NUTRIENT AND ENERGY RECOVERY FROM SEWAGE:
TOWARDS AN INTEGRATED APPROACH

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NUTRIENT AND ENERGY RECOVERY FROM SEWAGE: TOWARDS AN INTEGRATED APPROACH

Report to the

Water Research Commission

by

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This report is accompanied by an extended report and a technical report, both in electronic version only available on the CD enclosed at the back if this report.

Where reference to a figure or table is found in this report and the figure or table does not appear in the report, kindly refer to the Extended Report appearing on the enclosed CD.

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EXECUTIVE SUMMARY

The transition to a low-carbon and resource-efficient economy has begun, also in South Africa. Wastewater is increasingly viewed as a "water-carried waste", presenting opportunities for recovery of nutrients and energy, as well as water. Ecologically and economically more sustainable sanitation and wastewater management solutions are being explored and implemented. Amongst the sewage-borne resources, phosphorus is an important, non-substitutable nutrient for all life forms, particularly in the growth of plants, and is therefore essential in ensuring universal food security. Human activities have disturbed the natural phosphorus cycle and remain heavily dependent on mining of non-renewable rock phosphate. As a result, there is a particular interest in phosphorus recovery.

This technology transfer report firstly explores phosphate recovery possibilities from wastewater, relative to its potential South African market and developments in wastewater treatment. It is structured to address the following aims:

- Investigate available nutrient recovery technologies and their products, focusing on phosphate;
- Describe a number of cases that have adopted nutrient recovery and assess these from a sustainability perspective;
- Investigate the characteristics of recoverable fertilizer products and obtain viewpoints of experts along the fertilizer-produce value chain on likely social acceptance;
- Present and analyse two cases of how a nutrient recovery process could be incorporated together with energy recovery via anaerobic digestion.

Technology review

Within nutrient removal wastewater treatment works (WWTWs) some 40% of the phosphorus load reports to the sewage sludge and another 55% may have to be removed in tertiary treatment. The main points of recovery from wastewater treatment systems include:

- Liquid phase: secondary effluent, anaerobic digestion side stream, sludge liquor or source-separated urine;
- Solid phase: sludge, digested sludge, sludge ash.

For liquid phase extraction, a minimum concentration of 50-60 mg/L of orthophosphates is required for economically feasible recovery. Source separated urine contains 300-570 mg/ L and together with sludge liquor and the anaerobic digestion (AD) side streams (20-100 mg/L) makes up the liquid streams that are economically feasible for phosphate recovery. Of all nutrient extraction techniques, industrial crystallization technologies are common due to their ability to produce high purity, water-free and marketable final products, namely *Struvite* and *Calcium Phosphates*. Crystallization methods typically achieve a recovery of > 90% and an effluent phosphate concentration of 0.3-1 mg/L and are often located at WWTPs with anaerobic digesters. The most efficient phosphorus removal methods would involve the use of both chemical and biological methods simultaneously to reach levels between 0.5 and 1 mg/L. However, to meet phosphorus levels less than 0.1 mg/L (required to avoid eutrophication in receiving wetlands), additional tertiary treatment is required.

Case studies

Three industrial scale installations and one community-scale pilot project were investigated. These case studies illustrated crystallization and wet chemical phosphate recovery processes, producing struvite for fertilizer use. The Ostara Pearl®, Multiform Harvest and the Seaborne processes are centralized and are located at WWTPs with anaerobic digester units, treating the anaerobic digestion sludge liquor and sewage sludge, respectively. The Nepal struvite precipitation of source-separated urine project (STUN) was a decentralized attempt at phosphate recovery at community scale, with potential relevance to the situation in peri-urban eThekwini where 85 000 urine diversion toilets have been installed. The two competing struvite production processes installed at wastewater treatment works (WWTW) in the United States appear to be both fully operational and economically sound, addressing a technical plant problem in a way that saves costs for tertiary phosphate removal at the end of the process.

Products, markets and acceptance

Struvite is reported to be a good slow release phosphate fertilizer derived from human waste, which may replace rock phosphate derived fertilizers. Despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulation and be comparable to most phosphate fertilizers on the market. Expert interviews revealed that health and safety was the universal concern of most stakeholders, over and above fertilizer quality and quantity. To date, there are no South African policies on organic agriculture or certification. Although most stakeholders recognized the importance of phosphate recycling in tackling food security and achieving sustainable water and nutrient cycles, it is believed by industry experts that the South African organic markets and its consumer appear not ready for fertilizers produced from human waste. More feasible markets may lie within ornamental plant fertilization, commercial fertilizer production and fertilizer use within closed community gardens. Therefore, there is potentially a larger market for lower grade struvite.

Feasibility of nutrient and energy recovery as part of urban infrastructure

The potential for recovery of energy and nutrients was investigated through two techno-economic pre-feasibility studies: i) of three means of achieving phosphate discharge limits at a large centralised wastewater treatment plant in Cape Town and ii) of a conceptual design for energy and nutrient recovery plants in Cape Town's Foreshore precinct on the site of the current pump station directing sewage to ocean outfall.

The first assessment shows that production of low-grade struvite would have lower life cycle costs than either chemical precipitation (yielding an additional waste) or high-grade struvite production, and would thus be the most cost-effective way of lowering phosphate discharge levels of an established large wastewater treatment works with existing AD plant to within regulated limits.

The second assessment shows that diverting half of the urine from commercial building male urinals could produce approximately 75 kg/d of dried struvite fertiliser. The co-digestion of primary sludge from the Foreshore wastewater with 10% of the available food waste generated in the Foreshore could result in an electrical surplus of 27 kW to be fed to the grid. Over a 20 years forecast period, the additional operating costs incurred by the proposed scheme would result in a net cost more than four times the costs incurred by the existing scheme (wastewater to ocean outfall and food waste to landfill). The additional labour and maintenance requirements (and costs) associated with new treatment infrastructure makes the recovery of nutrients and energy unattractive when compared against the existing cheap, yet increasingly unacceptable disposal schemes – but they appear to be within the cost envelope for more standard sewage treatment.

Conclusion and Outlook

This report demonstrates that technologies for phosphate recovery from water-borne wastes have reached the stage of early full-scale use at reasonable cost, if fed from well-selected sources. Crystallisation-based technologies, to produce struvite, a potentially marketable phosphate fertilizer, are central in this regard, and often draw from side streams of anaerobic digesters, thus providing link to energy recovery. The South African fertilizer markets are immature for phosphates from wastewater sources, least of all the organic production route, which might well bar them, but other market segments may not have any significant concerns. A concept design and pre-feasibility cost estimation for a retrofit to lower phosphate discharge levels of a large wastewater treatment works to within regulated limits showed that production of low-grade struvite would have lower life cycle costs than either chemical precipitation (yielding an additional waste) or high-grade struvite production. A 2nd pre-feasibility study considered nutrient and energy recovery at the central city precinct scale and estimated them to be four times more expensive than outmoded disposal options but well within the cost envelope for standard treatment. We conclude that our project to develop a technology innovation for further reducing reactor costs for struvite precipitation is on a sound footing. This investigation has identified the minimum feed concentrations for which our innovation should cater as 50 mg/L but also shown that there remains a big opportunity for crystallization technology to achieve the 0.1 mg/L effluent standard, as secondary treatment effluent still carries the majority of the phosphate load.

This essence report, aimed to be a resource for infrastructure designers and decision-makers, provides the evidence in support of the above summary in a concise format. An extensive technical report mirroring the essence report structure is also available in electronic format.

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GLOSSARY, ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
BNR	Biological Nutrient Removal
BOD	Biochemical Oxygen Demand
CAP	Calcium Phosphate
CSRTs	Continuous Stirred Tank Reactor(s)
EBPR	Enhanced Biological Phosphorus Removal
EPC	Effluent Phosphorus Concentration
EU	European Union
FBR	Fluidized Bed Reactor
MAP	Magnesium Ammonium Phosphate (a.k.a. Struvite)
MBR	Membrane Bio-Reactor
NPV	Net Present Value
P	symbol of the chemical element Phosphorus
PAOs	Polyphosphate accumulating organisms
RO	Reverse Osmosis
SEP	Seeded Electrochemical Precipitation
STUN	Source-Separated UriNe
TSS	Total Suspended Solids
UCT	University of Cape Town
WRC	Water Research Commission
WWTPs	Wastewater Treatment Plant(s)
WWTW	Wastewater Treatment Works
ZA	South Africa country code
ZAR	ISO 4217 code of Rand, the South Africa currency (from Dutch Zuid-Afrikaanse Rand)

Currency symbols: € = Euro; R = Rand; $ = U.S. Dollar.

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1 Introduction

Twenty years after the democratic transition, the dual challenges of sustainable development remain starkly contrasted in South Africa: on the one hand, the necessary transition to a low-carbon and resource-efficient economy has begun, on the other hand, the delivery of basic services, including sanitation, remains a challenge especially in informal settlements and rural areas. The ability to address both imperatives simultaneously, with limited resources, has become something of a grand challenge for concerned engineers. In this light, it is encouraging that ecologically and economically more sustainable sanitation and wastewater management solutions are being explored and implemented, for centralised and de-centralised treatment alike.

Amongst the sewage-borne resources, phosphorus is an important, non-substitutable nutrient for all life forms, particularly in the growth of plants, and is therefore essential in ensuring universal food security. Human activities interfere with the natural phosphorus cycle and remain heavily dependent on mining of non-renewable rock phosphate. As a result, there is a particular interest in phosphorus recovery.

Humans produce a significant amount of sewage, containing large quantities of nutrients (phosphates, nitrates and micro-nutrients). For example, humans typically excrete 1.6-1.7 g phosphorus per day, most of which (approximately 60%) is found in urine (Schouw, et al. 2009). Considering that natural phosphorus reserves are on the decline and are expected to deplete by 2033 (Cordell, Drangert and White 2008), the use of sewage waste has the potential to be a major source of new phosphorus. This source of phosphorus is argued by some to simultaneously alleviate the challenges facing developing countries in terms of sanitation and also offer a “low cost source of phosphorus in the form of struvite”, a magnesium ammonium phosphate based fertilizer (Etter, et al. 2011). Bhuiyan et al. (2008) successfully demonstrated the use of a fluidised bed reactor for the production of struvite while in 2009, Etter et al. (2011) successfully demonstrated the use of low cost struvite production in a village in Nepal.

The other track for resource recovery from sewage is concerned with energy, in the form of biogas from the sludge stabilisation operation through anaerobic digestion. Anaerobic digestion (AD) has been successfully utilised for the stabilisation of settled sewage, generating biogas (Musango and Brent 2010) and the technology is well developed for this application. Significantly, AD produces a solution (digestate) enriched in dissolved phosphate, providing possible synergy between energy and phosphate recovery retrofits to sewage treatment works. Alternatively, urine diversion toilets, which separate urine and faeces at source, might be a good source of a urine waste stream for phosphate recovery and a black water for energy recovery. It is known that AD processing of sewage sludge is constrained by a sub-optimal carbon-to-nitrogen ratio, as this substrate is too rich in nitrogenous species found in urine.

As innovations and experiences with new technologies are made, there is a need to provide this knowledge to infrastructure planners and decision-makers who wish to or need to include resource recovery into their planning and design. There is also an opportunity for innovations to further improve these new technologies.

2 Objectives and Scope

The project aimed to address both the knowledge integration need and the innovation opportunity. The central aim of this report is to address the former, i.e. to review nutrient recovery technologies within the relevant, evolving systems of wastewater treatment (incl. energy recovery) and agricultural production. This aim focuses specifically on situation analysis and comprehensive technology review and is divided into a number of specific objectives:

1. Investigate available nutrient recovery technologies and describe the recoverable products;
2. Describe a number of case studies that have adopted nutrient recovery and assess these from a sustainability perspective;
3. Investigate the characteristics of recoverable fertilizer products and obtain the viewpoints of experts along the fertilizer produce value chain on products grown from fertilizers manufactured from wastewater;
4. Present and analyse two cases of how a nutrient recovery process could be incorporated together with energy recovery via anaerobic digestion.

This essence report addresses these objectives as follows:

Chapter 3 offers an overview on analysis of nutrient flows, particularly of phosphate, whilst Chapter 4 provides a comprehensive review of nutrient recovery technologies. Chapter 5 illustrates various case studies of wastewater treatment plants that adopted nutrient recovery methods and compares the selected onsite nutrient and energy recovery cases. Potential markets that could use products of nutrient recovery are identified in Chapter 6, where the views of industry experts (e.g. fertilizer advisors, organic food producers and green supply chain managers in food retail) are presented, focusing on trends in organic production and in particular on meeting phosphate requirements, and also on the acceptance in the food market. Chapter 7 deals with the investigations done on the supply side, through concept design phase for a nutrient and energy recovery solution at a large centralised wastewater treatment works. An economic analysis of new and existing nutrient recovery technologies as well as new products has been conducted. This phase involved no experimental work but it was rather focused on data collection from various sources. The integration of renewable energy sources together with nutrient recovery technologies was also investigated using available literature and knowledge. Energy recovery from wastewater was the subject of a recent WRC study (WRC K5/1732) and is thus not discussed in depth in this report – but is taken to be part of the context in which wastewater treatment is currently evolving. Chapter 8 illustrates a Systems Theory approach for water infrastructure and management practices within the Foreshore precinct in Cape Town's central business district, whilst Chapter 9 summarizes all the findings and the conclusion drawn.

This essence report is accompanied, in the electronic version only, by a full report, consisting of a separate volume, matching the nine chapters and providing more detail for each.

The second objective of the project was to investigate the use of seeded electrochemical precipitation as a means to produce struvite crystals of a similar or better quality and size when compared to conventional precipitation techniques. The research completed in support of this objective is covered in the technical report.

3 Phosphate Recovery: Global Context and Wastewater Source

3.1 Strategies for sustainable phosphorus use

Attaining a sustainable phosphorus (P) cycle involves an integrated systems approach, which includes the efficient use, reuse and recovery of phosphorus in waste streams. To achieve this, it has been estimated that the global business-as-usual demand will have to decrease by 70%, so that the remaining demand can be met by recovery from all possible waste streams (Schroder, et al. 2009). Figure 3-1 illustrates how future demands for phosphorus can be meet through efficiency in use, changes in demand and recovery from waste streams.

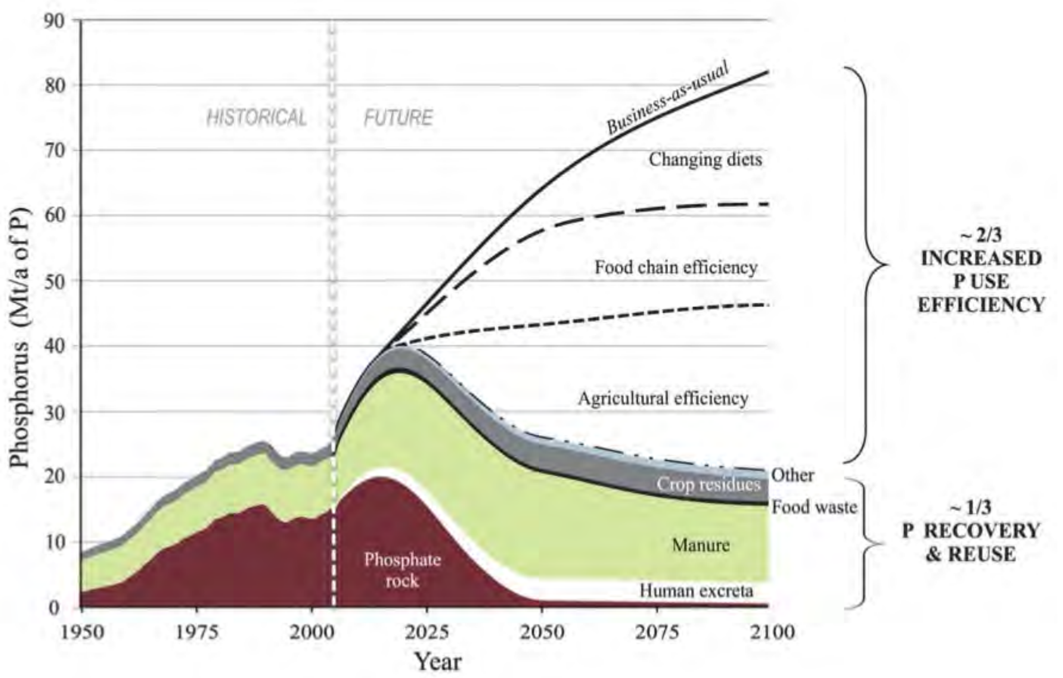


Figure 3-1: Meeting future phosphorus demands through efficiency and demand (Cordell, Drangert and White 2008)

3.2 Secondary phosphate sources

Waste streams contain phosphorus at different concentrations: Table 2 and Table 3 in the extended report list them along with methods for phosphate recovery. Animal manure and human excreta have been used for thousands of years and the latter is recognized to be the largest source of phosphorus in urban areas (60-70% of the total phosphorus excreted). Other less common sources are mineral phosphate, algae, aquatic sediments and seawater. Ash and sewage sludge have been used in the past for land application, however the use of the latter has been restricted due to health concerns (Werner 2006; Adam 2009) since organic waste began to be recycled.

Cities have been reported as the major phosphate sinks and it has been estimated that about a third of the mined phosphorus ends up in urban areas (Kalmykova et al., 2012; Cordell et al., 2011). A material flow analysis is mandatory to quantify these phosphate waste streams, especially in developing countries where increased wealth magnifies waste production.

Phosphorus concentrations in waste streams differ from region to region. The source of the phosphorus is the major determinant of its concentration and affects the viability of its recovery: lower concentrations alongside with transportation of low concentrated products will have high cost implications. Table 4 and Table 5, in the extended report, summarize typical phosphorus concentrations of a range of waste streams.

3.3 Phosphorus concentrations and deportment in wastewater

Phosphorus is available in various forms of phosphates in wastewater. The phosphates present are categorized physically into either particulate or soluble and further categorized chemically as follows:

- Orthophosphates are readily available for biological uptake;
- Polyphosphates (condensed) are phosphate molecules formulated from varying combinations of hydrogen, oxygen and phosphorus atoms at various pH levels;
- Organic phosphates are biodegradable and can be converted to orthophosphates and polyphosphates during activated sludge treatment (Neethling, et al. 2009, deBarbadillo, Levesque and Maxwell n.d.)

An investigation undertaken as part of this project and based on sewage sludge sampled from the Cape Flats WWTW, was aimed at quantifying phosphorus in wastewater and at confirming its behaviour following AD. Knowledge on the effect of anaerobic digestion on phosphorus distribution between the liquid and solid phase is beneficial for determining which phase of the digestate can be used as organic fertiliser or for phosphorus recovery. The study showed that whilst AD mobilized some of the phosphorus into the liquid digestate, more remains in the solid fraction of sewage digestates, which should be further investigated as possible candidates for phosphorus recovery.

Figure 3-2 and Table 7 in the extended report describe the mass balance of a wastewater treatment plant and the typical phosphate concentrations of raw wastewater: for South Africa the average phosphate loading of raw sewage is approximately 15 mg/L or 1.3 g P/cap·day (Vinneras and Jonsson, 2002). Primary and secondary treatment remove an average of 11% and 28% of the phosphorus load respectively; the South African legislative standard of 1 mg/L of phosphate in effluent requires an additional 50-55% removal of the phosphorus load by a phosphate removal or recovery technology.

3.4 Point of phosphate recovery from sanitation systems

Sanitation systems represent an important sector of phosphate recovery and removal. Section 3.4 in the extended report illustrates sanitation system options and shows that phosphorus recovery is physically feasible from liquid phase, sludge and ashes (incinerated sludge); as far as the liquid phase is concerned phosphorus recovery is reportedly economically viable from an orthophosphates concentration greater than 50-60 mg/L.

3.5 Centralized vs. decentralized phosphate recovery solutions

Phosphate recovery processes may either be small-scale, low-tech, low-cost (decentralised units) or larger, high-tech, costly methods (centralised units). Decentralised systems range from onsite to community-scale systems, suitable for low-density populations and remote areas (Cordell, et al. 2011). Small-scale systems typically practice the separation and direct use of excreta and wastewater onto land and advantages include reduced energy consumption, phosphate losses, water consumption, and raw materials. Major costs of centralised water systems are due to transportation through sewage network (50-70%), whereas land availability, management and maintenance are major factors that may hinder the use of small-scale systems (Cordell, et al. 2011).

3.6 Integrated vs. single nutrient recovery approaches

Recovery technologies have the advantage of generating large amounts of (potentially) marketable products as well as being easy to retrofit. However, they are costly, energy intensive and susceptible to nutrient losses and it remains challenging to remove these nutrients economically within the legislative compliance limits (Wang, et al. 2009).

Nitrogen is typically removed biologically from wastewater, and is often a prerequisite for biological phosphorus removal. However, the method is often complex and results in inconsistent effluent concentrations and in a nitrogen removal rate of about 10-30% (less than optimal). Advanced nitrogen removal technologies can achieve removal rates between 51-64% (Washington state department of health 2005), and include:

- Breakpoint chlorination
- Air stripping
- Ion exchange
- Struvite precipitation (both nitrogen and phosphorus) (Constantine 2008)

Macronutrient removal in WWTPs is achieved mainly by means of biological treatment, but can be accompanied by fermenting the waste activated sludge, followed by the further recovery of ammonium and phosphate from the digestate.

Historically, land application of stabilized/fermented sludge and/or ash has provided extensive nutrient recycling. Nowadays, in many countries this practice in agriculture has decreased, due to farmland safety and human health concerns (Werner, 2006; Adam, 2009); similarly, surface or spray irrigation of sand filtered secondary treated wastewater effluent, is either no longer permitted or under strict regulations.

Alternatively to the use of sludge recovered from sewers, animal manure and human excreta have also been used directly as an organic fertilizer on a global scale (Liu et al., 2008). Urine and faeces are source separated and stored for further use: composting allows the return to the soil of micronutrients in faeces, whereas urine is either converted into struvite or used directly as an organic fertilizer (Ganrot, 2005; Etter, 2009).

Recently, crystallization to produce struvite (see Section 4.6) has drawn much attention as it recovers both ammonium and phosphorus simultaneously and provides a good slow release phosphate fertilizer derived from human waste, replacing rock phosphate derived fertilizers. Dual nitrification, struvite production (VUNA, 2013), as well as ion exchange to produce a fertilizer mix of ammonium phosphate and sodium nitrate (Muzanenhamo & Sikosana, 2012) are alternatives to the traditional biological recovery methods for nitrogen and phosphate removal.

3.7 Potential uses and markets

Struvite can be used as a cost effective replacement of industrial grade phosphate, when formation and collection are controlled. Suggested market routes for struvite use include:

- Replacement for secondary phosphate ore;
- Industrial grade phosphate;
- Slow release fertilizer;
- Animal feed additive;
- Fire proof agent and cement adhesive (Zhou and Tang 2008).

Schipper et al. (2001) argued that struvite has limited applications in electro-thermal processes due to its ammonia content, although it has been suggested that struvite could be ideal for industrial processes: as a fertilizer, it could be used directly if harvested properly or as a speciality fertilizer in nurseries as well as a component for agricultural fertilizer production.

4 Review of Phosphorus Recovery Technologies

This chapter reviews and illustrates the available phosphorus recovery technologies: sections 4.1 and 4.2 give an overview and categorize the available phosphorus recovery processes and technologies from wastewater, as well as their limits to phosphorus removal. Sections 4.3, 4.4, 4.5 and 4.6 provide details on different techniques for the phosphorus recovery – biological, sewage sludge, chemical precipitation and crystallization respectively. Full-scale processes are compared in section 4.7 and their resulting products described and compared in section 4.8. Section 4.9 deals with struvite production whilst section 4.10 concerns with the cost associated with phosphate elimination and recovery. Conclusion are drawn in section 4.11.

4.1 Phosphorus recovery processes and technologies

It is estimated that 75% to 90% of phosphate in urban flows end up in sewage (Cordell et al., 2011). Policies pertaining to wastewater, water quality, agricultural and solid waste management affect phosphate resource management plans, resulting in different solutions on a city, national and global scale.

Figure 4-1 in the extended report illustrates the steps to take for achieving phosphate recovery and reuse; usually they include collection and storage, treatment and recovery (phosphorus extraction by separation), transport, further refinement and reuse. Phosphorus extraction depends on the available sources, the recovery technology and the reuse capabilities. Phosphate recovery, removal and reuse processes ranges from decentralised units to industrial scale operations.

Table 9-Table 11 in the extended report review and summarise the most common phosphate removal, recovery and reuse technologies. Methods for achieving phosphorus removal are classified as Physical processes – those which involve the removal of particulate phosphorus; Chemical processes – those in which the recovery or removal is attained through the conversion of soluble phosphates into insoluble form; Biological processes – those involving microorganisms in bioreactors to perform the biological uptake of nutrients; Wet-Chemical processes – those involving the base/acid leaching of phosphate from sewage sludge or ash; Incineration of sludge – able at removing toxic compounds and heavy metals; Combined processes – for design optimization.

4.2 Limits to phosphorus removal techniques and minimum achievable phosphorus concentrations

Drawing conclusion on which process is better than other may involve matters as economic viability and priorities of the WWTP. The most efficient phosphorus removal methods would involve the use of both chemical and biological techniques simultaneously; filters are often included in WWTP when phosphorus levels < 1 mg/L are required. Phosphorus levels < 0.1 mg/L, representing the limit of the technologies, would also include Chemical clarification, Ion exchange and Adsorption processes; the latter two are yet to reach full-scale, but they are potentially able to eliminate both organic and condensed phosphates. The achievement of ultra-low levels of phosphorus in wastewaters must remove all particulate phosphorus and since not all soluble phosphorus is susceptible to precipitation, a deep understanding of P speciation is required.

Table 12-Table 14 in the extended report summarise the phosphate recovery technologies including their limitations to phosphorus recovery adapted and modified from. Today, precipitation and crystallization are the main recovery practices utilized in industrial and municipal waste streams (Cornel & Schaum, 2009; Le Corre et al., 2009; Sartorius et al., 2011): these processes can result in a removal rate of between 70 and 80% (Cornel & Schaum, 2009). However, some industrial scale practices have reported recovery rates as high as 95% (Le Corre et al., 2009).

4.3 Biological Phosphorus removal

Microorganisms, including bacteria and microalgae, in bioreactors perform biological uptake of nutrients. Several technologies have been established and are available at industrial scale for large populations. Biological uptake can take place in three ways: Assimilation – involving the direct absorption of phosphorus by plants or by microorganism in treatment ponds; Enhanced biological phosphorus removal – the enhancement of the storage of polyphosphates by microbial biomass in activated sludge; Simultaneous chemical and EBPR – where metal salts are dosed in the effluent following the secondary biological sludge treatment.

4.4 Nutrient recovery from sewage sludge

Sewage and sewage sludge ash usage in the agriculture have been one of the first applications of nutrient recovery, but its use nowadays it very limited. The growing awareness upon environmental issues will prevent sludge being used agriculturally in the near future and it will increase the market potentialities for nutrient recovery technologies. Table 15 in the extended report recaps the organic and inorganic substances found in municipal sewage sludge. Major issue to cope with sludge handling include: Stabilization – easily achieved through AD and incineration, Volume minimization, Removal of toxic compounds and heavy metals, especially from sludge ash, and the economical use of its full energy potential. Table 16 in the extended report illustrates different forms of sludge stabilization, whereas Table 17 and Table 18 in the extended report summarise the methods to obtain phosphate recovery from sewage sludge.

Sludge ash requires further purification using thermal-metallurgical methods as Wet-chemical processes able to extract phosphorus, either chemically or biologically; and Thermo-Chemical treatments. Table 19 and Table 20 in the extended report present a collection of phosphate recovery methods from sewage sludge ash.

4.5 Chemical precipitation with metal salts

Chemical precipitation involves the addition of divalent or trivalent metal salts to wastewater (Calcium (lime), aluminium and iron, as chlorides or sulphates) to precipitate dissolved inorganic phosphorus out of solution as low solubility metal phosphate compounds, which are then flocculated and extracted via sedimentation or filtration (Strom 2006, Rybicki 1997, Morse, et al. 1997, Neethling, et al. 2009). Required steps to follow and a range of available technologies used for chemical precipitation are reported in section 4.5 in the extended report.

Although a very flexible phosphorus removal approach, chemical precipitation is rare in newer WWTP plants as it produces additional waste sludge, which after dewatering contains a water content of 60-85% as well as non-biodegradable material and hence remains an environmental liability (Rybicki 1997, Morse, et al. 1997, Le Corre , et al. 2009, Crutchik and Garrido 2011, Giesen, et al. 2009).

4.6 Crystallization

Precipitation and crystallization differ mainly in the speed of reaction and the size and shape of particles produced. Chemical precipitation involves chemical reactions that result in an irreversible change in chemical compounds in contrast to crystallization products that are formed through solubility variations and are easily dissolved and recrystallized (Gordon n.d., Le Corre , et al. 2009). The comparison of chemical and crystallization products is summarized in Table 21 in the extended report.

Crystallization technologies in phosphorus recovery are based on the FBR developed in 1938 (Zhou and Tang 2008) and industrialized in 1972. The Crystalactor® (see section 4.6.4 in the extended report for details on the technology) developed in the 80's and 90's is a well-established technology and is endorsed in Southern Africa in full plant engineering and operation (Giesen, et al. 2009). A summary of available bench, pilot and full-scale crystallization installations is presented in Table 22, Table 23 and Table 24 in the extended report.

4.7 Comparing commercialised processes

Nieminen (2010) evaluated different commercial processes for struvite recovery from liquor sludge: AirPrex, Ostara Pearl© and Unitika Phosnix showed the best operative performances; the Seaborne technology and the Crystalactor® – that produces calcium phosphate – experienced difficulties. Table 25 in the extended reports a summary of industrial-scale processes.

4.8 Products

Different reasons drive the phosphorus recovery from waste streams: pollution prevention; improved wastewater treatment; fertilizer production; industrial use as well as sustainable water and sanitation management, and affect the design of P recovery systems.

Main recovered products are: Calcium Phosphate – comparable to virgin phosphate rock – which can be used both in industrial and agricultural sectors; and phosphate in the form of struvite mostly recommended for wastewaters with high orthophosphate concentrations. Struvite may precipitate spontaneously and represents a sustainable alternative to current chemical precipitation methods, as it has proven to economically recover high concentrations of phosphate from WWTP, in addition to MAP potentially being a valuable commercial fertilizer (de- Bashan and Bashan 2004, Le Corre , et al. 2009, Crutchik and Garrido 2011).

4.9 Factors affecting struvite production

A range of factors that affect Struvite crystallization include: pH, super saturation, seeding material, mixing energy and temperature (Le Corre , et al. 2009). Essential conditions and their effects are summarized in Table 27 in the extended report.

Struvite precipitates spontaneously in the presence of orthophosphates, ammonium and magnesium: WWTPs with a Mg concentration of 3-10 mg/L and favourable pH conditions will result in struvite formation in pipes (OSTARA 2013); the presence of orthophosphates and Mg ions from the biomass as well as some ammonium compounds may result into struvite precipitation in AD plants.

4.10 Cost of phosphate elimination and recovery

Phosphorus recovery and elimination costs account for the chemicals purchases, sludge treatment and disposal – subject to local conditions – hence are subject to regional variations; the cost of an additional magnesium source is important as well for struvite production, since up to the 75% of the total production cost of struvite is due to magnesium (B. Etter 2009). Mg sources, criteria selection and implications of use are summarised in Table 29 in the extended report.

Considering the price of phosphate rock of about $0.1/kg (R1070/ton) (Infomine 2014), and the European market price for 1 kg phosphorus recycled of €0.5-1 (R7.5-15) (Kroiss, Rechberger and Egle 2011), phosphate recovery is yet to be cost effective. Specific phosphorus removal and phosphate recovery estimates have been quoted by Kroiss et al. (2011) and by Petzet and Cornel (2013) and are summarized in Table 28 in the extended report.

4.11 Conclusions

Human excreta are the largest source of phosphorus in urban areas. However in developing countries, the organic fraction of municipal solid waste may become an even larger sink. Within biological wastewater treatment plants, up to 90% of the phosphorus load maybe incorporated in the sewage sludge. The main points of recovery from WWTPs include:

- Liquid phase: secondary effluent, anaerobic digestion side stream and sludge liquor
- Solid phase: chemically/biologically bound in primary, secondary or digestate sludge, or in sludge ash after incineration.

A concentration of 50-60 mg/L of orthophosphates is required for economically feasible recovery from the liquid phase. The wastewater effluent is typically < 5 mg/L and is thus not favourable for phosphate recovery or removal. Source separated urine contains 300-900 mg/L and together with sludge liquor and the AD side streams (20-100 mg/L), are economically feasible for phosphate recovery. Precipitation is affected by impurities, so the TSS found in sludge liquor may need to be controlled.

Phosphate recovery technologies include physical, biological, chemical and physical-chemical procedures. The focus has shifted from chemical processes in the 1980s to biological in the 1990’s and more recently to crystallization. Of all technologies available the Crystalactor® is the most advanced crystallization method. Crystallization methods typically achieve a recovery of > 90% and an EPC of 0.3-1 mg/L.

Industrial crystallization technologies are common due to their ability to produce high purity, water-free and marketable final products, namely struvite and calcium phosphates. An evaluation by Nieminen (2010), illustrated that the AirPrex, Ostara Pearl® and Unitika Phosnix process which all recovered struvite from sludge liquor demonstrated the best operative performances. All these processes are located on WWTPs with anaerobic digesters and produced final marketable products.

The most efficient phosphorus removal methods would involve the use of both chemical and biological methods simultaneously to reach levels between 0.5 and 1 mg/L. When phosphorus levels below 1 mg/L are to be achieved, filters are often included in WWTP systems. However, to meet phosphorus levels less than 0.1 mg/L (the limit of technologies), chemical clarification, ion exchange and reverse osmosis are to be incorporated with filters.

The two most common crystallization products are calcium phosphate (CAP) and magnesium ammonium phosphate (MAP), also known as Struvite. CAP is comparable to virgin phosphate rock and has both industrial and agricultural use. Struvite production from conventional sewers is energy intensive, therefore anaerobic digestion sludge as well as source separated urine are ideal sources of struvite production. The best feed stream for struvite formation is the supernatant of EBPR sludge Struvite can be a cost effective replacement to industrial grade phosphate. The suggested market avenues include:

- Replacement for secondary phosphate ore
- Industrial grade phosphate
- Slow release fertilizer
- Animal feed additive
- Fire proof agent and cement adhesive

5 Case Studies of Implemented Phosphorus Recovery Technologies

The second aim of this positioning part of the project was to investigate a number of technologies that have been adopted for phosphorus recovery. This chapter presents and evaluates case studies by presenting summaries, informed by sustainability analyses of four different technology installations.

Three industrial scale installations and one community-scale pilot project were investigated. In all four cases the final product, mainly struvite, is sold for fertilizer use. These case studies illustrate both centralized (Ostara Pearl®, Multiform Harvest and Seaborne, all located at WWTPs with AD units treating the sludge liquor or digestor centrate and sewage sludge, respectively) and decentralized (The Nepal struvite precipitation of source-separated urine project (STUN) at community scale) phosphate techniques as well as solid and liquid phase phosphate recovery. The four case studies investigated illustrate both crystallization and wet chemical processes to produce (low and high-grade) struvite for fertilizer purposes.

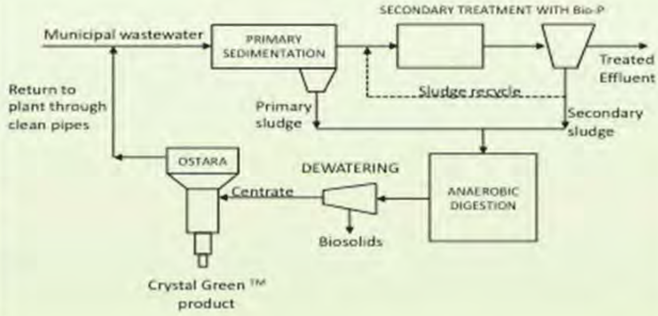
5.1 Case Studies

In the following, key details of each case study are provided. For more information refer to sections 5.1, 5.2, 5.3 and 5.4 in the extended report.

Case Study 1: Ostara installation by Hampton Roads Sanitation District, at the Nansemond Treatment Plant, Suffolk, Virginia. 2010

Key Driver: An Ostara's Pearl® reactor was installed to recover an excess loading of nutrients (phosphorus, nitrogen and magnesium) from the sludge handling process at the The Nansemond WWTP, Virginia (USA). The biological nutrient removal (BNR) facility installed has to meet permit limits of 8 mg/L nitrogen and 1mg/L phosphorus.

Process Description: the pilot facility with the Ostara Pearl® process (patent 7622047) comprised of a fluidized bed reactor that recovered 40% ammonia and 85% phosphorus from the sludge liquor. At maximum loading of 900mg PO_4-P/L, the full-scale reactor has been projected to release an effluent of 50 mg PO_4-P/L (Britton, Prasad, Balzer, & Cubbage, 2009).



Limit to recovery: The full–scale Pearl® reactor is designed to handle a maximum liquor flow of 416 kL/day and maximum loading of 186 kg PO4-P/day at a concentration of between 150-450 ppm. The process effluent released can reach a minimum of 30 kgPO4-P/day at a concentration <75 ppm (Hampton Roads Sanitation District, 2010).

Product use & Market: Approximately 1650 kg/day (Britton, Prasad, Balzer, & Cubbage, 2009) and up to 500 tons per year (OSTARA, 2013) of Crystal Green® (struvite) is produced. This is used in fertilizer blends for agriculture, turf grass and horticulture both in Canada and the USA. Ostara distributes the fertilizer and pays HSDS for the magnesium chloride used for struvite production as well as royalties to offset capital and production costs.

Cost information
based on the US dollar – ZA Rand exchange rate of: 1:10,72 – The money Converter 2014 and considering a Projected Payback period of 6 years

Cost description	Total Amount (ZAR)
Capital Cost	32.3 million (including insurance)
Annual cost saving*	6.43 million/year (including struvite profit)
Treatment fee	4.82 million/year
Treatment cost (calculated)	R180-240 kg/Precycled

** The WWTP savings include reduced ferric chloride use, reduced chemical sludge disposal, reduced aeration and methanol costs for (de)nitrification*

Case Study 2: Multiform Harvest in Yakima Wastewater treatment works, USA, 2012

Key Driver: Yakima is within an industrial area that results in high total phosphate concentrations which may cause eutrophication in the Yakima River. Two Multiform Harvest reactors were installed at the Yakima WWTW to recover excess nutrients from the activated sludge treatment with enhanced phosphorus removal.

Process description: The Multiform process comprises of conical fluidized bed reactors, with no recycle and a short retention time, which recovers up to 90% of the influent phosphorus. These reactors are currently operating at 832 kL/day and producing about 453 kg/day of struvite.

State of development: The Yakima Regional WWTW is a biological nutrient removal treatment plant, with anaerobic bioreactors for energy generation. It receives wastewater from a range of industrial and business districts, which are obliged to pre-treat their waste streams before they enter a separate industrial treatment line. The WWTP installed an anaerobic digester for sludge stabilization, with subsequent centrifugation for dewatering. The Yakima WWTP treats approximately 52 ML/day of wastewater and has a design capacity of 75 ML/day. The Nutrient Facility equipped the first full-scale Multiform Harvest system became operational in May 2012 (City of Yakima, 2014)

Product use & Market: Approximately 453kg/ day of low quality raw product in the form of struvite is produced. This is not processed onsite and is taken by Multiform for fertilizer blending and distributed for various uses.

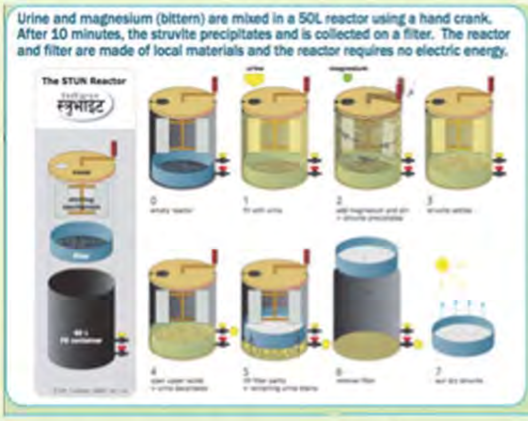
Cost information (West Boise WWTW)
based on the US dollar – ZA Rand exchange rate of: 1:10,72 – The money Converter 2014

Description	Amonut
Capital Cost	35.5 million ZAR
WW Volume	4,5 Ml/day
Phosphate load	544 kg/day
Low-grade struvite (sold)	R 2,15 kg/day

Case Study 3: Struvite recovery from urine at community scale Nepal (2009-2010)

Key Driver: Nepal is a net importer of fertilizers (Etter, Tilley, Khadka, & Udert, 2011). Rising fertilizer prices, low fertilizer quality and informal trade directly affect food production; therefore the need for nutrient security is high. Collecting, transporting and spreading urine is not cost–effective; hence odourless, lightweight struvite is a more attractive option.

Process description: Approximately 250 L of urine was collected each day from a dozen households in Siddhipur village. A low cost 50L reactor was constructed using a modified polypropylene (PP) druml. 50 L of urine, with an average orthophosphates concentration of 388 mg/L (Etter, Tilley, Khadka, & Udert, 2011), is hand mixed in the PP drum and the struvite precipitate collected on the filter and sundried.
Two reactor types were tested, a sedimentation reactor and a filtration reactor. The reactor with the external filtration (nylon filters) achieved a maximum of 90% phosphorus recovery at a dosage of 1.1 mol magnesium, within 1 hour; the sedimentation reactor only achieved 50% phosphate removal, with a 12-hour retention time.



Limits to Recovery: The pilot study illustrated that the reactor prototype had inefficient, liquid-solid separation. Flocculants for larger struvite crystal formation were investigated, but unavailable in Nepal. Hence higher phosphate recovery rates, increased urine volume and filtration as well as a sustainable magnesium source (Nepal has no magnesium mines) are necessary.

Product use & Market: With a filtration reactor size of 500 L, operating 8 cycles a day at 90% phosphorus recovery; a yearly magnesium load of 170 kg is required and will produce 1400 kg struvite per annum (Etter B. , 2009)

Cost information (West Boise WWTW)
based on the Nepales Rupee– ZA Rand exchange rate of: 1:0,11 – The money Converter 2014

Description	Amount
Struvite value (referred to the market price of R 4.51 /kg)	2.76-6.27 (inclusive of magnesium value)
Struvite sold	4.73 /kg (inclusive of magnesium value)
Profit generate by 4000L of stored /day *	ZAR3500
Filtration reactor with 400 L capacity, 2000 cm filter surface	ZAR660

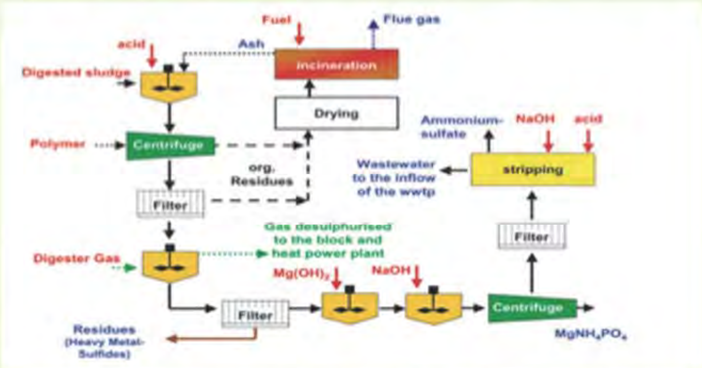
**regression model by Etter et.al (2011) and South African fertilizer prices ZAR1.53*

Case Study 4: Seaborne process in Gifhorn WWTP, Lower Saxony, Germany (2009)

Key Driver: Thickened sludge from the Gifhorn WWTP, was previously used as a fertilizer for agriculture. However, legislative pressures to limit heavy metal, organic toxins as well as drug residues in the sewage sludge, led to the need for alternative sludge treatment methods (Muller, et al., 2007).

Process description: The Gifhorn WWTP treats approximately 6500 m3 /day and serves a population of 50 000. It has two 2000 m3 mesophillic digesters installed, which treat 60 m3/day, 40m3.day and 20 m3/day of primary, secondary sludge and waste grease from food production respectively. The Seaborne process has a maximum operating capacity of approximately 1000 tons of dry solids per year.

The digester effluent enters a surge tank that moderates the process influent to 110-120 m3/day (2% DM) (Seaborne), with a phosphorus concentration of 600 mg/L. The Seaborne process consists of 4 steps, which include: acid leaching (flow rate 4.5 L/m$^{3.}$ residence time 2h), removal of heavy metals (liquor is treated with Na_2S precipitating about 20 kg/day of metal sulphides), precipitation (NaOH is added to increase the pH to 8.7-9 and the $Mg(OH)_2$ to induce struvite precipitation) and stripping.



Limits to Recovery: The design capacity for the process is 140 m3/day biomass (3% DM) and 1800 mg/L and 1000 mg/L of phosphorus and nitrogen respectively. The Gifhorn process and the the patented Seaborne process differ for a variety of factors (Table 4 in the extended report) and due to thermo-technical and economic reasons these units did not reach full-scale application.

Product use & Market: Nitrogen and phosphorus is precipitated into struvite and di-ammonium sulphate. The plant, as of March 2010, produces approximately 250 t/a of struvite (1300 kg/day N-P fertilizer) with a 50% DS and is sold as fertilize at R75/ton. In addition to this, 4500 m$^{3/}$day of desulphurised biogas is produced (Seaborne).

Cost information
based on the Euro – ZA Rand exchange rate of: 1:15.02 – The money Converter 2014

Description	Amount (Million ZAR)
Shed building	19,2
Digestion, energy, misc.	19,3
Technical costs	44,9
Engineering costs	15,2
Monitoring	15

5.2 Sustainability Framework

The system framework developed by Cordell (2011) investigates the applicability and challenges associated with phosphate recovery and recycle techniques in order to address phosphate security. The framework, in conjunction with management tools to promote efficient use of phosphorus in agriculture, has been applied to six case studies from around the world; highlighting phosphate recovery and reuse technologies from a global perspective (developing and developed countries), ranging from large industrial scale to small and pilot-plant applications. Table 35 and Table 36 in the extended report provide details on the Sustainability system summary.

5.3 Conclusions

The four case studies investigated illustrate crystallization and wet chemical processes to produce (low and high-grade) struvite for fertilizer use. The Ostara Pearl®, Multiform Harvest and the Seaborne processes are centralized and are located at WWTPs with anaerobic digester units, treating the sludge liquor (a.k.a. digestor centrate) in the first two cases, and sewage sludge, respectively. The STUN project is a decentralized phosphate recovery solution at community scale.

At Sidduhlpur, a peri-urban farming community in Kathmandu (Nepal), an urine diversion toilet system was installed since 2002, making it an ideal setting for the local recovery of struvite from source separated urine. A pilot scale struvite production process, aimed at subsidizing fertilizer imports to help ensure food security in the region, was implemented in 2009 and was concluded by the end of 2010. A maximum of 90% phosphorus recovery was achieved, producing 1400 kg/ year struvite in a 500 L low-tech reactor. Nowadays, fertilization by direct urine application by farmers continues.

The Seaborne wet-chemical process treats solid digested sewage sludge to produce struvite and it is the first industrial-scale installation of this nature. Thickened sludge from the Gifhorn WWTP was previously used as fertilizer for agriculture. However, legislative pressures on health and safety matters led to an alternative sludge treatment method. Currently, the process is not economically feasible, however its re-evaluation over 5-10 years (since 2010) will see the trend that will have had in both chemical and fertilizer prices.

Both the Ostara Pearl® and Multiform Harvest processes are the most sustainable choices, as they showed to be both fully operational and economically sound: both installations resulted in cost cuts in maintenance, effluent polishing, denitrification and chemical sludge disposal. Also, the reactor operators pay for all magnesium and struvite transportation costs incurred; in the case of Ostara Pearl®, a portion of the profit generated is paid back to the WWTP. However, the Multiform Harvest process reports lower maintenance, operational and up to 4 times lower installation costs compared to the Ostara Pearl® setup. However in the long term, the cheaper, low-grade struvite produced by the Multiform Harvest installation results in half the Net Present Value offered by Ostara Pearl® over a 20-year period.

All in all the Ostara Pearl® installation is economically more attractive to potential investors. In contrast, the Nepal project showed to be unsustainable due to the high costs incurred when transporting large volumes of urine by bicycle. The Seaborne process showed to be the least sustainable as there were several conflicts in regards to chemical, maintenance and fertilizer production costs. Even with adjustments in operating conditions, the plant has been deemed unfeasible.

6 Recovered Fertilizer Characteristics and Social Acceptability

The third aim of this positioning part of the project was to investigate the characteristics of fertilizers such as quality, purity and price. An investigation was also done of stakeholders' opinion regarding products grown from fertilizer that is manufactured from wastewater.

Section 6.1 gives an overview of the current agriculture and growing organic agriculture markets, while the fertilizer markets in South Africa are described in section 6.2, highlighting the importance of harnessing an alternative and sustainable sources of phosphates fertilizers. Section 6.3 compares the fertilizer potential of phosphorus recovery from wastewater to current phosphate fertilizers on the market; with an emphasis on the fertilizer quality and health concerns inherent in the production of food fertilized with struvite derived from human waste. Section 6.4 presents views of various stakeholders down the agriculture chain, on the use of fertilizer from human waste and its place in the emerging South African market. The section 6.4 in the extended report also includes raw data from the semi-structured interviews, which are then summarized under concluding themes.

6.1 South African Agricultural Scene

The South African agriculture sector contributes 7% to formal employment and a further 8,5 million jobs in linked sectors (GCIS 2012) and commercial farms. When including the agro-processing industry, the sector accounts for 12% of the country's GDP.

Approximately 13% of South Africa's surface is suitable for crop production but only 3% of soils can be considered fertile (Goldblatt 2011). Crop harvesting is responsible for the excessive removal of nutrients from soils, which is 4 times more than what is returned naturally by fertilizers and/ or manure (Morris et al., 2007). Soil fertility has been maintained by using synthetic fertilizers, accounting for up to 16% of farming input expenditure. The primary input for commercial fertilizers are mineral resources and the production is heavily dependent on fossil fuels for energy.

From this perspective, harnessing locally available nutrients from municipal and human waste streams to produce organically derived fertilizers would subvent the synthetic fertilizer shortage, improve soil fertility and help achieve food security (IFDC, 2012), and potentially address greenhouse gas emissions.

6.2 South African Agro-Mineral Sector

World phosphate rock extraction was 220 million tons per year in 2012. South African phosphate rock mining production is of the order of 2.5-3.0 million tons with the world's fifth highest reserves of 1500 million tons. The agro-mineral sector in South Africa has the potential to grow considering the need of development of low-cost alternatives for subsistence farming and the increasing attention that waste mineral stream gained as potential sources of fertilizers.

South African phosphate supplies sources can be classified into:

- Igneous phosphate supplies: the largest igneous phosphate rock is located in Phalaborwa (ZA) – a 20 km^2 area. Foskor Ltd supply close to 2.9 million tonnes of phosphate concentrate: 900 000 tons are exported, 1 million tons are sold to the domestic fertilizer industry – although is not suitable for direct use as it in the low reactive form of calcium fluorophosphates (Ca5(PO4)3F), (Rocks for Crops, 2001), the remaining 1 million tons are processed into phosphoric acid and exported (Sims, Profile: Foskor. Industrial minerals, 1999);
- Secondary phosphate supplies: Secondary rocks are formed from the biodegradation of animal manure, bones and beneficiated rock; it is more soluble than igneous rocks and beneficiated for fertilizer use. Some of these sources are found in the coastal areas of

KwaZulu-Natal and Upper Dwyka Shales and Upper Ecca Shales of the Karoo super group. Other offshore sedimentary phosphate resources are found between the Cape Agulhas and Cape Recife shelf contain an average 16% P_2O_5;

- Other essential fertilizers sources: South Africa has alternative potassium sources, including a range of potassium silicates, found in feldspar as well as glauconite (an iron potassium complex) in Phalaborwa. Approximately 1500 million tons of phlogopite (magnesium mica in the phyllosilicate family) are discarded each year that when acidified, will have significant amounts of K and Mg for agriculture use (Weerasuiya, Pushpakumara, & Cooray, 1993).

6.2.1 Fertilizer market in South Africa

The South African fertilizer market is fully affected by the international markets because the government does not regulate this sector; there are neither import taxes nor fertilizer subsidies. South Africa shifted from being a net exporter in the late 90’s to be a net importer of fertilizer: in 2013, imports and costs increased by 21.1% and 27% (R2900 million) respectively. Table 40 in the extended report provides a summary of South Africa’s fertilizer market.

All nitrogenous compounds for fertilizer blends, in the form of urea and ammonia, are derived from the petrochemical industry in Mpumalanga and Free State; products include: Merchant grade phosphoric acid; MAP powder; Ammonium sulphate; Phosphogypsum; Technical grade (99.9%) MAP; Animal feed grade MAP; Deflourinated phosphoric acid and liquid fertilizer (South African department of Transport 2005).

6.3 Fertilizer potential of Phosphorus recovery from wastewater

Sewage sludge and sewage sludge ash usage in the food production industry decreased due to farmland safety and human health concerns (Werner 2006, Adam 2009). Other phosphate fertilizer options that exist are summarized in Table 41 in the extended report. The most promising and the most investigated phosphorus recovery product from wastewater is magnesium ammonium phosphate (struvite).

Struvite has the advantage of high purity – it meets the heavy metal (section 6.3.1.3 in the extended report for further details), organic toxins (section 6.3.1.5 in the extended report for further details) and pathogens (section 6.3.1.4 in the extended report for further details) regulations, and has phosphorus content comparable to other phosphate fertilizers currently available on the market (Table 42 in the extended report). Struvite solubility is affect by pH, temperature, soil moisture as well as Mg^{2+}, NH_4^+ and HPO_4^- ions in soil; struvite will dissolve in moist soils with low ammonium ion concentrations. Struvite increases the Magnesium levels in crop biomass, with no adverse effect on human intake (Gell et al., 2011). Struvite also complies with the chlorine content requirements for inorganic fertilizers.

6.4 Stakeholder opinions in the agriculture value chain

Urine separation and sewage nutrient recovery technologies for fertilizers production are becoming increasingly useful in improving the sustainability of urban wastewater management (Pahl-Wostl et al., 2001). However, the social acceptability of these innovations will play a major role in their potential implementation and success. As such, stakeholders will have to consider their participation as potential consumers or manufacturers of urine-fertilized products. Focus group studies conducted by Pahl-Wostl et al. (2001) as well as a stakeholder participation investigation by Sartorius et al. (2011) assessed the acceptability of various wastewater treatment technologies using expert interviews and surveys.

The project itself made use of semi-structure interviews (refer to Appendix B in the extended report for the methodology and summaries) with three academic experts in struvite production, an organic farming expert, an organic farmer, one representative from retail sector and two representative from two different organic certification boards. Based on the synthesis of the views of these experts, the following assertions were drawn:

- The ‘resource-recovery’ nature of Struvite is insufficient for it to be considered an organic farming input, even though both resource recovery and organic farming are associated with ‘sustainability’. Struvite use may be an option for smallholder farmers, although organic certification has to be considered as a hindrance to them;
- It has been argued that struvite production is an agro-chemical rather than an organic farming input, since though it may be an acceptable inorganic input in organic farming (replacing phosphate rock), it is dependent on the source of magnesium used in the processing step;
- South Africa does not have any set of organic agriculture policies in place; however South African organic certification boards have standards that are compliant with the EU standards and equivalent to the International Federation of Organic Agriculture Movements (IFOAM) certification boards that do not allow the use of human waste of any form as organic fertilizer. Hence organic certified farming for food production is not a viable market route for fertilizers derived from human waste. Overall, most parties agreed that community scale gardens are the most viable food production routes, if economically feasible;
- Since food health and safety is of high concern, struvite has been investigated extensively in terms of: solubility, inorganic fertilizer equivalence, pathogen and toxin loading, salinity, metal content as well as plant nutrient availability. Despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulations, whereas in terms of quality, it is comparable to most phosphate fertilizers on the market;
- Stakeholders recognized the importance of phosphate recycling in tackling food security and achieving sustainable water and nutrient cycles, however South African markets and retail consumer may not to be ready for fertilizers produced from human waste. This illustrates that acceptability may be subject to the source of recovered phosphate that have to be proven to be safe.

Figure 6-1 overleaf summarizes the possible market routes based on these stakeholder views as well as literature. From this it was possible to postulate the potential scale and type (centralized or decentralized) of phosphate recovery technologies.

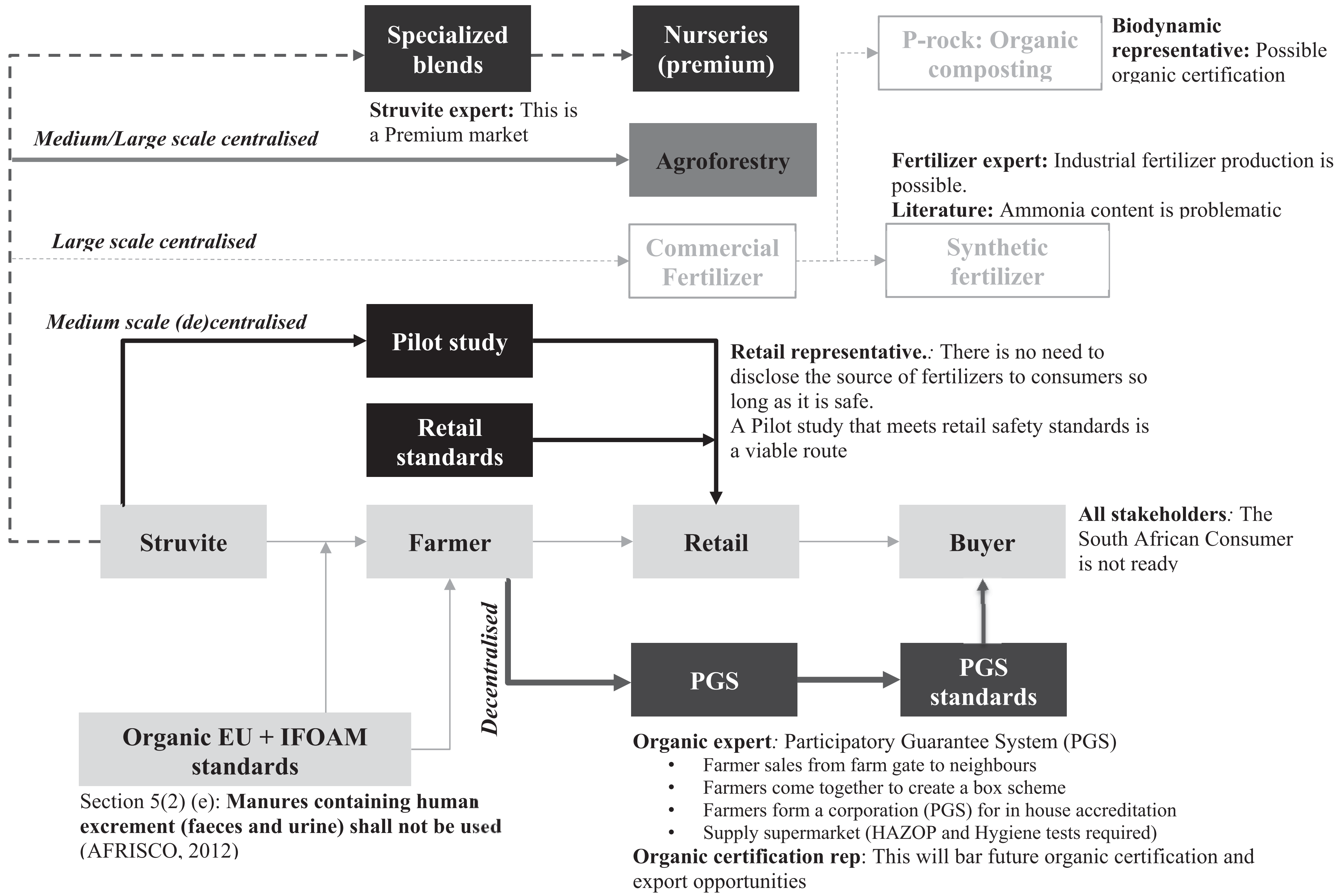


Figure 6-1: Summary of feasible market routes based on expert interviews and literature in the South African context

6.5 *Conclusions*

As of the 2000s, South Africa is a net importer of fertilizers. Foskor Ltd supply close to 2.9 million tons of phosphate concentrate, 900 000 tons of which are exported and 1 million tons of which are sold to the domestic fertilizer industry. The remaining 1 million tons are processed into phosphoric acid and exported. Approximately, 110 000 tons of MAP, 40 000 NPK and 35 000 DAP were imported per annum between 2007 and 2013. Fertilizer prices have increased by 4,8% between 2012 and 2013 to an average of R4104 per ton. In the year 2003, approximately 130 000 tons of phosphorus was used in agriculture. Alternative fertilizer use such as cattle and chicken manure, amounted to 30 000 tons in 2013; 3-4% equivalence to inorganic fertilizers. Similar to urea, all potassium is imported, as there are no known sources of potash in South Africa.

Various potential phosphate fertilizers from wastewater are comparable to soluble inorganic fertilizers on the market. Struvite is an example of a slow release fertilizer that has been investigated extensively in terms of; solubility, inorganic fertilizer equivalence, pathogen and toxin loading, salinity, metal content as well as plant nutrient availability. Despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulations. In terms of quality, struvite is comparable to most phosphate fertilizers on the market. It is more effective than SSP and DAP, but less than TSP.

Expert interviews were conducted to assess the acceptability of phosphate fertilizer production from human waste, as well as the potential markets within the South African context. Health and safety was the universal concern of most stakeholders, over and above fertilizer quality and quantity. To date, there are no South African policies on organic agriculture or certification. Both the organic certification and biological association boards in South Africa are compliant with the EU standards (and so do not allow human waste) and equivalent to the IFOAM certification board (that allows human waste fertilization). As it stands, fertilizer derived from human waste is not permissible in organic agriculture and is therefore not a viable market route for organic production. A participatory guarantee system was suggested as an alternative route to enter the food production market, but was disputed by one organic certification expert. Most stakeholders recognized the importance of phosphate recycling in tackling food security and achieving sustainable water and nutrient cycles. It is believed by the most of the experts, that the South African organic market and its consumer may not be ready for fertilizers produced from human waste to be used in food production. Better acceptability could be experienced within the inorganic fertilizer production market, if struvite is proven to be safe and a purification process is identified.

Therefore this is not a viable intervention to tackle food security in South Africa, from an organic standpoint. More feasible markets for struvite may lie within ornamental plants or as input into commercial inorganic fertilizer production, and possibly also in community scale gardening.

7 Techno-Economic Prefeasibility of Retrofitting in Centralised Wastewater Treatment

The fourth aim of this positioning part of the project was to explore how phosphorus recovery processes can be incorporated with existing energy recovery via anaerobic digestion, either on the site of a wastewater treatment works, or at source.

This is explored in the form of two techno-economic pre-feasibility case-studies: the first, in this chapter, comparing three technology retrofit options for achieving phosphate discharge standards at a large centralised wastewater treatment works in Cape Town. The second pre-feasibility study, in the next chapter, considers the conceptual design of two different resource recovery installations in the context of a South African urban centre: the Cape Town Foreshore precinct, located within the city's central business district:

7.1 The conceptual design and techno-economic pre-feasibility of two phosphate recovery options, at the largest WWTW in the Western Cape, South Africa

This study explored the potential for centralized recovery of nutrients, through the conceptual design and techno-economic pre-feasibility assessment of two phosphate recovery options, at the largest WWTW in the Western Cape, South Africa. These were then compared to the more conventional phosphate removal technique: aluminium chemical precipitation. The Ostara Pearl® (Sections 5.1 in this report and 5.1 in the extended report) and the Multiform Harvest (Sections 5.1 in this report and 5.2 in the extended report) installation were the basis for design for high-grade (Option 1) and low-grade (Option 2) struvite production, respectively.

7.2 Technical assessment

The techno-economic assessment reveals that the digestate stream at the 200 ML/day WWTW has the potential to produce ~470 kg/d (dry wt) of struvite fertilizer, recovering 58 kg/day of phosphorus at a 90% conversion rate. Chemical precipitation would result in 2400 kg/day of excess sludge, which represent 0,2 % increase in the overall Cape Flats sludge production and must be disposed of off-site. Similar to literature, chemical precipitation had a higher energy footprint, but only slightly, than that of low-grade struvite production. High-grade struvite production carries a significant electrical energy use and thus carbon footprint, due to the addition of drying and packaging equipment; this cannot be ignored.

7.3 Economic assessment

At the current fertilizer prices, only 1-3% of the plant costs are recovered in 20 years. Revenue is subject to prices on the South African fertilizer market; and as it stands, the selling price of struvite for both low- and high-grade treatment is significantly lower than the cost of recovering them.

Net present costs of R76,2-, R25,4- and R51,2 million were calculated for retrofit projects for high-grade struvite, low-grade struvite and chemical precipitation respectively, for installation and 20 years operation. From this perspective, low-grade struvite production is the most attractive process option. The establishment costs for chemical precipitation showed to be the lowest, with a CAPEX of R2.5 million, 10 and 30 times less than that of low-grade and high struvite production. Although this is the most common treatment technique in South Africa, it is the least sustainable process option resulting in the formation of a waste that must be disposed of at significant cost in off-site landfills – an important factor that cannot be overlooked.

Table 1: Summary of Economic assessment

	Option 1	Option 2	Option 3
CAPEX	76.5	20.6	2.49
OPEX	3.97	1.51	5.18
Sludge handling R	N/A	N/A	44000
Selling price of struvite R/kg	1.84	0.37	N/A
Revenue	31 000	63 300	0
Cost/kg struvite	22.1	9.01	N/A
Cost/kg PO_4 recovered (removed)	56.6	23.5	86.2
Cost/kg P recovered (removed)	173	72	263
Treatment cost/kL (influent)	0.05	0.03	0.12
Net projected costs (R million)	76.2	25.4	51.2

7.4 Factors affecting affordability

The high capital costs and unprofitable operations of struvite production are attributed to the high flow rate to phosphate loading ratio experienced at the Cape Flats wastewater treatment works (CFWWTW). Other WWTW with a more concentrated wastewater profile may yield better economics. However, unless the value of struvite increases, the cost of running the additional plant will not be recovered. Yet again, production does fall within the cost bracket for struvite production at R8.90/kg P removed. Hence investment may be justified from this angle.

7.5 Conclusion

If a WWTW is to reduce effluent phosphate loading to within regulated standards, low-grade struvite production has thus been shown to be the most ecologically and economically sustainable option from a life-cycle-costs perspective. From a social stand-point (both chapters 6 in this report and 6 in the extended report), the experts interviewed believe that the South African food market could resist fertilizers derived from human waste, hence potentially indicating a more likely use of low-grade struvite in non-food markets. Although it is a simple process, it is not cheap; the capital investment is 10 times that of the more familiar chemical precipitation route. Municipalities will have to consider the lower operating costs, as well as the environmental benefit of producing a useful phosphate fertilizer, over the immediate capital costs.

8 Conceptual Case of New Resource Recovery Infrastructure for Cape Town's Central Business District

The configuration of the wastewater infrastructure in Cape Town's Foreshore area presents a strategic opportunity for further energy and nutrient recovery. A conceptual design and techno-economic pre-feasibility assessment were developed for two process options:

Option A Recovery of nutrients from source-separated urine from commercial buildings (Ostara Pearl® set-up as seen in Section 5.1 in this report and 5.1 in the extended report)

Option B Recovery of energy by biological treatment of primary sludge and food waste

These options were developed from a Systems Theory analysis of water infrastructure and management practices within the Foreshore precinct in Cape Town's central business district (Petrie, 2013). Notably, sewage from this area is directed largely untreated to ocean outfall, via a pump station located next to the unfinished Foreshore freeway.

8.1 Technical assessment

The assessment shows that diverting half of the urine from commercial building male urinals could produce approximately 75 kg/d of dried struvite fertiliser, at 95% conversion. The co-digestion of primary sludge with 10% food waste available in the area can produce up to 1063 Nm^3/d of biogas (55% methane and 45% carbon dioxide); with the potential to produce 232 kW of thermal energy when compressed and combusted: 58 kW is converted to electrical and 45 kW for use for heating the digester feed. In addition, 2706 kg/d of biosolids is produced and must be disposed of off-site.

Both options present significant technical challenges relating to the amount of useful products (energy and nutrients) recovered given the extent of equipment and operating input required.

8.2 Economic assessment

Struvite sales can generate about R42 000, whereas energy recovery will earn about R0.5 million per year. These options combined would incur R4.5 million in net operating costs for the plant; which is up to 4 times the business as usual scenario. Additionally, in this case, nutrient recovery comes at a cost of R325/kg P, significantly higher than phosphate removal by chemical precipitation, despite the earnings from a saleable fertilizer. On the other hand, the estimated treatment cost of ~ R2/kL for the combined nutrient and energy recovery plants is well within the current sewage treatment cost envelope of R2.90/kL in Cape Town.

CAPEX of R6,9- and R11,5 million were calculated for the nutrient and energy recovery options respectively. Although small in scale compared to the centralised works, the capital outlay and equipment costs are significantly high.

A combined net present cost of R42 million after a 20 year period, suggests that the extra effort to recover energy and nutrients may not be justified economically (Figure 8-1). Even dramatic changes in key parameters will not make the proposed options financially attractive as compared to the business as usual ocean outfall, which has a -R10 million NPV over the same period. But then again, ocean outfall may not be a permitted option for much longer.

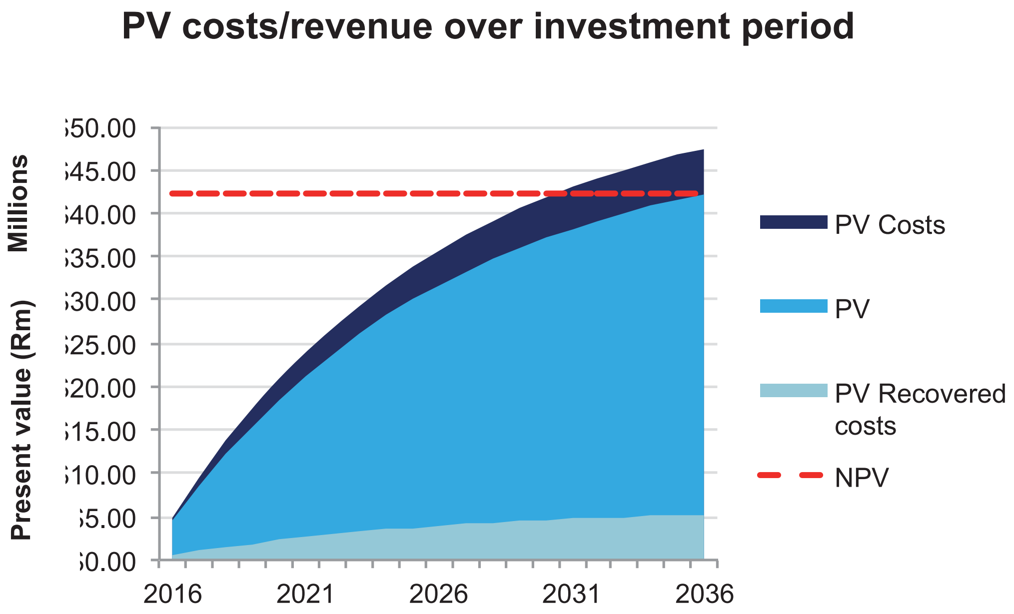


Figure 8-1: Projected discounted cumulative costs and cost recovery for a 20 year investment period for proposed combination of options

On the other hand, the estimated treatment cost of ~ R2/kL for the combined nutrient and energy recovery plants is well within the current sewage treatment cost envelope of R2.90/kL in Cape Town.

8.3 Conclusions

The potential for decentralised recovery of energy and nutrients was investigated through the conceptual design for two treatment plants and a techno-economic pre-feasibility assessment.

These results emphasise that from a financial perspective only, it will be difficult but not impossible for wastewater management officials to now consider alternative treatment technologies to the existing ocean outfall (which has minimal labour and maintenance requirements). The additional labour and maintenance requirements (and costs) associated with new resource recovery infrastructure exceed the potential income from the recovery of nutrients and energy, but are broadly in the same range as other sewage treatment options. Furthermore, the relatively small quantities found in human excreta, makes it technically and economically challenging to justify the capital and operating inputs required for recovery. It may therefore be worthwhile to prioritise phosphorus recovery from other sources (such as agricultural processing facilities, abattoirs, etc.) as well as improving agricultural efficiencies in phosphorus application.

9 Conclusion

This report and the study of which it formed part, are based on the premise that a more resource-efficient economy need to also include resource recovery from wastewaters, which involves viewing sewage as a source of nutrients as well as energy. Whilst there still is a backlog in South Africa in providing basic sanitation to a sizeable part of the population, both the strategies for addressing this backlog and the modernisation of existing infrastructure need to consider the employment of more ecologically and economically sustainable solutions.

This concluding chapter revisits and synthesise the findings from the chapters 3-8 above.

9.1 Context for a focus on phosphate

Environmental (and thus human health) protection has always been a central objective of wastewater treatment, including now for some decades nutrient removal by tertiary treatment. Energy recovery, in the form of anaerobic digestion of sludge has recently become more widespread again. Nutrient recovery, however, which had earlier been limited to land application of (treated) sludge, is increasingly becoming a serious issue.

In terms of sustainable management of phosphorus, a number of potential secondary sources exist, especially from agricultural residues and food wastes, whilst in urban areas human excreta is the largest source, with urine containing 60-70% of the phosphorus excreted.

In biological wastewater treatment plants, ~10% of the phosphorus load reports to the primary sludge, ~ 30% to the secondary sludge and another ~ 55% may have to be removed in a tertiary process for the effluent to be safely released to surface waters.

The main points of phosphorus recovery include:

- Liquid phase extraction from secondary effluent, anaerobic digestion side stream or sludge liquor (P content of 20-100 mg/L); source-separated urine is an alternative option (P content of 300-900 mg/L). The recovery is economically feasible at a minimum concentration of 50-60 mg/L of orthophosphate;
- Solid phase extraction from chemically/biologically treated sludge and sludge ash (P content of 360 g P/kg), digestate sludge or mono-incinerated dried sludge ash (P content of 64-180 g P/kg). Sludge and sludge ash can be further treated to increase P recovery potential.

The maximum recovery rates from these streams are 90% from sewage sludge and ash, and 85-90% in the liquid phase side streams.

9.2 Phosphorus recovery processes and technologies from wastewater

The methods of phosphorus removal, recovery and recycling include:

- Biological treatments: bioreactor with microorganisms – bacteria and microalgae – that perform biological uptake of nutrients;
- Chemical treatments: convert dissolved phosphates into solid form by chemical dosage. Crystallization methods produce high purity, water-free and marketable final products.
- Sludge or sludge ash treated via wet chemical or thermal processes to increase the plant availability of the phosphate; Wet chemical processes involve the recovery of phosphorus by acid or base leaching, then phosphorus in the liquid phase is further extracted; mono-

incinerated ash undergo thermal or metallurgical treatments, for heavy metals removal, while increasing the plant availability of phosphorus.

The most efficient phosphorus removal methods should involve both chemical and biological methods simultaneously to reach levels between 0.5 and 1 mg/L; meeting phosphorus levels less than 0.1 mg/L (required to avoid eutrophication in receiving wetlands), would require additional tertiary treatments.

Amongst nutrient extraction techniques, industrial crystallization methods are the most common, technically and economically feasible and produce high purity, water-free and marketable final products, namely struvite and calcium phosphates. The methods typically achieve a recovery of > 90% and an effluent phosphate concentration of 0.3-1 mg/L and is often located at WWTPs with AD facility. In terms of phosphate fertilizer products, struvite is most-liked over calcium phosphate, as it is simple to produce and well investigated compound; also, it is an example of good slow release phosphate fertilizer derived from human waste, which may replace rock phosphate derived fertilizers. Despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulation and be comparable to most phosphate fertilizers on the market.

9.3 Case studies of installed phosphate recovery technology

Three industrial-scale installations and one community-scale pilot project were investigated. These case studies illustrated crystallization and wet chemical phosphate recovery processes, producing struvite for fertilizer use. The Ostara Pearl®, Multiform Harvest and the Seaborne processes are centralized and are located at WWTPs with anaerobic digester units, treating the sludge liquor (sometimes known as digestor centrate) and sewage sludge, respectively. The Nepal struvite precipitation of source-separated urine project (STUN) is a decentralized phosphate recovery solution at community scale.

- The Ostara Pearl® process installed at the HRDS Nansemond WWTP, Virginia (United States) appears to be a sustainable process and is the only studied process that is both fully operational and economically sound. The nutrient recovery facility treats digester centrate with 140-900 mgPO_4-P/L and 500-800 mgNH_4-N/L, and recovers 85% and 40% of phosphorus and nitrogen respectively. Approximately 1650 kg/day (up to 500 tons per year) of Crystal Green® (struvite) is produced.
- In Yakima U.S, the Multiform Harvest nutrient recovery facility treats about 867 kL/day of digester sludge liquor to produce 450 kg/day of low quality, powdered struvite. Although similar to the Ostara Pearl® installation, this process reports lower maintenance, operational and up to 4 times lower installation costs. But in the long-run, if profitable, the Multiform process could be less financially attractive to investors as the sale of low-grade struvite may result in a lower net present value over a 20-year period.
- The only full-scale wet chemical process is the Seaborne process installed to produce struvite from digested sludge at the Gifhorn WWTP in Germany. However, the process is currently not economically feasible. The re-evaluation of plant scale as well as fertilizer and chemical prices over the next 5-10 years may solve the feasibility issue.
- In Kathmandu, Nepal, a pilot scale struvite production process was implemented in 2009 for nutrient recovery from diverted urine. A maximum of 90% phosphorus recovery was achieved, producing 1400 kg/year struvite in a 500 L low-tech reactor. This was a less sustainable approach due to high costs associated with urine collection and distribution, bringing the project to an end in 2010. Today, fertilization by direct urine application by farmers continues.

Both the Ostara Pearl® and Multiform Harvest processes appear to be sustainable choices, as they showed to be both fully operational and economically sound: both installations resulted in cost cuts in maintenance, effluent polishing, denitrification and chemical sludge disposal. In contrast the Nepal project showed to be unsustainable due to the high costs incurred when transporting large volumes of urine by bicycle. The Seaborne process showed to be the least sustainable as there were several conflicts in regards to chemical, maintenance and fertilizer production costs.

9.4 Fertilizer market and societal views

Fertilizer prices in South Africa depend on international markets. In the year 2013, approximately 130 000 tons of P was used in agriculture. Alternative fertilizer use such as cattle and chicken manure, amounted to 30 000 tons in 2013; 3-4% equivalence to inorganic fertilizers. Phosphate fertilizers are largely produced from domestic mining of rock phosphate and its processing via phosphoric acid.

Various potential phosphate fertilizers from wastewater are comparable to soluble inorganic fertilizers on the market such as DAP, MAP and TSP60/100. Expert interviews were conducted to assess the acceptability of such phosphate fertilizer production from human waste, as well as the potential markets within the South African context. The following conclusions were made:

- Health and safety was the universal concern of most stakeholders, over and above fertilizer quality and quantity.
- To date, there are no South African policies on organic agriculture or certification. Organic certification boards such as AFRISCO in South Africa are compliant with the EU standards (does not allow human waste) and compliant with the IFOAM certification board (that allows human waste fertilization).
- As it stands, fertilizer derived from human waste is not permissible in organic agriculture.
- The South African consumer is not ready for the use of fertilizers derived from human waste in food production, and hence it is not a feasible intervention (at this time) to tackle the growing food security crisis.
- More feasible markets may lie within ornamental plant fertilization, commercial fertilizer production and fertilizer use within closed community gardens.

9.5 Techno-economic pre-feasibility studies of the incorporation of phosphate and energy recovery processes in urban infrastructure

9.5.1 The conceptual design and techno-economic pre-feasibility of two phosphate recovery options, at the largest WWTW in the Western Cape, South Africa

The project investigated the viability of two phosphate recovery options at the largest WWTW in the Western Cape, South Africa. The nutrient recovery designs, Option 1 and 2, were based on the Ostara Pearl® and Multiform Harvest installations respectively, and then compared to the more conventional phosphate removal technique, namely aluminum chemical precipitation. The techno-economic analysis assessed the following:

- The 200 ML/day WWTW has the potential to produce ~470 kg/d (dry wt) of struvite fertilizer.
- The net present costs for high-grade, low-grade and chemical precipitation installations at the CFWWTW, discounted at 10% over a 20 year period were R76,2, R25,4 and R51,2 million respectively
- Low-grade production suited for secondary markets comes in cheapest, regardless of key parameter changes.
- Chemical precipitation CAPEX is the lowest: this is within the allocated budget for the planned CFWWTW upgrade.

- The high flow rate and relatively low phosphate concentration in the digester centrate stream is such that:
    - Struvite sales cannot recover the facility's operating costs
    - Nutrient recovery at the CFWWTW will not be financially net positive.

Option 2 can be profitable within 19 years if the price of struvite is increased 12 fold to about R14,00/kg struvite. Despite changes in key design parameters for both options, the Option 2 base case design criteria at the CFWWTW, will always come in cheaper, and complies with the legislative standards, being the most ecologically and economically sustainable option from a life-cycle-costs perspective. From a social stand-point, the experts interviewed believe that the South African food market could resistance fertilizers derived from human waste, hence potentially ruling in favour of low-grade struvite for use in non-food markets. Although it is a simple process, it is not cheap; the capital investment is 10 times that of the more familiar chemical precipitation route. But even then, this process only marginally increases treatment costs to R1,42/kL which is well within an acceptable range for wastewater treatment.

9.5.2 Conceptual Case of New Resource Recovery Infrastructure for Cape Town's Central Business District

The project investigated the potentialities of decentralised recovery of energy and nutrients through a conceptual design of new resource recovery plant at Cape Town's Foreshore precinct. A techno-economic pre-feasibility analysis resulted in the following findings:

- Diverting urine from male urinals can produce about 75 kg/d of struvite
- This could recover some R42 000 p.a. in operating costs
- The co-digestion of primary sludge can generate a surplus of 27 kW
- At a feed tariff of R1.00/kWh this presents a cost recovery of ~ R500 000
- The operating costs would be significantly higher than the achievable revenue, resulting in a net present cost of R42.3 million for a 20-year period. This is more than four times the net cost incurred by the existing scheme (wastewater to ocean outfall and food waste to landfill).

The costs of removing phosphorus as struvite, estimated at R325/kg for this case, are significantly higher than through conventional chemical precipitation (with ferric chloride, for instance), despite the potential earnings from saleable fertiliser (see Table 63 in the extended report for details). The additional labour and maintenance requirements (and costs) associated with new treatment infrastructure makes the recovery of nutrients and energy unattractive when compared against the existing disposal schemes in this case, which are however outmoded. On the other hand, the estimated treatment cost of ~ R2/kL for the combined nutrient and energy recovery plants is well within the current sewage treatment cost envelope of R2.90/kL in Cape Town.

It is also interesting to note that the costs of recovering energy and nutrients from wastewater as estimated in the concept design, are well within the costs of recovering the water itself for re-use (approximately R7.00/kL).

In a water-stressed city such as Cape Town, investing in water re-use infrastructure may be more worthwhile in the short term. Then again, this would have to include treatment, which might be offered by nutrient and energy recovery.

9.6 Synthesis and Outlook

It is clear from this investigation that technologies for phosphate recovery from water-borne wastes have reached a stage of early full-scale use at reasonable cost, if fed from well-selected sources.

Crystallisation-based technologies to produce struvite, a potentially marketable nitrogen and phosphate containing fertilizer, are central in this regard, and often draw from side streams of anaerobic digesters, thus providing link to energy recovery.

The South African fertilizer markets are immature for phosphates from wastewater sources, least of all the organic production route, which might well bar them, but other market segments may not have any significant concerns.

The value of phosphate recovered remains significantly less than the cost of recovering it from wastewater, an observation confirmed in both of the two pre-feasibility studies. Phosphate recovery can, however, be incorporated into environmentally required treatment within an acceptable cost envelope for wastewater treatment – and the evidence indicates that it could be the cheapest option of meeting phosphate discharge standards.

In relation to the technical report, it was concluded that the aim of developing a technology innovation for further reducing reactor costs for struvite precipitation is on a sound footing. If the innovation is to compete with technologies already in use, then it should provide significant capital cost savings for processes that aim to precipitate phosphate from feed streams with a minimum feed concentration of 50 mg/L. On the other hand, recognising that the largest portion of phosphorus to be removed from wastewater (where the 0.1 mg/L effluent standard applies) is still in the liquid phase after secondary treatment, the innovation process would do well to also aim to be cost comparative to ferric precipitation, the current technology of choice which does, unfortunately, render the phosphate in a non-useful form.

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