxide and aeration into a mixed biological basin. The aeration raises the pH due to carbon dioxide stripping and provides some mixing energy. A proprietary internal clarifier design retains the fine struvite crystals within the vessel. The final struvite product is enmeshed in the biological waste sludge and removed via the wasting of activated sludge through a dewatering device. . In this sense, this process is similar to co- crystallization of phosphorus in sequencing batch reactor systems – a method used by some meat processing companies in Australia.

The difficulties typically associated with dosing magnesium oxide slurry is not a major issue in the Phospaq^{TM} system. The mixed system allows time for magnesium oxide dissolution and controlled struvite crystal growth to produce large crystals is not a critical concern for crystal separation. Magnesium oxide is typically a cheaper magnesium source and eliminates the need for caustic dosing

The Phospaq^{TM} installation at Lomm treating wastewater from a potato processing factory successfully and consistently reduces phosphorus concentration from approximately 60mg/L to 15 mg/L. At this site it is the final stage of wastewater treatment before sewer discharge.

The Phospaq^{TM} design is particularly suited as an upstream process to the Anaerobic Ammonium Removal (AAR) process. The aeration step in the phospaq process also removes organic load that is otherwise detrimental to the AAR process. This was the treatment methodology in the first installation that has now been operating successfully since 2006. Further processing of the struvite/biomass blend involves drying and pressing into pellets to form a salable fertilizer product.

7.4.2 Recommended installation for red meat plants

Paques did not provide a capital or operational expense estimate for inclusion in this project. The capital expense would need to include the mixing chamber, blowers and diffusers, MgO dosing equipment and proprietary clarifier. The operational expense would differ from other designs with greater electrical demand for the aeration, but lower chemical costs due to the use of a cheaper magnesium source and no caustic required.

Johns Environmental recommend that the suitability of the Phospaq^{TM} system into an Australian red meat industry wastewater treatment plant would need to consider the following:

- The PhosPAQ system is a simple process that would require little operator intervention.
- The system would be easily up or downscaled to suit different process sites and could use existing infrastructure with some modification.
- Any COD removal in the Phospaq vessel is not desirable if downstream wastewater treatment involves conventional biological nutrient removal that requires a carbon source. This process is more beneficial in conjunction with emerging AAR technology that demands wastewater feed with low organic content.
- The final struvite product (Photo 12) is lost as a standalone fertilizer. It ends up in the waste activated sludge, which is much less user-friendly and faces usually stringent regulatory controls on its reuse, for example, on land.

Photo 12: PhosPAQ Final Struvite Product

7.5 Summary of four Proprietary Systems

Table 6 provides a summary of the four reviewed proprietary systems with comparisons of the major design options.

Table 6: Summary of Four Proprietary Systems

	Multiform	Phospaq	NuReSys	Pearl
Vendor	Multiform Harvest Inc	Paques	Akwadok	Ostara
Reactor type	Fluidised Bed Reactor	Stirred Tank reactor	Two reactors in series – Stripper & Crystallizer	Fluidised Bed Reactor
Batch/Continuous	Continuous	Batch	Continuous	Continuous
Mixing	Single Pass Liquid Fluidisation	Agitator and Air Fluidisation	Stripper – air Crystallizer - agitator	Multi Pass Liquid Fluidisation
Mg Source	$MgCl_2$	MgO	$MgCl_2$	$MgCl_2$
pH control	NaOH	Air stripping	Air stripping & NaOH	NaOH
Particle Type	Agglomerate "sand"	Sludge Flocs 0.7 mm	Agglomerate	Agglomerate 1.5 to 4.5 mm
Solid-liquid separation	Settling zone at top of reactor	Patented decant unit at top of reactor	Separate settler with decant weir	Settling zone at top of reactor
PO_4 as P influent			60 mg/L minimum	
PO_4 as P effluent	20mg/L	12 mg/L	30 to 35 mg/L 20mg/L possible with additional Mg dosing	15mg/L min
Industrial Applications	4	12	10	14
	Product used for blending to form fertilizer product	Product used for blending to form fertilizer product	Bio-Stru	Crystal Green

8.0 METHODOLOGY OF COST BENEFIT ANALYSIS

The cost benefit analysis (CBA) for this project examined a number of potential scenarios to provide information to meat processors that may be considering implementing struvite crystallization or chemical dosing for phosphorus removal at their facility.

Chemical dosing for phosphorus removal considered two alternatives, firstly if the site had an existing biological nutrient removal (BNR) treatment process and secondly, if it did not.

- The first alternative (existing BNR) assumed the ability to capture chemical phosphate precipitates in the biological flocs, remove them with the waste solids for dewatering using the existing dewatering equipment with only a small further investment needed to add chemical dosing equipment.
- The second alternative assumed the need for a standalone chemical precipitation plant (CPP) comprising chemical dosing equipment, storage tanks, mixing vessel, settling unit and solid dewatering device.

Struvite crystallization for phosphorus removal assumed the installation of a new, standalone struvite crystallization system including struvite product drying (if part of vendor system) and storage facilities.

Sensitivity analyses were performed on variables such as struvite market value, cost of sludge disposal, meat processing facility size and struvite process capital costs to give processors an indication of how various factors may impact the viability of these installations at their facility. The scenarios investigated are summarised in Table 7.

Table 8 to Table 10 provide a summary of the information used for the CBA.

Standard wastewater and process conditions (Table 8) reflect a typical medium-sized Australian meat processor based on our in-house knowledge. The range of wastewater flows cover the smallest size facility that may consider struvite crystallization to wastewater flows typical at some of the larger Australian meat processing facilities. Input phosphorus concentration was either 60 mgP/L or 80mgP/L with a final effluent target of 20 mgP/L, which appears to be comfortably achieved by most struvite processes operating at pH values that minimise the need to readjust the pH of the treated effluent prior to discharge. A 5 day/week operation has been assumed as typical for Australian facilities.

Capital costs (Table 9) are based on information gathered from a range of international suppliers for the struvite scenarios and a combination of vendor quotes and past experience for the chemical dosing scenarios. Installed capital costs are used where possible or vendor estimates otherwise. The range of capital costs for the struvite crystallization allows for the range of vendor estimates and includes a doubling of direct equipment costs to account for installation costs. Capital cost estimates for smaller and larger flows assumed a scaling factor of 0.6 from the standard value based on flow.

Table 7. CBA scenario descriptions

#	Scenario description
1	Chemical dosing - existing BNR on-site
2	Chemical dosing - no existing infrastructure on-site (CPP)
3	Struvite crystallization – base case
4	Struvite crystallization - zero struvite market value
5	Struvite crystallization - high struvite market value
6	Chemical dosing - no existing infrastructure on-site & zero sludge disposal cost
7	Chemical dosing - no existing infrastructure on-site & high sludge disposal cost
8	Chemical dosing - existing BNR, & zero sludge disposal cost
9	Chemical dosing - existing BNR & high sludge disposal cost
10	Struvite crystallization - small meat processing facility
11	Struvite crystallization - large meat processing facility
12	Struvite crystallization – low CAPEX installation
13	Struvite crystallization – high CAPEX installation
14	Chemical dosing - no existing infrastructure on-site & large meat processing facility
15	Chemical dosing - existing BNR on-site & large meat processing facility
16	Struvite crystallization – Best Case – high struvite value, low CAPEX, high P, large processing facility
17	Chemical dosing – existing BNR Worst case – high sludge disposal, high P, large processing facility
18	Struvite crystallization – high initial P concentration
19	Chemical dosing - existing BNR on-site – high initial P concentration
20	Chemical dosing - no existing infrastructure on-site (CPP)– high initial P concentration

Table 8: Wastewater conditions used for CBA

Parameter	Unit	Standard value	Low value	High value
Flow	ML/d	3.0	1.0	5.0
Feed PO_4 as P	mg/L	60		80
Discharge PO_4 as P	mg/L	20		
Production days	d/yr	240		

Table 9: Capital costs used for CBA

Phosphorus Removal system	Standard value	Low value	High value
Struvite crystallization System	$6,500,000	$5,000,000	$8,500,000
New CPP system - including dosing system, mixing vessel, solids separation and solids dewatering	$2,100,000		
Chem P Retrofit into existing BNR - including dosing system	$200,000		

Operating costs (Table 10) were based on a range of information sources including international struvite suppliers, typical industry values and JEG experience. The range of struvite values covers from where the struvite has no realized value, through to the theoretical maximum struvite value based on the wholesale cost of phosphorus in commercially available fertilisers (A$400/tonne). The range of sludge disposal costs allows for free onsite composting or removal to a possible high future sludge disposal cost based on that for contaminated solids.

All scenarios were prepared using standard cost benefit methodology in accordance with MLA CBA Guidelines with annual time-steps out to 20 years of operation. Capital expenditure (CAPEX) for each scenario was spent over one year (the construction phase), before operation of the treatment unit commences, resulting in positive revenue in the form of struvite sale and reduced nitrification costs as well as operational expenditure (OPEX) in the form of chemical costs, power consumption, sludge disposal and maintenance. The savings and OPEX combine to form the Earnings Before Interest, Tax, Depreciation and Amortisation (EBITDA). Taxation, interest, depreciation and amortisation are not considered as part of this CBA.

A discount rate of 7% was used as per the MLA CBA Guidelines to account for the time value of money and opportunity cost of the investment. A project lifetime of 20 years of operation was used.

It is important to note that intangible assets have not been considered as part of this project. These include additional benefits that construction of the phosphorus treatment system may bring which are difficult to quantify, such as:

- More robust, reliable treatment of wastewater.
- Meeting EPA discharge licence limits.
- Reduced trade waste charges.
- Improved reputation and branding.
- Social licence to operate.

Table 10: Operating costs used for CBA

Parameter	Unit	Standard value	Low value	High value
Struvite				
Struvite Value [1]	$ per tonne	200	0	400
$MgCl_2$ dose rate [2]	kg/d	1,800		
$MgCl_2$ [3]	$/kg	0.61		
NaOH dose rate [2]	Kg/d	210		
NaOH cost [3]	$/kg	2.5		
Electricity				
O_2 per N removed [4]	kg O_2 /kg N rem	4.33		
AOTR for N removal	kg O_2 /kWh	1.7		
Struvite process power [2]	kW	25		
Chem P into BNR power [5]	kW	0.5		
Chem P into non BNR power [5]	kW	12		
Electricity [3]	$/kWh	0.12		
Chemical Dosing				
Al/P molar ratio in BNR (long HRT) [6]		1.5		
Al/P molar ratio in non BNR (short HRT) [5]		3.0		
PAC [3]	$/kg	1.15		
Maintenance				
Struvite % install	%	5		
Chem P into BNR % install	%	10		
Chem P into non BNR % install	%	5		
Solids Disposal				
Chem P waste solids [7]	t/d	6.2		
Disposal costs [5]	$/t	130	0	250

1. Struvite high value reflects wholesale fertilizer product at $3.3/kg P
2. Based on information from industrial suppliers
3. Current supply cost to Australian market
4. Struvite crystallization removes some nitrogen that saves $ to denitrify in downstream BNR
5. JEG experience
6. (Bratby, 2006) and JEG experience
7. Calculations

9.0 DISCUSSION - OUTCOMES OF THE COST BENEFIT ANALYSIS

The cost benefit analysis comprises five separate groups of analyses:

- An analysis of the base case scenarios (1, 2 and 3) to determine whether chemical dosing or struvite crystallization is a more cost-effective method of phosphorus removal from the wastewater.
- A sensitivity analysis on the market value of struvite (scenarios 3 - 5) to determine the impact that this has on the viability of a struvite installation.
- A sensitivity analysis on the disposal cost of sludge (scenarios 1, 2, 6 - 9) to determine how the chemical dosing options are affected by this variable.
- A sensitivity analysis on the size of the meat processing facility (scenarios 3, 10 and 11) to see if there is a cost advantage for smaller or larger processors for struvite installation. The cost comparison between struvite (scenario 11) and chemical dosing in larger facilities was also analysed (scenarios 14 and 15).
- A sensitivity analysis on the impact of struvite crystallization unit capital cost (scenarios 3, 12 and 13) to determine if this significantly affects process viability.
- A sensitivity analysis on the effect of the initial phosphorus concentration of the wastewater stream (scenario 18, 19 and 20).
- The worst case chemical dosing into an existing BNR scenario (17)
- The best case struvite crystallization scenario (16)

Table 11 summarises the outcomes of each of the scenarios and Table 12 summarises the breakdown of the operational expenses and savings.

Table 11. Summary of outcomes from cost benefit analyses

Scenario	CAPEX	Revenue	OPEX	Payback period	NPV
	$	*$/yr*	*$/yr*	*years*	*$*
1	$2,150,000	$0	$970,000	N/A	-$11,610,000
2	$200,000	$0	$560,000	N/A	-$5,730,000
3	$6,500,000	$50,000	$530,000	N/A	-$10,830,000
4	$6,500,000	$4,000	$530,000	N/A	-$11,280,000
5	$6,500,000	$95,000	$530,000	N/A	-$10,380,000
6	$2,150,000	$0	$770,000	N/A	-$9,630,000
7	$2,150,000	$0	$1,140,000	N/A	-$13,300,000
8	$200,000	$0	$370,000	N/A	-$3,850,000
9	$200,000	$0	$740,000	N/A	-$7,510,000
10	$3,400,000	$17,000	$212,000	N/A	-$5,310,000
11	$8,800,000	$83,000	$836,000	N/A	-$16,170,000
12	$5,000,000	$50,000	$530,000	N/A	-$9,430,000
13	$8,500,000	$50,000	$530,000	N/A	-$12,700,000
14	$2,900,000	$0	$1,590,000	N/A	-$18,450,000
15	$300,000	$0	$930,000	N/A	-$9,490,000
16	$6,800,000	$320,000	$1,010,000	N/A	-$14,470,000
17	$300,000	$0	$1,830,000	N/A	-$18,400,000
18	$6,500,000	$100,000	$660,000	N/A	$12,210,000
19	$200,000	$0	$830,00	N/A	$8,400,000
20	$2,150,000	$0	$1,420,000		$15,570,000

NPV = Net Present Value

Table 12. Summary of OPEX and Revenue for different from cost benefit scenarios

Scenario	Chemical Dosing	Electricity	Sludge Disposal	Maintenance	Revenue	OPEX – Revenue
	$/yr	*$/yr*	*$/yr*	*$/yr*	***$/yr***	***$/yr***
1	$710,000	$8,000	$190,000	$54,000	$0	$970,000
2	$350,000	$0	$190,000	$10,000	$0	$560,000
3	$390,000	$17,000	$0	$130,000	$50,000	$480,000
4	$390,000	$17,000	$0	$130,000	$4,000	$526,000
5	$390,000	$17,000	$0	$130,000	$95,000	$435,000
6	$710,000	$8,000	$0	$54,000	$0	$770,000
7	$710,000	$8,000	$370,000	$54,000	$0	$1,140,000
8	$350,000	$0	$0	$10,000	$0	$370,000
9	$350,000	$0	$370,000	$10,000	$0	$740,000
10	$130,000	$17,000	$0	$70,000	$17,000	$195,000
11	$650,000	$17,000	$0	$170,000	$83,000	$753,000
12	$390,000	$17,000	$0	$130,000	$50,000	$480,000
13	$390,000	$17,000	$0	$130,000	$50,000	$480,000
14	$1,180,000	$8,000	$320,000	$73,000	$0	$1,590,000
15	$590,000	$0	$320,000	$15,000	$0	$930,000
16	$870,000	$17,000	$0	$120,000	$240,000	$770,000
17	$890,000	$0	$930,000	$15,000	$0	$1,830,000
18	$530,000	$17,000	$0	$130,000	$75,000	$590,000
19	$530,000	$0	$290,000	$10,000	$0	$830,000
20	$1,060,000	$8,000	$290,000	$54,000	$0	$1,420,000

9.1 Base case analysis

Figure 10 shows the course of the Net Present Value (in 2018 AUD) of the three modes of chemical phosphorus removal (scenarios 1, 2 and 3) over their 20 year project lifetime.

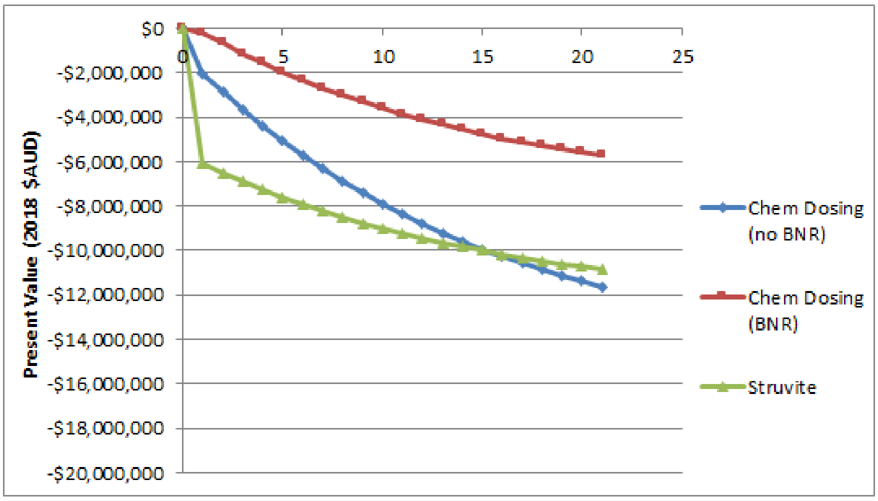

Figure 10. Base case analysis NPV graph

The following is shown in the Base Case Analysis:

- The major difference between the struvite option (scenario 3) and the two chemical dosing options is the large capital expense required for the struvite process installation in the first year. This is more than double that for the stand-alone chemical precipitation plant (CPP).

- The struvite scenario has lower operating costs compared to the chemical dosing options due to reduced chemical usage, no sludge disposal costs and some revenue from the sale of struvite. For the base case, this gives the struvite option a superior (but still negative) NPV from the mid-point of plant life relative to the CPP option.

- Chemical dosing into an existing BNR plant is a much more cost-effective option relative to building a dedicated CPP or struvite system. This is mainly due to the greater precipitant dose required for scenario 1 (no BNR) than scenario 2 (BNR) to achieve the same phosphorus concentration in the effluent. There is also a much greater capital expense for the CPP (no BNR) option than the BNR chemical dosed option where existing infrastructure can be used with little required modification.

- For the base case, the struvite process appears to be more attractive than a standalone CPP system over a 20 year period, if the facility does not have an existing BNR plant (which is usually the case for many medium and small facilities). Nevertheless, the high upfront capital cost of the struvite system is likely to be a strong disincentive to adoption of struvite for these facilities.

9.2 Struvite market value sensitivity analysis

Figure 11 shows the course of the Net Present Value (in 2018 AUD) of scenarios 3, 4 and 5 over their 20 year project lifetime to assess its sensitivity to struvite market value for a struvite plant installed in a medium sized processing facility (3 ML/day wastewater).

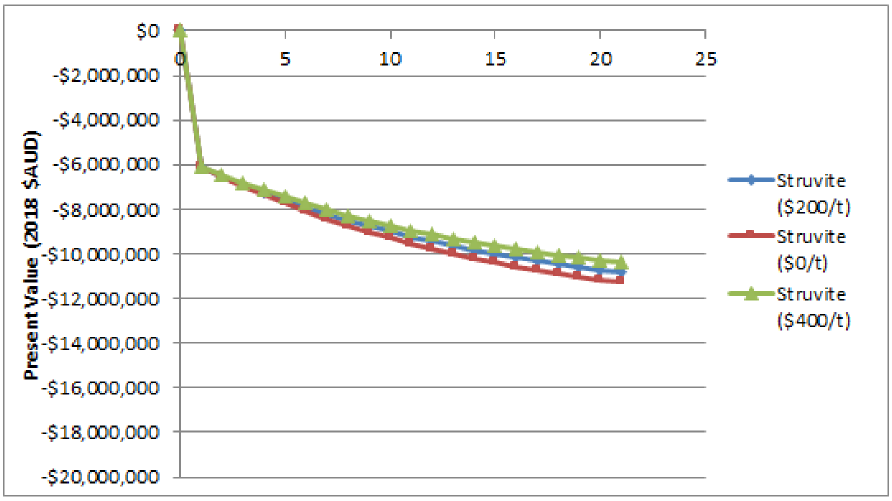

Figure 11. Struvite market value sensitivity analysis NPV graph

Figure 11 clearly demonstrates that the struvite market value is largely immaterial (given the large range in struvite value used) to the economic viability of a struvite installation. The revenue provided by sale of the struvite (varying between $4 – 95,000 p.a.) is dwarfed by the capital, chemical and maintenance operating costs.

A positive NPV can only be obtained from a struvite process by assuming unrealistic prices for the struvite product, which are not supported by its fundamental nutrient value.

9.3 Sludge disposal costs sensitivity analysis

Solid waste issues are becoming a significant issue of concern in Australia. Some companies – especially those exposed to consumers such as the supermarket chains – are setting tough recycling and solid waste reduction targets. Most Australian State governments are looking to increase levies on wastes to landfill. Unfortunately a significant downside of chemical phosphorus precipitation processes is the production of significant volumes of chemical sludge, often contaminated with organic material, which must be disposed to landfill.

Figure 12 shows the sensitivity of the Net Present Value (in 2018 AUD) over a 20 year project lifetime to sludge disposal costs for both traditional chemical phosphorus dosing options. The base case scenarios 1 & 2 are calculated at a relatively high $130/tonne disposal charge to account for the 20 year lifetime of the analysis. This is typical of the cost imposed by Australian States on disposal of industrial wastes to landfill. Queensland, the last State to impose such a levy, reintroduced a waste levy at $70/tonne in March 2018. This is substantially below the current NSW metro levy of

$138/tonne. The standalone CPP (no BNR) option and the co-precipitation (BNR) option are compared at a zero charge (scenarios 6 & 8, respectively) and a high charge of $250/tonne (scenarios 7 and 9, respectively).

Figure 12 shows that sludge disposal charges have a huge impact, especially for the CPP option. The charges represent a large fraction of the operating costs for the chemical dosing scenarios. Processors should look into sludge disposal options as part of the initial design scope of a chemical dosing system. However, even at the highest sludge disposal cost, the chemical dosing into an existing BNR is still more cost effective than struvite crystallization in a medium sized processing plant.

The major benefit of struvite processes is that the final solid product is considered environmentally friendly. In the context of the analysis above, this benefit is likely to become more profound with time as community opposition to wastes, and especially chemical wastes, strengthens.

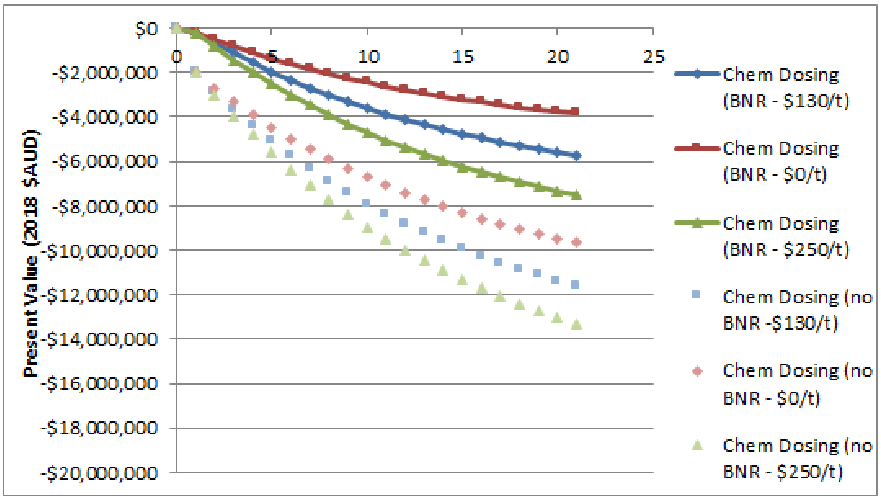

Figure 12. Sludge disposal costs sensitivity analysis NPV graph

9.4 Struvite Installation CAPEX sensitivity analysis

Figure 13 shows the sensitivity to struvite installation CAPEX with the course of the Net Present Value (in 2018 AUD) of scenarios 3, 12, and 13 over their 20 year project lifetime. These represent the spread of capital costs from the suppliers with allowances for installation costs at a medium-sized meat processing facility. Care must be taken with these estimates, since the costs are based on overseas estimates – in the absence of any struvite facilities in Australia - and construction, fabrication and labour costs can be substantially different (and usually less) than in Australia. The exchange rate (where equipment or services must be imported) is also a factor for consideration.

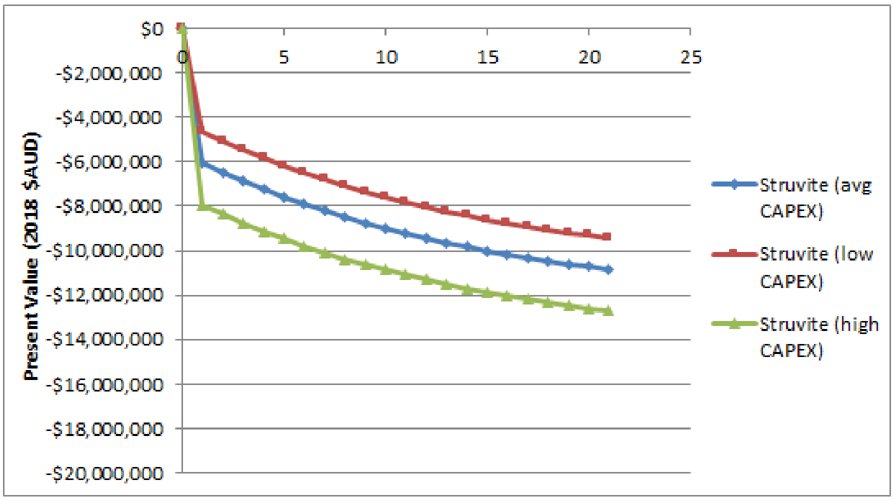

Figure 13. Struvite installation CAPEX (medium facility) sensitivity analysis graph

The net present value over a 20 year lifetime increases linearly over the CAPEX range by about $1 million for every additional $1 million CAPEX. The high capital cost of struvite facilities is a significant disadvantage for this technology and likely to be a strong deterrent to their adoption by small to medium sized facilities, despite the benefit of a superior NPV to standalone CPP systems. For larger plants, the benefit over the CPP system (no BNR) is compelling and likely to improve further with time as sludge disposal charges increase. However, many of these facilities have BNR systems where the CAPEX increment for chemical precipitation is minor.

In any event, good capital cost control will be essential for the economics of struvite installations.

9.5 Meat processing facility size sensitivity analysis

Figure 14 shows the sensitivity of struvite installation to facility size (determined by wastewater flow) with the course of the Net Present Value (in 2018 AUD) of scenarios 3 (medium size plant), 10 (small) and 11 (large) over their 20 year project lifetime. This assumed that the capital expense increased with the flowrate. As expected the trend in NPV with time is similar for each size of struvite facility. The larger processor benefits from economies of scale, with a smaller CAPEX cost per kilogram of phosphorus to be treated, but a greater absolute capital cost. The economy of scale benefit is captured because, although operating costs are proportional to throughput, the capital cost of the struvite installation increases at a lower exponent with scale.

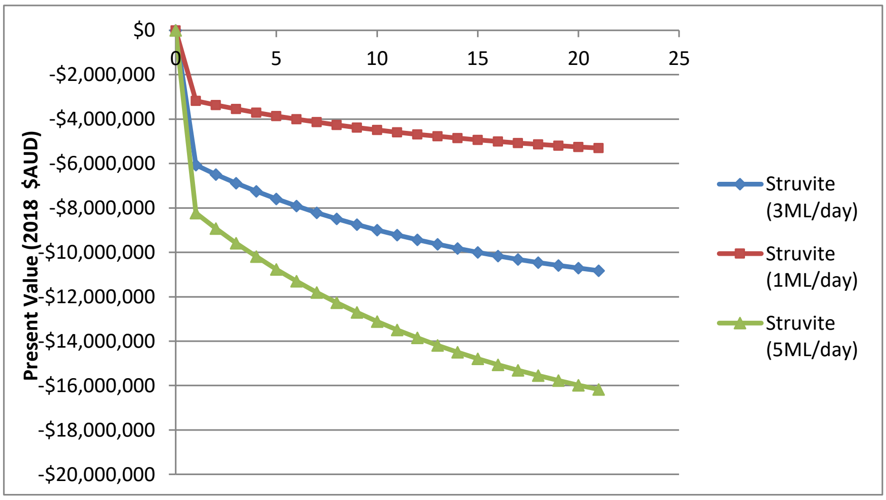

Figure 14. Meat processing facility size sensitivity analysis NPV graph

Figure 15 compares the outcomes for the three phosphorus removal options for a large meat processing facility (5 ML/day) with the course of the Net Present Value (in 2018 AUD) over the 20 year project lifetime. The options are struvite (scenario 11), a standalone CPP (scenario 14, chem dosing, no BNR) and chemical dosing in a BNR system (scenario 15).

Even for a large facility, the struvite installation is still less economic than chemical dosing into an existing BNR with a $4 million NPV differential by project end. However, it is a superior proposition to a standalone CPP with a similar NPV differential in favour of struvite. The benefit of a struvite process is realised within 10 years of operation. Further analysis of this outcome would be needed if sludge disposal costs and chemical costs increase and/or struvite installation costs reduce.

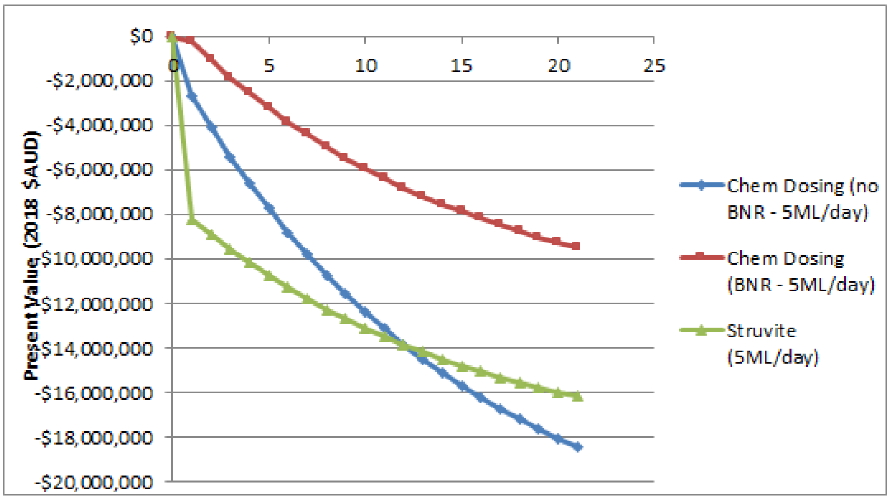

Figure 15. Large meat processing facility analysis of chemical dosing versus struvite NPV graph

9.6 Initial phosphorus concentration sensitivity analysis

Figure 16 shows that as the phosphorus concentration increases (high P, scenarios 18 – 20), the associated operating costs also increases for both chemical dosing and struvite crystallization. The greater phosphorus concentration magnifies the operating cost effect on the NPV for the three options with struvite being the least affected and the standalone CPP being the most affected. As the initial phosphorus concentration increases, the payback of the struvite option over the CPP reduces but it is still not cost effective over dosing into an existing BNR after 20 years.

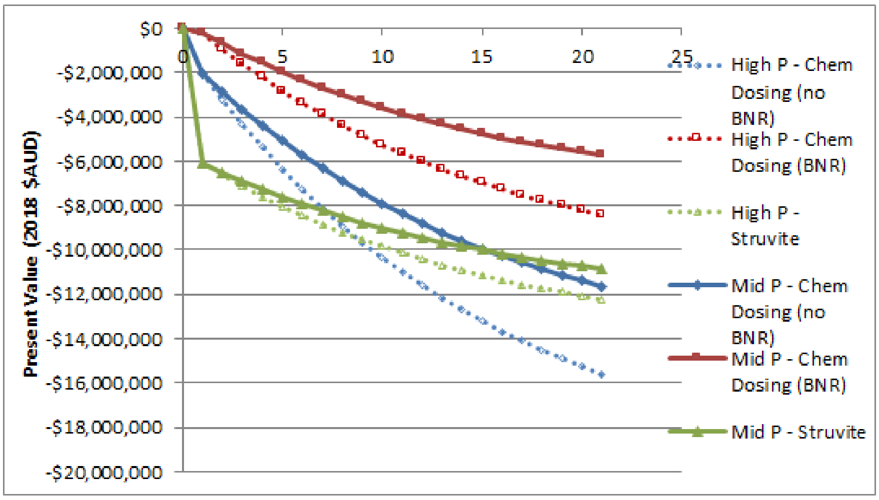

Figure 16. Phosphorus concentration sensitivity analysis in BNR NPV graph

9.7 Best case struvite versus worst case chemical dosing in existing BNR

Figure 17 shows the comparison between the best case struvite installation (scenario 16) and the worst case chemical dosing into an existing BNR (scenario 17) with the course of the NPV (in 2018 AUD) over their 20 year project lifetime. The best case struvite installation was for a large meat processing facility (treating 5 ML wastewater per day), with low struvite CAPEX ($6.8 million), high phosphorus concentration (80mg/L) and high struvite value ($400/tonne). The worst case chemical dosing into an existing BNR was also for a large scale meat processing facility with high sludge disposal costs ($250/tonne) and high phosphorus concentration (80 mg/L). In this somewhat extreme situation, the struvite installation returns a superior NPV to the chemical dosing into the BNR after approximately 10 years.

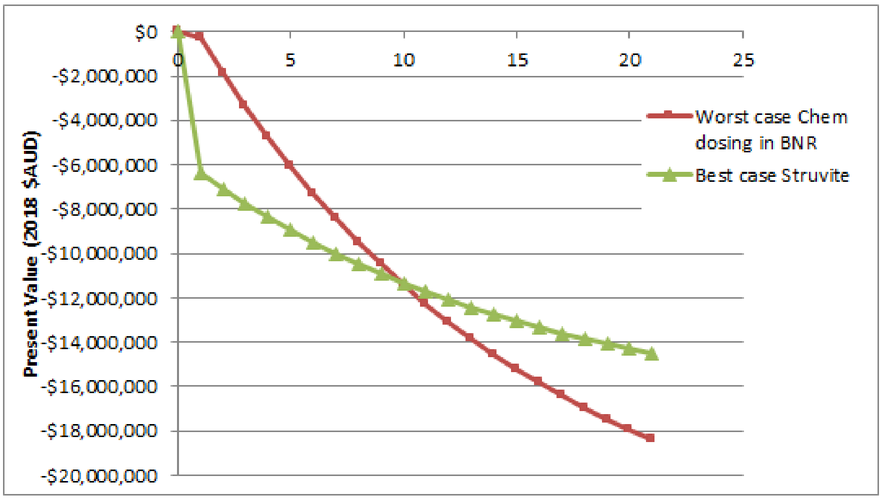

Figure 17. Best case struvite versus Worst case chemical dosing into existing BNR NPV graph

10.0 CONCLUSIONS

1. Struvite crystallization is a proven technology with many vendors supplying full-scale plants in countries around the world with mainly municipal and some industrial applications. There are currently no known meat processing applications.

2. A holistic view of the wastewater treatment system is necessary when choosing the best struvite crystallization system. The best struvite design will depend on the wastewater flowrate, downstream nitrogen removal process, existing wastewater infrastructure, footprint constraints and consistency of feed flow.

3. Struvite processes typically achieve a treated TP concentration of 15 to 20 mgP/L. The concentration is set by the struvite solubility at the operating pH (usually about pH 8) and allows for a small loss of struvite fines. Further phosphorus uptake is possible in downstream biological nutrient removal which may allow discharge to irrigation areas or sewer but probably not surface water.

4. There are no operating struvite crystallization plants in Australia, even in the domestic wastewater sector. Some home-grown attempts have been made in the past, but not by the major vendors covered by this review.

5. In comparison to chemical precipitation, the net present value after 20 years of struvite operation is generally greater compared to chemical phosphorus precipitation (CPP) but less than when integrated into an existing biological nutrient removal (BNR) system.

$$BNR > Struvite > CPP$$

6. The greatest drawback to struvite is the upfront CAPEX (more than double that of a CPP). This renders struvite adoption unlikely by small to medium sized plants. Care needs to be taken with cost estimates for struvite capital as these are based on offshore manufacture and current exchange rates.

7. The value of the struvite product has little consequence to its viability. The difference in the NPV between the highest struvite value and zero struvite value was only $900,000 representing less than 10% of the total capital and operating costs over 20 years.

8. The NPV is strongly dependent on the sludge disposal costs. This is especially prominent for the standalone CPP with a difference of $3.6 million over 20 years from zero sludge disposal costs to high sludge disposal costs. This increase represents a 38% deterioration in NPV. Sludge disposal costs are an expense that is highly likely to increase in the future.

9. Comparison of NPV for large scale meat processing plants shows a significant advantage of struvite over CPP. However, large plants often have a BNR plant that may allow co-precipitation in the BNR basin – a result which is cheaper than struvite implementation.

10. Struvite is the most economical phosphorus treatment option for large scale plants (>5ML/d) with high phosphorus concentrations (>80 mgP/L) where there is high sludge disposal costs ($250/tonne) and the struvite system can be installed at a capital cost of < $7 million AUS.

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