AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION FOR SUPPLEMENTAL VFA IN ENHANCED BIOLOGICAL TREATMENT

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ABSTRACT

The development of fermentation systems to enhance nutrient removal (i.e., biological uptake of phosphorus and reduction of nitrates) in wastewater treatment has evolved primarily as a side stream process. This has taken shape largely through the introduction of sewage wastes that were observed to contain volatile fatty acids (VFA), particularly acetic and propionic forms. Where plants did not have sufficient VFA in the incoming sewage, supernatant from sludge thickeners showed benefit in improving the performance of the enhanced biological nutrient removal (EBNR) process. This appears to have promoted the development of separate fermentation reactors to produce VFA. The conventional fermentation process that evolved used either a dedicated thickener or primary clarifier in conjunction with a mixed tank to allow fermentation of primary sludge. The fermented product was elutriated in either the primary or thickener tanks to carry the soluble fermented products (VFA) to the EBNR process. The conventional fermenter typically requires about 8 to 12 days or more of solids retention and a 10 to 14 hour hydraulic retention time. This compares with the use of an acid digester or first stage Autothermal Thermophilic Aerobic Digester (ATAD) where it is shown that the VFA can be doubled over the fermentation of primary sludge in solids retention times of 2 to 3 days.

Dayton & Knight Ltd (2008), Dirk (2009) and by Kelly (2009) identified that the production of VFA in the digesters is substantial and that through use of either a coagulant such as alum of a struvite crystallizer, phosphorus can be separated from the liquid through precipitation leaving the high concentrations of VFA for return to the EBNR facility.

Cost comparisons show that use of a crystallizer for phosphate and VFA recovery is competitive with use of coagulants alone at an average day flow of about 60,000 to 70,000 m^3/d. The use of either chemical addition or the installation of a crystallizer shows advantage in providing natural VFA to offset the cost of acetate or methanol, if purchased as a carbon source..

KEYWORDS

Cost comparison, volatile fatty acid (VFA) for EBNR, phosphorus and ammonium recovery, phosphorus removal from centrate by alum or struvite crystallizer, ATAD, thermophilic, nutrient recovery, cost comparison.

INTRODUCTION

The author's of this investigation show a general business case for process selection using investigations from a pilot study for struvite and VFA recovery. The investigation was undertaken at the City of Salmon Arm, B.C., enhanced biological nutrient removal, (EBNR) water pollution control centre, (WPCC). The VFA is produced in an acid digester or in this case an ATAD, which due to micro-aerophilic fermentative conditions and volatile solids reduction, solubilizes phosphates and increases VFA largely in the form of acetate. A comparison is made between the use of a full scale struvite crystallizer and addition of a chemical (alum) to remove phosphorus from the centrate prior to its return to the EBNR treatment process against the potential requirement to purchase a carbon substrate (acetate). The investigation includes reference to the pilot study report, published papers resulting from the pilot work and papers presented by others that are relevant to the findings. Cost implications for average domestic wastewater flows from 4,600m^3/d to 500,000 m^3/d are compared.

The significance of this investigation is that it includes the use of the normally used primary sludge for fermentation as well as biological sludge (phosphate accumulating organisms, PAOs) as the source for natural VFA and phosphorus supply. The increase in natural VFA as a result of both souces is measured against the cost of purchasing acetate to supplement nitrogen and phosphorus removal. Further, since in the one case under study, struvite is being produced by a crystallizer, ammonium ion removal is acknowledged through a treatment cost reduction. Struvite removal is also a consideration to wastewater facilities, which may be losing capacity due to struvite formation and whose administrators have increased costs for its removal from equipment and pipe lines.

The details of the pilot study are presented in referenced reports and are briefly restated in this work for general reference. Costs for the Struvite Crystallizer were determined from information provided by the Ostara Nutrient Recovery Technologies, Inc. Other costs were provided from current market information.

BACKGROUND

The reviewed literature by Kelly et. al., (2009) illustrates the following:

1. "VFA (as acetate, HAc) produced from acid digester processes appeared to provide a valuable substrate for the EBNR process and does not inhibit but improves the stability of phosphorus removal and denitrification,

2. Waste biological sludge can be a valuable source of VFA and can supplement the production of VFA normally obtained from primary sludge alone; a means of removing soluble phosphate and ammonia improves the benefit of the fermentation of waste biological sludge.

3. Micro-aerophilic ATAD and TAD processes are shown to produce a higher concentration of the preferred VFA as acetate over propionate and butyrate for EBNR.

4. Use of chemicals for soluble phosphate removal or the use of a struvite crystallizer to remove both ammonia and soluble phosphate, does not appear to reduce the available VFA for use in an EBNR process; the struvite crystallizer may however, be impeded by high concentrations of TS in the feed,

5. Micro-aerophilic thermophilic processes such as TAD and ATAD will minimize methane formation while providing high concentrations of VFA in short fermentation times of 1 to 5 days,

6. A probable optimum HRT and SRT is about 1 to 2 days for maximizing the VFA in an acid digester, TAD or ATAD. In the latter case it would mean using the first stage of a series digester and loading it to a sufficiently high rate to achieve the desired SRT.

7. Probable pH range for optimum production of VFA is 5.5 to 6."

Comparative costs for use of naturally formed VFA against purchase of carbon supplies such as acetate or methanol, and the costs of removing the struvite forming chemicals as precipitated phosphate or struvite crystals are of interest.

The EBNR plant requires several controlled conditions for biological phosphorus and nitrogen removals but a common factor in the efficiency of the processes is the addition of an organic carbon source that is available in sufficient concentrations for hetrotrophic organisms to store soluble phosphates and denitrify in the anoxic, anaerobic and oxic stages of treatment throughout the process. deBarbadillo et. al (2008) and Anipsitakis et. Al (2008) provide reviews of the supplemental carbon sources that may be used where natural carbon or VFA is not sufficient to meet the biological plant needs.

A source of carbon currently overlooked is the biological solids of the treatment plant. Fermentation design has not yet included biological solids as a source; this may be because it is reasoned that the return of the biological solids could mean return of phosphorus such that the value gained by return of the new VFA would be lost in reabsorbing the returned phosphorus.

In the review by Kelly et. al.,(2009), VFA from primary and biological solids following acid digestion or ATAD in thermophilic or mesophilic operation, can be anticipated >30 to 170 mgVFA/g VS with one report as high as 550 mgVFA/g VS. This compares to classical fermenter designs that yield less than 20 mgVFA/g VS. The concentration of acid digester or ATAD VFA is shown to range from 1,500 to 10,000 mg/L. The concentration will depend on the design and operation of the digester. The microaerophilic ATAD will provide acetate consistently over 50% of the VFA, while a normal acid digester will provide acetate and propionate in near equal amounts with one often higher than the other by factors of 2 or more. Reactor hydraulic and solids retention time is less than 2 to 3 days.

The Salmon Arm Pilot study provide VFA on average of 1259 mg/L out of a >11 day SRT ATAD reactor train. The nature of the test set up required that the full ATAD reactor be used. The use of the first cell of the reactor would have increased the return VFA to the process by up to 2 to 4 times. The VFA production at Salmon Arm was therefore only 22.5 mgVFA/g VS. This represents 7 mg VFA/L addition to the average day flow. With the higher potential concentrations of the first reactor this would represent 15 to 30 mg VFA/L addition to the average day flow. The VFA was 60 to 70% acetate.

The ATAD reactors are observed release soluble phosphorus and produce ammonia in high concentrations. Phosphorus concentration averaged 433 mg/L from the ATAD and ammonium as nitrogen averaged 871 mg/L. With the addition of alum and polymer to the centrate feed, the phosphorus in the return centrate was reduced 75% and the captured phosphorus is contained in the solids. The use of the struvite crystallizer showed a 77% capture of the phosphorus and a 34% capture of the ammonia although only 26% of the ammonia loss could be accounted in the mass balance. Ammonia loss may be from unaccounted for gas release. The ammonium and phosphorus are contained in struvite crystals. The pilot is shown in Figure 1 and the struvite product is shown in Figure 2.

Figure 1: Crystallizer UBC Pilot Assembly

Figure 2: Struvite Crystals Formed During Pilot Study

The crystallizer used in this demonstration project received a flow rate of 1.7 L/min of clarified centrate. The total amount of centrate produced by the plant is approximately 25 m^3/d or 17 L/min; exactly ten times the flow being treated through the crystallizer.

For a full scale crystallizer, about 26% of the incoming phosphorus to the plant could be recovered and made available as a saleable fertilizer as struvite, which is over 90% pure and comprised an equal molar ratio of nitrogen as ammonia, phosphorus and magnesium.

COST ANALYSIS

A analysis was done to determine the costs and benefits of using a crystallizer or chemical addition against the cost of purchasing acetate for three sizes of treatment plant. The daily flow into the Salmon Arm WPCC is 4600 m^3/d; it has a centrate flow rate of approximately 25 m^3/d. The larger plants considered had overall flow rates of 50 000 m^3/d and 500 000 m^3/d with centrate flow rates of 200 m^3/d and 2000 m^3/d respectively. The cost analysis was divided into two parts, one for costs and one for savings, to identify the trade-offs of the selections. Savings and costs were totalled. The difference was divided by an equivalent population assuming 350 L/c-d, to determine per capita savings or losses.

Recent construction of primary sludge only fermenters in Calgary, AB at EBNR Bonnybrook treatment plant is reported to be over $25 million CDN for an average plant flow of 500,000 m^3/d. They are designed to ferment primary sludge and anticipate a production of VFA at 11.5 mgVFA/g VS. Similarly, construction of one primary sludge fermenter for Whistler, BC for a flow of 25,000 m^3/d is estimated at about $3 million CDN. A significant source of VFA and the opportunity to recover phosphate are being ignored.

Acid digesters and first stage ATAD reactors could be used at a lower capital and operating cost to provide increased benefit in VFA production and potentially reclaim phosphorus and nitrogen for reuse. Since phosphorus is becoming a limiting element, the selection of processes that better recover materials for the environment and offer lower costs will need to be considered more carefully. See Cordell (2009). Capture of ammonia in fertilizer directly reduces sidestream treatment process requirements in the plant.

Cost of Crystallizer

Part of the crystallizer analysis includes the cost of setting up and running the struvite reactor, and the cost of additional polymer needed to clarify the centrate in lieu of the use of a less expense coagulant that would remove phosphorus. The costs are itemized in the following list; all were supplied by Ostara Nutrient Recovery Technologies, Inc. (Ostara) except for the building cost and the cost of extra polymer.

- Fluidized bed reactor
- Reactor structural support
- Instrumentation
- Electrical
- Mechanical
- Building, HVAC, Lighting and Services
- Tie-In and Integration with Existing Services
- Contingency
- Extra polymer

Ostara has two contract models for those clients wishing to use the Ostara reactors: a) capital purchase, and b) treatment fee or outsourcing. For both of these options Ostara manages the end product, struvite and provides all necessary maintenance and consumables. Therefore, these costs were not included and the revenue from the sale of Crystal Green™ was also left out. A royalty is however, believed to be negotiable.

Building Cost

The building(s) required for these reactors must be approximately 9 m in height in order to accommodate the reactor. However, this height is only needed in the section of the building where the reactor(s) are located and the remainder of the building can have the standard 3 m height. Therefore, the costs of the buildings were based on a market cost of $\$2000/m^2$ for those sections at the standard height and $\$2500/m^2$ for the sections containing reactors.

For Salmon Arm, Ostara predicted a building approximately 12 m by 18 m, (40ft by 60ft) would be required to house the one reactor required and all the associated thanks and equipment. So the cost estimate of the 216 m^2 building was based on 9 m high 64 m^2 and a 3 m high 152 m^2.

For the mid-size facility a total area of 285 m^2 was used, including a 9 m high 75 m^2. For the full-size facility a total area of 840 m^2 was used, including a 9 m high 240 m^2.

Benefits

In order to assess the benefits of using this technology several options were considered. To provide the VFA necessary for biological phosphorus removal, one option is to purchase acetate. This option would be used if there were no fermenters or ATAD system present or if it was not possible to return this stream to the bio-P process because of the high P load. According to Tchobanoglous et al. (2003) and Gibb (1995) approximately 8 mg acetic acid is needed to remove 1 mg of total P in the influent. They also report that, for medium strength wastewater, there is typically 7 mg/L total P in the influent. Neethling et. al., (2005) reports that approximately 41% of plants require some additional source of VFA to maintain their bio-P process

A second option, which is very common, is to use a coagulant such as alum or ferric to remove the phosphorus from the digester centrate/supernatant, so that the VFA-rich stream can be returned to the bio-P process relatively free of dissolved phosphorus. However, ferric and ferrous have become problematic if used in conjunction with a UV disinfection system and so alum is a preferred choice. For this study, alum was used as the example.

The third option is to use a struvite crystallizer to remove the phosphorus and make the VFA available for use in the bio-P process. The struvite crystallizer also removes a significant amount of ammonia-nitrogen and so the savings accumulated from not removing nitrogen using a sidestream or mainstream biological treatment was included in the benefits. The Pennsylvania department of environmental protection reports that on average it costs $8.01 CDN (5 euros) per kg N removed (http://www.dep.state.pa.us/dep/deputate/watermgt/wsm/WSM_TAO/InnovTech/ProjReviews/SharonHiRate.htm). Also, the Maryland department of environment estimates $13.27/kg CDN (US$5.90/lb) nitrogen removed (http://www.mde.state.md.us/assets/document/BRF%20Gannett%20Fleming-GMB%20presentation.pdf). So an average cost of $10.64/kg N CDN removed was used.

Therefore the benefits that were included for a system using alum are as follows:

- Alum savings
- Capital cost of alum system
- O&M cost of alum system
- Sludge disposal avoided (from addition of alum)
- Cost of treating NH_4-N using another system
- Cost of pigging or acid cleaning (to remove naturally formed struvite)

The benefits included for a plant using acetate are as follows

- Cost of treating NH_4-N using another system
- Use of naturally formed volatile fatty acid as Acetate
- Cost of pigging (to remove naturally formed struvite)

The benefits of a plant purchasing both alum and acetate are cumulative.

Cost Comparison

The cost comparison assumes that an acid digester or first stage ATAD is available for production of VFA. Figure 3 shows a process flow diagram of the options. The figure illustrates a combined biological and primary sludge being fed to an acid reactor or first stage ATAD. The reactor solids and liquid reaction time is less than 2 to 3 days. The digester contents is fed through a recuperative thickener and separated into liquid and solids flow fractions. The solids are directed to the final downstream treatment digestion and the liquid containing VFA and soluble phosphorus is treated for return to the EBNR process. The liquid treatment is shown to be either the addition of a coagulant to precipitate the phosphorus or diversion to a crystallizer to remove the phosphorus as struvite.

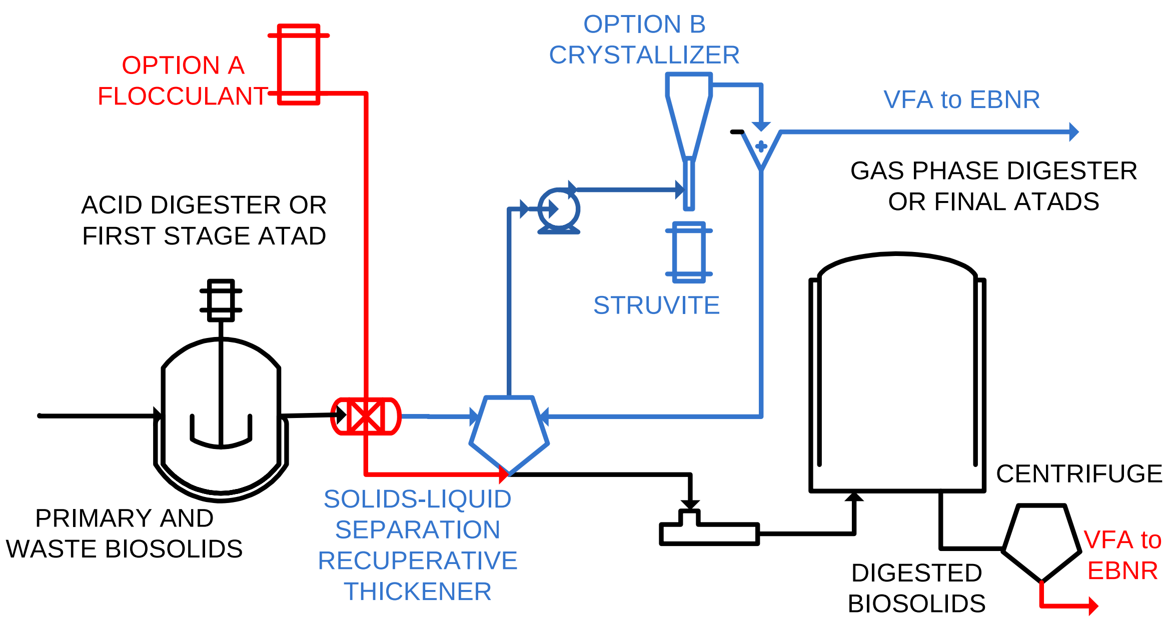

Figure 3 Process Flow Diagram for Recovery of VFA and Precipitation of Phosphorus in the Digested Product or as Struvite.

DISCUSSION

The EBNR plant combines the primary and biological sludge for digestion. Therefore phosphorus and ammonia will also be increased in the liquid fraction through hydrolytic and solubilization processes. In Salmon Arm the digested product is dewatered by a centrifuge and the centrate treated and returned to the EBNR. This is less efficient since the VFA concentrations are lower. Recuperative thickening however, can be used between the acid digester or first stage ATAD and the final digestion stages. The liquid fraction will contain large concentrations of VFA and phosphorus. For larger plants the digestion process is assumed to be anaerobic and for smaller plants it is assumed to include additional stages of ATAD or similar staged digestion systems. No cost is provided for the digester since it is assumed to be part of an existing solids treatment. A cost for the recuperative thickener would be additional. The thickener can be assumed to be ballanced by the additional capacity obtained in the digestion process. Each case would need to be explored and compared against the cost of a fermenter and is in contrast to the construction of a stand alone fermenter, which appears to be a larger cost to the overall treatment facility and not contribute to the solids treatment train.

The EBNR plant functions by either a natural supply of incoming VFA in the inflow or by the addition of supplement VFA from the purchase of acetate. The natural VFA can be diverted back to the EBNR process from the acid digester or first stage ATAD through a recuperative thickening treatment step such as the Torpey or Burke processes as described by Kelly (2006). The two options are:

a) The addition of a coagulant to the the recuperative thickener inflow to precipitate the phosphorus into the returned thickened solids, and divert the supertantant and VFA to the EBNR reactor,
b) Without the addition of chemical and after thickening, the removal of phosphorus and ammonium in a Struvite Crystallizer and return of supernantant to the EBNR and thickened solids to the following stages or the biosolids treatment process.

The base case is use of Alum and Polymer to precipitate phosphorus and recover VFA with no acetate purchase set to $ 0 saving. In case a) the capital costs for the crystallizer and structures are ammortized using a 6% annual discount rate and a 15 year repayment. Figure 4 shows the savings for case a) for use of a coagulant against case b) for the purchase of a struvite crystallizer. The savings of precluding the purchase of acetate with addition of natural VFA from an acid digester or ATAD are shown for three conditions; 50 percent, 25 percent and no replacement. The latter condition of no acetate purchase recognizes that sufficient VFA is in the influent wastewater.

The savings of ammonia-nitrogen removal, cost of acetate and savings avoidance of struvite removal are compared against, a) the use of chemical addition alone, or b) the cost of the amortized capital cost of the crystallizer. For all acetate supplement conditions, annual savings for adding the crystallizer would not be apparent until the plant reached a flow of about 60,000 to 70,000 m^3/d (or 170,000 to 200,000 people)[1]. Otherwise the use of chemical additions provide greater savings. Where no acetate supplement is purchased, the savings are not significant and the choice to reclaim the VFA requires that the influent VFA in the sewer is sufficient without the addition. The addition of natural VFA in the Salmon Arm investigation did however, show a greater stability in the process and fortified the EBNR process through a confirmed VFA supply.

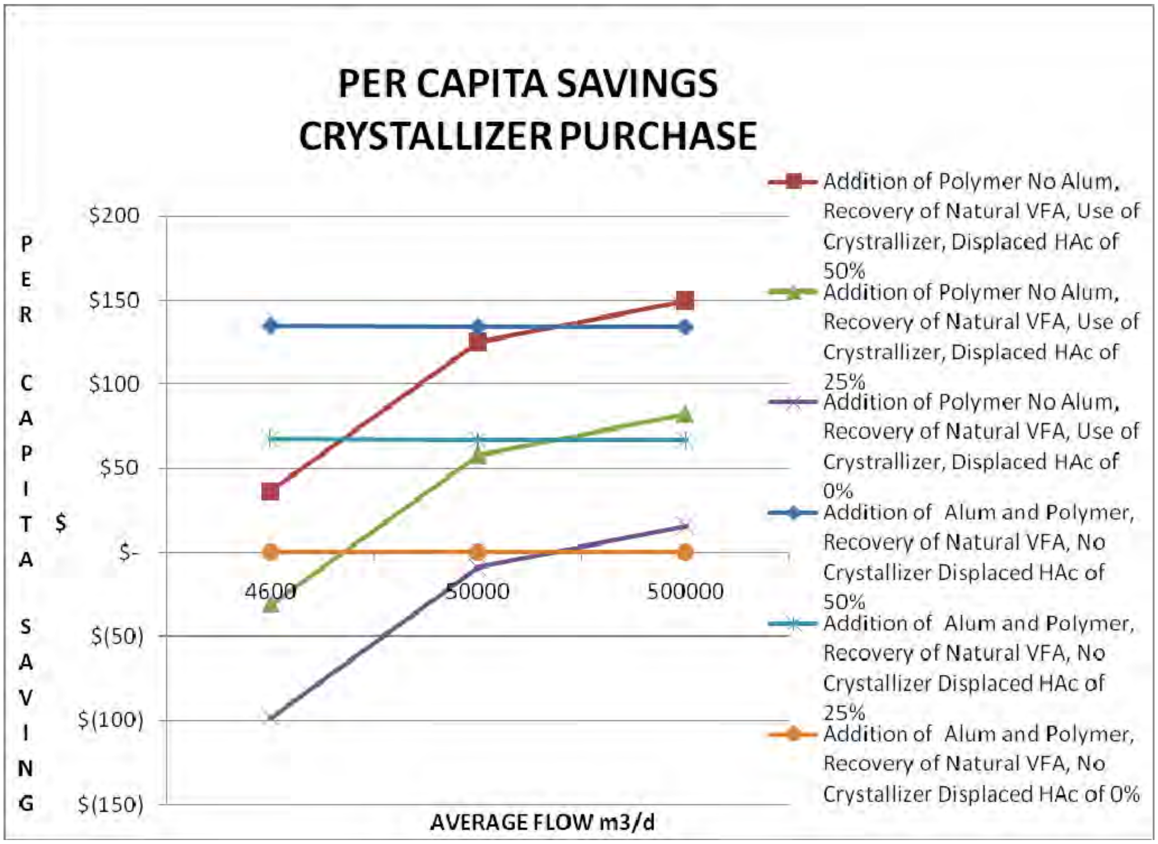

Figure 4: Normalized comparison of Crystallizer purchase versus Chemical Use for differing requirements of VFA purchase; 50 % , 25% and 0% of VFA needs

The value of the struvite product at the lower flows is probably not sufficient to warrant support of the crystallizer purchase. At 4600 m^3/d it is about $32,000 per year. The use of the alum is then more cost effective at the lower flows or up to 60,000 to 70,000 m^3/d.

Figure 5 compares the outsourcing of a cystallizer against the use of a phosphorus precipitating chemical. In all cases the use of a crystallizer shows greater benefit to the wastewater plant owner-operator. It is however unlikely that the Crystallizer provider would consider a low flow plant below the 60,000 to 70,000 m^3/d flow rate given the assessment of Figure 4 unless the value of struvite increased to show a profitable margin or favourable grants are provided.

[1] Where amortization periods are less than the assumed 15 years, the flows where the advantage of a crystallizer becomes apparent increase to as high as 500,000 m^3/d for 5 year payback at 6% discount.

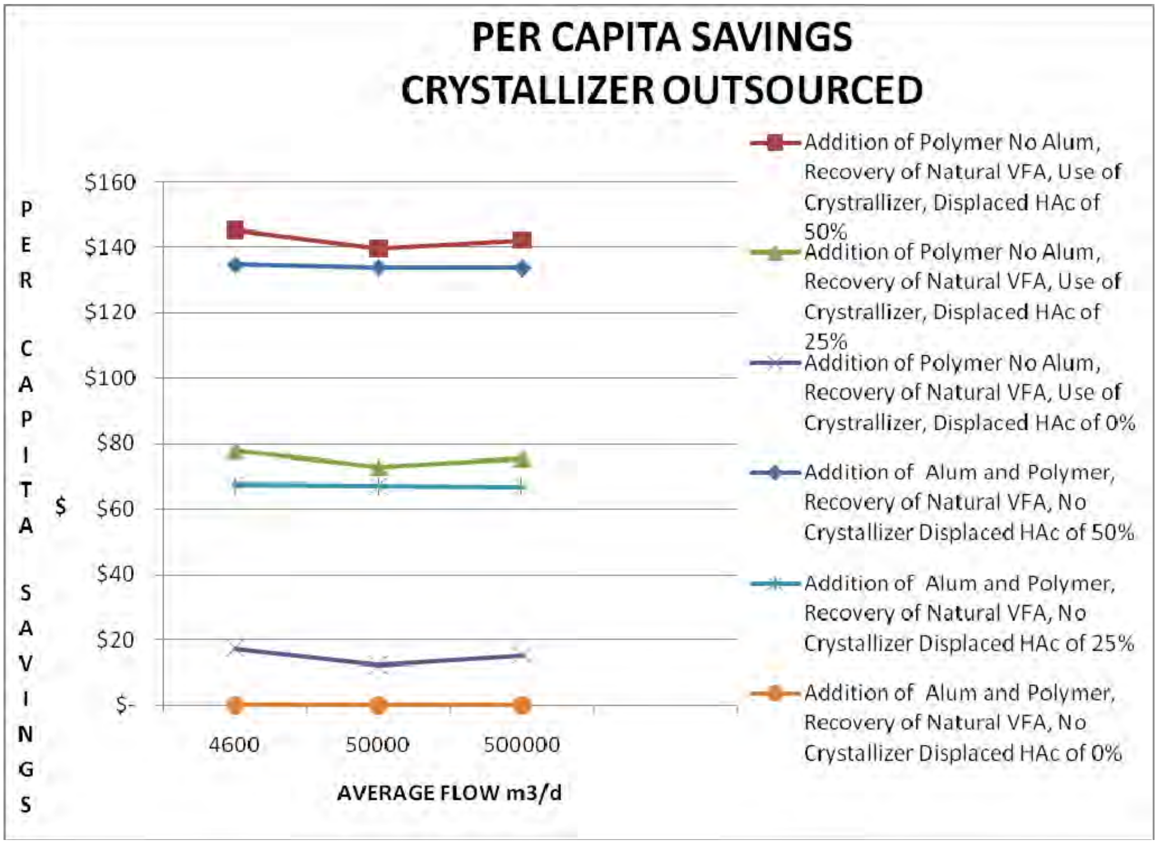

Figure 4: Normalized comparison of Outsourced Crystallizer with Royalties versus Chemical Use for differing requirements of VFA purchase; 50 % , 25% and 0% of VFA needs

CONCLUSION

This was a demonstration project that supports a full scale application. The study provides evidence that at full scale the combination of fermenter/ATAD and struvite crystallizer could improve the performance of the nutrient removal process and the solids digestion process, eliminate the need for ferric or alum for phosphorus removal from the centrate, and provide consistent nutrient recovery in the form of a saleable end product.

At full scale, the diversion location of the digester liquor would be the first reactor, and concentrated solids from the separation of the liquid fraction could be returned to the ATAD system to improve digester performance. In the pilot study, to facilitate the existing process configuration, the diversion took place at the final reactor where VFA was lower concentration. Nevertheless, the VFA recovery was significant. The use of a

2 day SRT ATAD reactor would improve the VFA recover significantly from 20 mg VFA/g VS to potentially 100 mg VFA/g VS. The majority of the VFA is acetate, and ranged from 60 to 70%.

Formation and recovery of struvite produces a saleable chemical fertilizer, and also avoids costly operational challenges of struvite removal from the dewatering centrifuge, related equipment and piping. It also benefits the treatment process by reducing the phosphorus and ammonium content of side streams that are returned to the wastewater treatment plant.

The use of alum to precipitate dissolved phosphate into the biosolids and allow recovery of VFA shows advantage over the use of a crystallizer at low to medium average day plant flow in a municipal wastewater treatment plant. Otherwise the installation of a crystallizer is warranted. Where an outsourced crystallizer provider can install and operate the crystallizer to manage the resources separate from the treatment plant process, the crystallizer shows advantage over the use of chemicals for soluble phosphate removal. It is doubtful that the crystallizer would however be offered at flows below 60,000 to 70,000 m^3/d unless the value of struvite increases and/or grants can be obtained to offset the cost of the equipment. If the supply of struvite is critical, grants may be an appropriate solution giving greater advantage to the use of the crystallizer technology.

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