DISCUSSION PAPER

Capital Regional District
Core Area Wastewater Management Program

Integrated Resource Management Strategy

Discussion Paper – Phosphorus Recovery
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1 Objective

This Discussion Paper provides an overview of phosphorus (P) from the perspective of its importance in society and, in the context of wastewater management, its recovery from wastewater as a valuable resource. The paper also provides an overview of technology that can be applied to recover P from wastewater. In addition, the paper examines the regional potential to recover P from wastewater generated within the Capital Regional District in the context of the Core Area Wastewater Management Program.

2 Topic Area Overview

2.1 Phosphorus in Society and Wastewater Management

Society

An integral component of DNA and RNA, phosphorus is essential for all living cells, and thus our existence. However, given the current state of operation in modern society, much of it is discharged into the aquatic environment via effluents or landfills through sludges and deemed unfeasible for recovery, or essentially lost.

There are currently four main applications for phosphorus by society. By far the most prevalent use is through the application of agricultural fertilizer, which represents about 80 to 85% of all consumption. Together with nitrogen and potassium, they are the three main plant inorganic nutrients required for agriculture. The second application of phosphorus is in the food and animal feed industry, due to its high value as a nutrient. The third is the use of phosphorus in detergents, which have greatly increased the efficiency of cleaning products for domestic use. Its success has been due to its ability to perform several functions within the detergent, and that because as an element of life, toxicity is not an issue. The fourth application refers to the use in industrial applications such as metal surface treatment, fire safety, chemical production, and others.

In its natural state, phosphorus combines with other elements and is commonly found in the form of phosphates. As required, phosphate is a resource that can be mined and extracted from the ground in the form of phosphate rock. However, unlike the forestry and fossil fuel industry, phosphorus is not a resource that is either sustainable, or replaceable by other resources. There are several reserves around the world from which phosphate rock is exploitable. However, the general train of thought regarding our current extraction rate is that these reserves will be depleted within the next 100 to 250 years (Shu et al., 2006). It is, therefore, important to consider the recovery of phosphorus due to reasons of depletion of the natural reserves, and growth in use of phosphates as fertilizers in agricultural areas that are nutrient poor.

Humans have historically ensured some level of phosphorus recycling through the application of animal manures back onto agricultural land, which in turn provided food. However, through population increase of cities and the disposition of farmlands to areas further away, this nutrient recovery cycle has more or less been ceased. It is further compounded by the fact that there is a disproportional amount of human and livestock excrement generation, and a lack of farmlands in local urban areas for its application. Unfortunately, the transportation, storage and treatment of wastewater for use in agricultural settings may not always prove to be economically and socially acceptable.

Wastewater Management

Other equally important reasons for the removal of phosphorus and other nutrients from wastewaters include discharges of nutrients into receiving waters such as lakes and rivers to prevent the process of eutrophication, or excess nutrients. Once this process establishes in a body of water, excess nutrients encourages the growth of undesirable algae that can severely deplete the level of oxygen available in the water for use by fish and other animals.

From a wastewater treatment facility (WWTF) perspective, if phosphorus was left unremoved, deposition of phosphorus compounds (e.g. struvite) within pumping equipment and piping in a WWTF can severely damage the treatment system under the right conditions. It has been reported that the cost associated with remediation can range from $2,000 to $10,000 per MGD (3.7 MLD) (Parsons et al. 2001) or exceed $100,000 USD for a 25 MGD (94.6 MLD) treatment plant (Doyle and Parsons 2002).

There are many reasons and benefits for the recovery of phosphorus from our wastes. Up to now however, most of the recovery technologies were still under research and developmental and would be considered “embryonic” at this time. Others have been used in demonstration systems, reaching what can be considered an “innovative” state of development and application. However, within the last two decades, the wastewater treatment industry is starting to see fruits of this progress, some of which are presented below.

2.2 P Recovery Technology

Traditional and Non-Crystallization Technologies

Recovery of phosphorus can take several forms, such as through the reapplication of stabilized wastewater sludges (i.e. biosolids) to agricultural lands. This is a conventional method that has its strengths and drawbacks, but will not be the focus of this Discussion Paper as they are well known. Traditional precipitative methods such as the use of iron or aluminum compounds for phosphorus removal limit the usefulness of the recovered phosphorus. This is because a substantial amount of energy is required to separate the phosphorus from the metal ions used for its precipitation, into a form that is usable. Due to feasibility issues, this method of phosphorus sequestration will not merit further investigation here.

Other methods of phosphorus recovery include the release of phosphorus into concentrated solutions through the use of either one or a combination of thermal energy, pressure, and acidification. Examples of this are three types of commercial processes that currently exist in Sweden: KREPRO, BioCon, and Aqua Reci. The KREPRO process utilizes thermal hydrolysis together with pressure and acid to breakdown wastewater sludges to recover phosphorus from within the biomass cells, which is then precipitated out with iron. The BioCon process incorporates sludge drying and incineration, followed by acid leaching from the ash, which is then passed through an ion exchanger to produce phosphoric acid. The Aqua Reci process utilizes water in its supercritical state to oxidize organic compounds, followed by the recovery of phosphorus in the form of calcium phosphate (Hahn et al., 2002).

Unfortunately there are disadvantages to these technologies. Both KREPRO and BioCon leach out inorganic materials at the same time when phosphorus is recovered. Both processes also require a significant amount of chemical to release and recover the phosphorus product. As mentioned previously, the commercial use of iron phosphate precipitates are limited. Aqua Reci has not had significant applications at full-scale. The calcium phosphates produced by this process are similar to mineral phosphate rock, but require further processing prior to use.

The use of adsorbents has been investigated for the removal and recovery of phosphorus. Adsorbents such as activated alumina, half-burned dolomite (calcium/magnesium carbonate), and red mud (residue from bauxite refining in the aluminum industry) have the added advantage such that no additional sludge is produced (Morse et al. 1997). However, the products of adsorption will likely require further refinement to gain value as fertilizer.

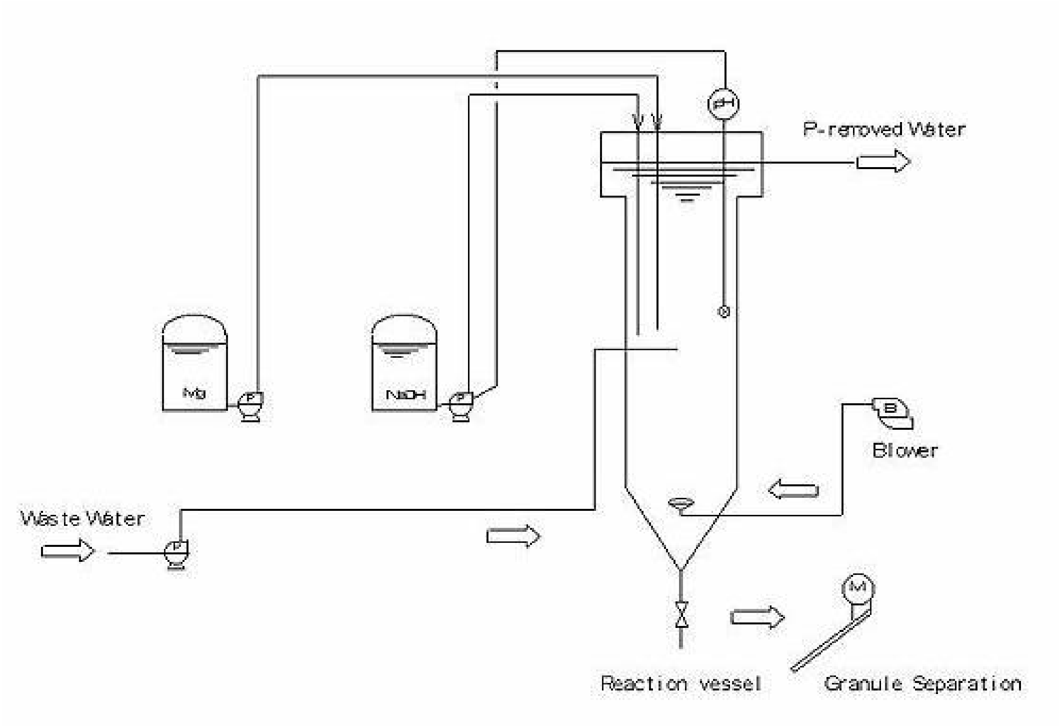
Crystallization Technology

The remainder of this Discussion Paper focuses on P recovery using crystallization, as this technology can be considered to be an innovative technology that has seen some limited application at WWTFs. In crystallization, P is recovered from wastewaters in high quality solids in the form of struvite, which is a compound made of magnesium ammonium phosphate (MAP). Wastewater-derived struvite can be used directly as a non-burning, slow-release fertilizer, which can be created in high purity.

Although phosphorus recovery systems vary somewhat in their configuration, some of which are marketed products (i.e., Crystalactor®, Phosnix, Ostara), all utilize the process of crystallization of solids within a solution. The process usually occurs in a system called a fluidized bed reactor, which is essentially a circular (sometimes funnel like) vertical tank that promotes upwards flow of liquid by injecting the feed (ingredients) from the bottom of the reactor. Air bubbles are also sometimes discharged from the bottom of the reactor through a blower to fluidize the struvite granules. This method allows for mixture, detention time, and the suspension of any struvite pellets that may have nucleated through the precipitation process. With the right conditions, the crystals formed within the reactor begin to grow, and have been observed to reach diameters of between 0.5 to over 2 mm (Mavinic et al. 2007).

Typical Struvite Crystallization Configuration

Source: http://www.phosphorus-recovery.tu-darmstadt.de/index.php



Conditions suitable for struvite crystallization are governed by the pH, supersaturation (dissolved more solids in a solution than can normally be dissolved), temperature, and presence of impurities (Parsons et al., 2001). To initiate precipitation of struvite in the reactor, an increase in pH through the addition of a base is often used. Addition of magnesium ions is also used to initiate or sustain the crystallization process.

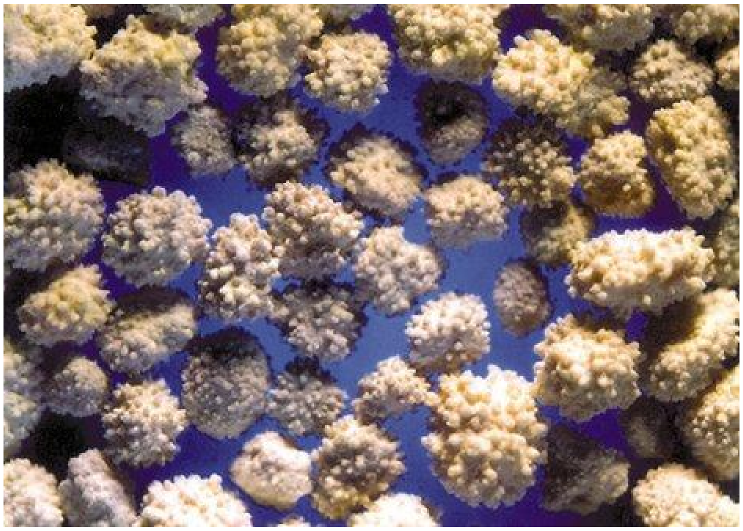
The source of phosphorus feed can be derived from several different locations within a WWTF. One approach is to utilize the phosphorus available in the influent wastewater stream. However, the phosphorus concentration from this source is generally very low and thus would require a very large struvite crystallization reactor, which translates to higher costs. Alternatively, anaerobic digester supernatant or sludge dewatering liquors contain phosphorus concentrations that are many times higher than those found in influent wastewater and thus are the most suitable source for phosphorus. Anaerobic digesters are utilized in WWTFs to hydrolyze and stabilize sludges produced as a byproduct of wastewater treatment, through heating and mixing in an insulated tank devoid of oxygen. Digester supernatant, separated from the stabilized solids, is usually returned to the head of the WWTF and is referred to as a “side stream”.

Side streams rich in phosphorus can also be derived from technologies other than anaerobic digesters. Research experiments have made use of microwaves and ultrasounds for phosphorus release into the liquid stream from waste biological sludge as the source of phosphorus for struvite (Liao et al., 2005). The use of selective ion exchange, a process where phosphate and ammonium ions are removed from dilute wastewater streams followed by precipitation of struvite has also been under investigation (Liberti et al., 2001).

Utilizing crystallization technologies on anaerobic digester supernatant feed streams, phosphorus recovery at bench, pilot, and full scale have observed recovery rates of 80 to 97%. Struvite crystals produced in studies have been reported to be 91% pure, with only small amounts of calcium, carbonate, and trace metals (Mavinic et al., 2007). Given this purity and value as a fertilizer, it has been estimated that the fertilization of about 2.6 ha of arable land can be accomplished by a struvite application rate of 1 kg/day, based on a P_2O_5 equivalent (Shu et al. 2005).

Magnified Struvite Pellets

Source: http://www.phosphorus-recovery.tu-darmstadt.de/index.php



Successful struvite formation depends on various factors such as phosphorus loading in the reactor, an elevated pH and magnesium level, and reactor turbulence (Mavinic et al. 2007). Studies have shown that, as the level of pH and magnesium increase, performance of struvite recovery increases as well. This can be achieved either through pH or magnesium ion increase, or both. Adjusting these two parameters provides an efficient method for reactor control.

2.3 Conventional and Advanced Treatment Facility Application

Crystallization P recovery technology can be applied to both conventional WWTFs (i.e. treatment objective is to remove suspended solids and organics that exert a biochemical oxygen demand (BOD) in the wastewater) and advanced WWTFs that provide nutrient (i.e. nitrogen and phosphorus) removal. Advanced WWTFs provide the greatest opportunity for P recovery, since enhanced biological phosphorus removal (EBPR) processes greatly concentrate P in the biomass. As a result, the amount of P that gets released into side-streams, due to anaerobic digestion, tends to be much greater than that for conventional WWTFs. However, P recovery has been implemented at both conventional and advanced WWTFs, as discussed in the following case studies.

Metro Vancouver Lulu Island WWTF

A pilot-scale P recovery system receiving anaerobic digester supernatant exists at Metro Vancouver's Lulu Island WWTF. This WWTF is a conventional secondary treatment facility that has an annual average wastewater flow of about 80 ML/D. It utilizes the trickling filter solids/contact tank system for wastewater treatment and anaerobic digesters for sludge stabilization.

Since the beginning of 2004, results from a pilot-study indicate that over 90% phosphate recovery could be achieved from the side stream feed and that up to 86% struvite recovery efficiency was observed (Mavinic et al. 2007). Of the struvite crystals harvested, the struvite purity was about 94%. The process also utilized anaerobic digester supernatant feed from the Annacis Island WWTF and yielded similar results.

On the basis of values presented and discussed by Fattah (2008), approximately 0.6 kg of struvite per 100 m^3 of raw wastewater received at the Lulu WWTF can potentially be produced with a full-scale P recovery system.

City of Edmonton Gold Bar WWTF

The City of Edmonton owns and operates the Gold Bar WWTF that serves more than 700,000 people in the greater Edmonton area. Situated along the shore of the North Saskatchewan River, Gold Bar is an advanced treatment facility that utilizes biological nutrient removal (i.e. EBPR) and has an average annual flow of about 270 ML/D. The current volume of the liquid sludge side stream flow is about 2.5 ML/d. Due to the phosphorus rich streams of the waste sludge from the nutrient removal process, most of it is pumped offsite to the Clover Bar Lagoons for storage and eventual land application and/or composting. Recently, however, a proprietary struvite removal system developed by Ostara was installed to recover P from the Clover Bar Lagoons supernatant.

The initial stages of the P recovery project constructed a fluidized bed crystallization reactor that treats 20% of the total side stream flow, or 0.5 ML/d. Since commissioning, the system has achieved an average phosphorus recovery efficiency of greater than 80%, with an average struvite production rate of about 500 kg/d. This roughly equals to about 0.9 kg of struvite per 100 m^3 of raw wastewater received at Gold Bar WWTP (note: this value is significantly higher than the one presented above for the Lulu WWTF, most likely due to the use of EPBR at the Gold Bar facility). The struvite crystals are ready for immediate use and are marketed as a slow-release fertilizer product, with the City receiving a royalty for every tonne produced. The installation of this process also reduced the cost associated with removal of undesirable struvite in the sludge pipes at the Clover Bar Lagoons, which has historically cost the City $75,000 to $100,000 annually.

Shimane Prefecture Lake Shinji East Clean Centre (SECC)
The Shimane Prefecture Lake Shinji East Clean Centre (SECC), located in Japan, is an advanced wastewater treatment facility that also utilizes biological nutrient removal. During initial operations, the biomass generated in the liquid-stream treatment process underwent anaerobic digestion with the supernatant returned back to the head of the facility. This resulted in 70% of the total phosphorus loading at the plant originating from the returning side stream. As a result, two struvite recovery systems, with capacities of 0.5 ML/d and 0.15 ML/d were initially installed in 1998 to recover P and thus reduce the excess P load returned to the liquid-stream system. A subsequent P recovery system with a capacity of 0.5 ML/d was installed in 2000. The results of the operation yielded a phosphorus recovery efficiency of 90% from the anaerobic digester supernatant. With the three-reactor setup, approximately 500 to 550 kg/d of struvite is produced, which had very low concentrations of heavy metals. At the time of writing in 2001, the struvite was sold to a fertilizer company for about $400 per ton.

3 P Recovery Potential

3.1 Unit Basis

The potential amount of recoverable phosphorus, in the form of struvite (i.e. MAP) and expressed in terms of a unit basis, from raw wastewater depends on the type of recovery technology used, its efficiency and the P content of the raw wastewater. The literature indicates that 1 kg of struvite per 100 m^3 of wastewater received at a treatment facility can be recovered (Shu et al. 2006). This value is consistent with that observed at the Gold Bar WWTF, which uses a biological nutrient removal process with EBPR. Alternately, this value may be reduced notably for a conventional treatment facility that does not use EBPR. As discussed in Section 2.2, the unit potential for a conventional facility would be lower and more in-line with the 0.6 kg of struvite per 100 m^3 of wastewater received at a treatment facility estimated for the Lulu WWTF.

3.2 Regional Potential

The potential amount of P that could be recovered from wastewater generated within the CRD, in the context of the Core Area Wastewater Management Program, will depend on wastewater flow rates, wastewater P levels and the efficiency of P recovery. For the purpose of illustration, assuming a current average dry weather wastewater flow rate (ADWF) of 95 ML/d for the region and the unit recovery value for wastewater treated in a conventional WWTF from Section 3.1, approximately 210 tonnes/yr of struvite could potentially be recovered from wastewater generated with the CRD. This value increases to about 355 tonnes/yr for the Year 2065 scenario, where the ADWF increases to about 160 ML/d.

While the use of struvite as fertilizer appears promising, economic feasibility has generally not been profitable for broad-scale agriculture use due to the lower cost of phosphate rock extraction, among other factors. However, if the use of struvite was targeted for a more specialized application such as “boutique” fertilizers used for ornamental plants, vegetables, turf, orchard trees, and potted plants, a higher sales cost can likely be achieved (de-Bashan and Bashan 2004, Münch and Barr 2001).

From an economical standpoint, the historic market price for struvite reported in the literature ranged between $200 to $1,885 (USD) per tonne (Doyle and Parsons 2002, Münch and Barr 2001, Ueno et al. 2001). However, there is currently much uncertainty with the price of P/struvite products originating form wastewater. Ostara, a British Columbia company that develops and markets crystallization technology for the wastewater sector, has indicated that current revenues of wastewater-sourced struvite products, as fertilizers, at least cover 100% of the operating and maintenance costs of the P recovery system at this time (Ostara, 2008). Presumably, as the demand for such products increase in the future, net revenues may be possible and increase over time.

4 Summary

Phosphorus recovery technology, like some other resource recovery technologies in the wastewater management industry, is undergoing ongoing development and implementation at full-scale wastewater treatment facilities, some of which are similar to those anticipated for the CRD. Besides producing a useful fertilizer product, P recovery can assist WWTF maintenance by reducing the potential for undesirable struvite formation within treatment facilities systems. As fertilizer markets develop it is anticipated that P recovered, as struvite, will increase in commercial value and provide a potential net revenue stream to wastewater operations.

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