A TECHNOLOGICAL, ECONOMIC AND SOCIAL EXPLORATION OF PHOSPHATE RECOVERY FROM CENTRALISED SEWAGE TREATMENT IN A TRANSITIONING ECONOMY CONTEXT

DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS
FOR A DEGREE OF M.SC. CHEMICAL ENGINEERING

ENVIRONMENTAL AND PROCESS SYSTEMS ENGINEERING GROUP

by

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Synopsis

Phosphate is an important, non-substitutable nutrient for all life forms and is essential in ensuring universal food security. In the past, waste water treatment works (WWTW) typically installed effluent polishing technologies to eliminate phosphate and lower concentrations of both nitrogen and phosphate to below regulatory levels. More recently, there has been a global shift towards treating waste water as a "water-carried waste", presenting opportunities for both nutrient and energy recovery. South Africa is yet to embrace this shift, as it battles to provide universal access to basic sanitation needs and is faced with massive infrastructure maintenance and upgrading backlogs in the sanitation sector.

Mature phosphate recovery technologies that produce high quality struvite for use in food production do exist. However, there is little evidence to indicate that similar phosphate recovery techniques would be economically viable or socially accepted in South Africa. Therefore, this dissertation sets out to investigate the viability of a simpler and cheaper phosphate recovery technology. The dissertation addresses the hypothesis that the South African market is better suited for low quality struvite for use in secondary (non-food) markets and that this would be cheaper than both traditional chemical precipiation (phosphate elimination) methods and high-quality struvite production.

This dissertation attempts to answer two key questions derived from this hypothesis by means of two separate methodologies. A qualitative methodology explores socio-technical issues to understand the potential of sewage-recovered struvite in the South African markets. This sets out to explore: What space there is for fertilizer production (such as struvite) from human waste in the South African markets? The second research component uses standard engineeirng economic methods, to investigate the potential for centralized recovery of nutrients through the conceptual design and a techno-economic pre-feasibility assessment of two phosphate recovery options at the largest WWTW in the Western Cape. These options are contrasted with a more traditional chemical precipitation process.

Expert interviews revealed that although most stakeholders recognized the importance of phosphate recycling in tackling food security and achieving sustainable water and nutrient cycles. However, it is believed by the industry 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, regardless of source, if struvite is proven to be safe and a purification process is

identified. More feasible markets could 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.

The techno-economic assessment reveals that the digestate stream at the 200 ML/day WWTW has the potential to produce ~470 kg/d of struvite fertilizer, which only recovers 1-3% of the plant costs 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. From this perspective and as hypothesized, low-grade struvite production is the most attractive process option. The establishment costs for chemical precipitation showed to be the most economical, with a CAPEX of R2,5 million, 10 and 30 times less than that of low-grade and high struvite production; which is within the Cape Flats planned budget for a nutrient treatment facility. Although this is the most common treatment technique in South Africa, it is the least sustainable process option resulting in the formation of a toxic by-product that must be disposed of in off-site landfills – an important factor that cannot be overlooked.

The high capital costs and unprofitable operations of struvite, production are attributed to the high flowrate to phosphate loading ratio experienced at the CFWWTW. Other WWTWs with a more concentrated waste water 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/kgP removed. Hence investment may be justified from this angle.

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, 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 secondary non-food markets. Although it is a simple process, it is not cheap; the capital investment is 10 times that of South Africa's 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.

Declaration

I, Melissa Sikosana, hereby declare that:

1. I am presenting this dissertation in partial fulfilment of the requirements for my degree.
2. I know the meaning of plagiarism: the work contained in this thesis is my own work. This thesis contains no material previously published or written by another person except where due acknowledgement is made in the text. Guidance was, however, provided by my supervisors. The conclusions are based on my own understanding of the literature and results of both the qualitative studies and quantitative research performed.
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Melissa K.L.N Sikosana

Date 21/05/2015

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Last, but by no means least, I give special thanks to my family and friends for their support and encouragement throughout my life. Dr. Paulinus Sikosana and Najma Sikosana, my parents, who despite distance, gave continuous advice and encouragement from the start.

For any errors or inadequacies that may remain in this work, the responsibility is entirely my own.

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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, while 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" (Sikosana et al., 2014).

In this light, it is encouraging that ecologically and economically more sustainable sanitation and waste water management solutions are being explored and implemented, for centralised and de-centralised treatment options alike. Amongst the sewage-borne resources, phosphorous 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. It is estimated that 78% to 90% of the global phosphate demand is directly attributed to the production of synthetic fertilizers and livestock feed additive in the agriculture industry (Liu et al., 2008; Kalmykova et al., 2012). At current consumption rates, it is envisaged that phosphate reserves will reach depletion within the next 125 years; 347 years if additional investment is made into the extraction of hard to reach phosphate rock (SNB, 2013). These estimates, however do not account for the increase in demand that stems from the expected exponential global population growth, which in turn could result in a "peak phosphorus" situation by 2030 (Cordell et al., 2008). Therefore, there is a particular interest in phosphorus recovery. But, is there space for phosphate fertilizer derived from human waste in an emerging market such as South Africa? If so, is the implementation of phosphorus recovery techniques from waste water an economically viable venture? These questions form the basis of this research.

As such, this study set out to investigate the technological, social and economic dimensions of phosphate recovery from sewage in South Africa. It forms a part of a larger study, namely, Nutrient and Energy Recovery from sewage: Technology and exploration of possibilities in South Africa (WRC study No: K5/2218) (Sikosana et al., 2014). The intention is to build on the knowledge presented; with a particular focus on phosphate recovery potential from large centralised waste water treatment works, which had not been included in that study's report. Section 1.1, discusses the eight topics that jointly form the background to this research and from which the problem statement (Section 1.2 and objectives (Section 1.3) informing this dissertation will be synthesized.

1.1 Background

1.1.1 Phosphate pathways

Phosphate flows in nature are a series of chemical and mechanical processes that occur in a steady closed loop. Weathering of phosphate rock over centuries (even millennia), incorporates phosphorus into organic materials, which is subsequently returned to rock sediments. Over a shorter timeframe, phosphorus recycling is achieved by animal and plant uptake in soils. However, as is shown by Figure 1, with the turn of the industrial age human activities have since disturbed this natural cycle (Liu et al., 2008), creating large phosphate sinks in agricultural soils, within urban areas and in the oceans. Globally, about a third of the mined phosphorus ends up in urban areas (Cordell et al., 2011), with notable amounts accumulating in both landfills and waste water treatment plants. A large portion of the mined phosphorus is used to manufacture either synthetic fertilizers and animal feed additives; with other minor uses found in metal surface treatment as well as flame-retardant and ceramic production (Kalmykova et al., 2012). Overall, urban food systems from production to treatment of sewage are the most significant cause of human alteration of phosphorus pathways.

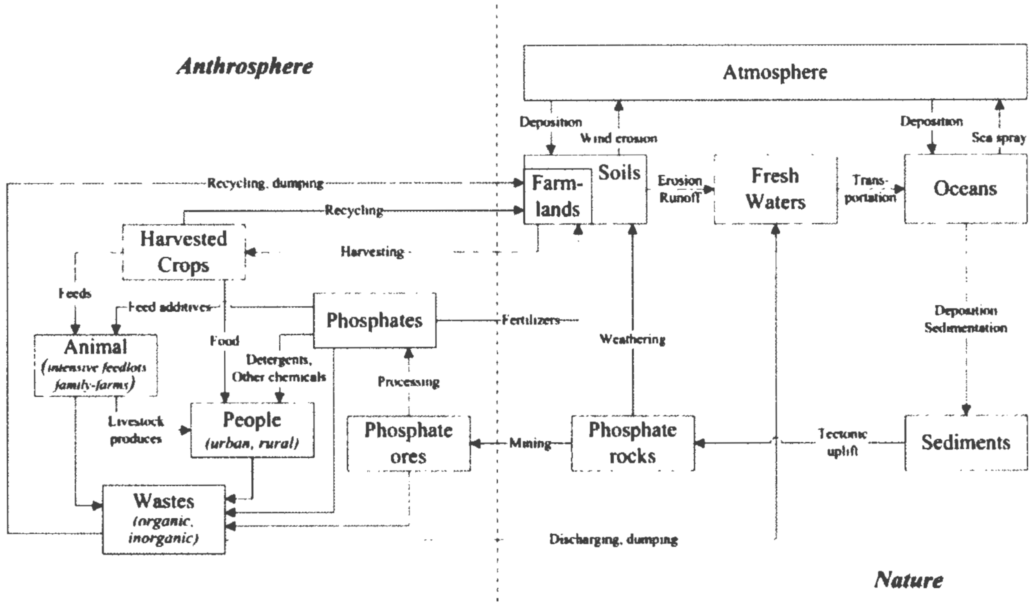

Figure 1: The human intensified global phosphorus cycle (Liu et al., 2008)

Currently phosphate application and management in agricultural systems is not strictly regulated; allowing for significant losses of phosphorus via cropland erosion and runoff. Approximately 87% of the 22,9 MT/year phosphate applied to cropland is lost via agriculture runoff and erosion

(Liu et al., 2008; SNB, 2013). Animal phosphate intake contributes significantly to the overall phosphate balance, but little work has been done in quantifying these flows (Kalmykova et al., 2012). Although developing countries raise approximately 70% of the world's livestock, less feed additives are used compared to that used in the developed world (Kalmykova et al., 2012). Much of the phosphate entering urban systems ends up in sewage: Cordell et al. (2008) estimate this to be between 75% and 90%. However, a more recent material flow analysis conducted in Gothenburg, Sweden, observed that waste water and solid waste facilities contribute equally as phosphate sinks, receiving 40% of the total urban phosphorus flows (Kalmykova et al., 2012). Therefore, differing provisional and national government policies for waste water, water quality, agricultural and solid waste management, influence both the major phosphate pathway patterns as well as resource management strategies. Approximately 50% of the global population is concentrated in and around cities (Liu et al., 2008), and with expected population growth these urban phosphate sinks will only increase. This effect will be most evident in developing countries where increased wealth amplifies waste generation (Kalmykova et al., 2012).

1.1.2 Strategies for sustainable phosphorus use

Attaining a sustainable phosphorus cycle involves an integrated systems approach, which includes the efficient use, reuse and recovery of phosphorus in waste streams. To achieve this, the global business-as–usual demand will have to decrease by 70% and the remainder 30% can be achieved by recovery from all possible waste streams (Schröder, et al., 2009). Figure 1, illustrates how future demands for phosphorus can be meet through efficiency in use, changes in demand and recovery from waste streams.

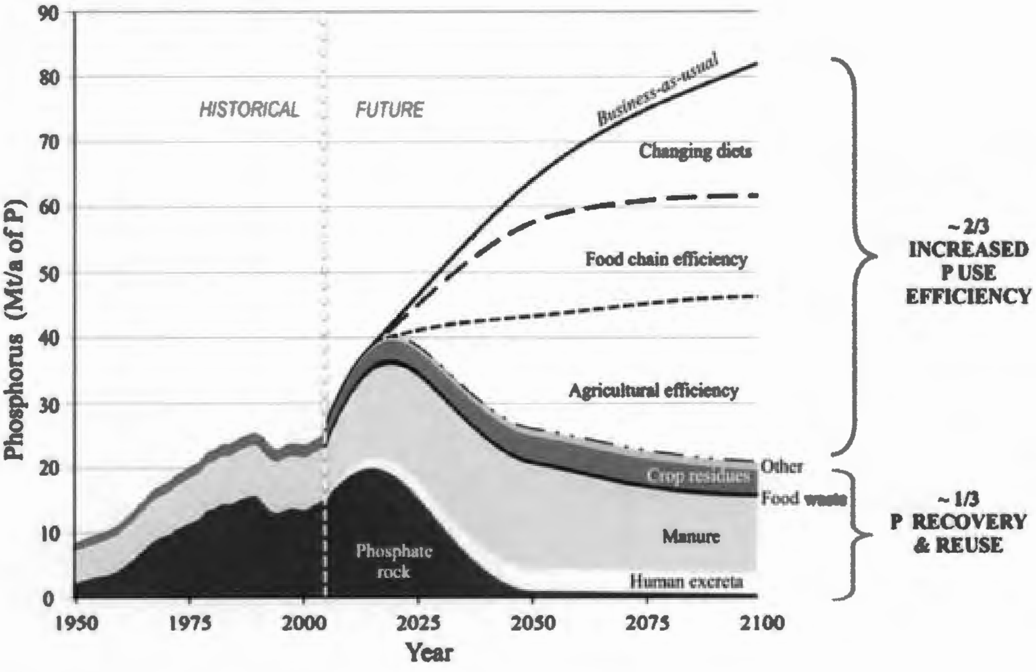

Figure 2: Meeting future phosphorus demands through efficiency and demand (Cordell et al., 2008)

As shown in the above figure, a large amount (15%) can be obtained from the reuse and recovery of manure, followed by recovery from human excreta.

1.1.3 Waste water treatment and sanitation: waste water as "water –carried waste"

Despite the various phosphate sources, as shown in Figure 1, in urban systems, phosphorus flows in the waste water sector have received the most attention, with most advances being in the reuse and recovery of phosphorus from sewage treatment plants. This study will concentrate on phosphorus flows and management techniques in sewage streams, in and around waste water treatment facilities. Although the reinvention of the waste water systems will be difficult, ecological and economically viable reuse and recycling of phosphorus from these streams is a promising route towards achieving a more sustainable phosphate cycle.

Today, conventional urban sanitation involves the flow of domestic waste water through sewer systems to a centralized treatment facility. The treated water is then discharged into nearby water bodies. These methods have been accepted globally and are widely employed in developed countries. However, in the developing world where sanitation is still a major issue, this infrastructure-intensive and 'once-through' sanitation approach may prove inadequate in meeting universal sanitation needs, and may further prove to be unsustainable from a resource-use perspective (Werner, 2006). Moreover, these centralized systems have drastically changed natural nutrient cycles, often causing the excessive nutrient loading in surrounding water bodies with nitrogen and phosphates possibly resulting in eutrophication; turning these valuable resources into pollutants (Muga & Mihelcic , 2007; Liu et al., 2008). Conventional flush-discharge systems and technologies cause small amounts of human waste to be diluted into large amounts of potable water. Such structures have been introduced into arid areas, which like South Africa, are on the verge of physical water scarcity. An ecologically and economically viable nutrient recovery and reuse system might have to consider decentralized source-separation. This technique has gained momentum since the mid 1990's and offers an alternative to more expensive end-of-pipe nutrient recovery technologies, in providing immediate phosphorus recovery pathways (Wilsenach, 2003; Ganrot, 2005; Etter, 2009; Kalmykova et al., 2012).

Decentralised systems range from onsite to community-scale and are most appropriate for low-density population and remote areas (Cordell et al., 2011). Examples of such practices include: urine diversion toilets, struvite production from source-separated urine, composting toilets, household greywater irrigation; biogas sludge use and farmyard manure. Advantages over larger systems include reduced energy consumption (when gravity driven), nutrient losses, water consumption, and raw materials. On the one hand, decentralized systems can save up 90% on construction costs (Liang & Pieter van Dijk, 2010); as 50-70% of the centralised water systems cost is due to transportation through sewage networks. However on the other hand, from an economic standpoint, the operating and maintenance costs accrued by a single private project manager are significant and may result in the failure of the system. In addition, land availability, management; ownership and multi-layer stakeholder involvement are major factors that may hinder the use of small–scale systems (Cordell et al., 2011).

Table 1 that follows illustrates phosphate sources and sinks, as well as the nutrient recovery and re-use potential from these streams.

Table 1: Matrix of all phosphate sources for recovery and reuse, including examples adapted and modified from Cordell et al (2011)

Phosphorus Source		**Source separation & reuse**	**Waste water mixing & reuse**	**Recovery & reuse of by-products & residuals**	**Struvite generation & reuse**	**Virgin extraction & processing**	**Incineration burning & reuse**
Used sources	Human excreta	Urine is stored for direct use; Faecal matter composted	Direct use of waste water as irrigation	Sewage sludge from WWTP; biogas sludge; compost filter cake	From mixed waste water or from urine.		Incinerating toilet Mono-incineration of sewage sludge
	Greywater	Treated for non-potable reuse					
	Animal manure	Manure			From dairy waste		Manure ash
	Other industrial waste						
	Animal meal	Ground bone meal, blood or meat or fish meal		Ground bone, meat and blood			
	Food waste	Compost	Sink grinder	Compost	AD sludge liquor		
	Crop residues	Compost		Oil press cakes	AD sludge liquor		Crop residue ash
New sources	Phosphate rock			Extracting P from phosphogypsum stockpiles		Mining of virgin phosphate rock.	
	Aquatic vegetation					From algae accumulation	

1.1.4 Sanitation in South Africa

Sanitation is a major challenge facing many developing countries, with sub-Saharan Africa having the lowest sanitation coverage in the world (SAKNSS, 2012). South Africa has made remarkable progress and has managed to meet the Millennium Development Goal (MDG) for halving the proportion of the population without sustainable sanitation (UNMDG, 2010) in 2008, by reducing the backlog from 52% in 1994 to 21% by 2010 (Deparment of Water Affairs, 2012). The South African government has since set a new target of universal access to sanitation by 2014. As it stands approximately 11% of formal households have never had access to basic sanitation and a further 26% (3.2 million households) have sanitation services that do not meet basic standards. Ventilated Improved Pit (VIP) toilets were employed in informal regions or have now been filled up and even abandoned (SAKNSS, 2012). Households that practice subsistence farming tend to have limited access to services; only 29% homesteads have "flush toilets" whilst 250 000 households do not have any sanitation facilities at all (StatsSA, 2013). With this in mind, it is in the best interest of the South African government to not only treat the access to sanitation issue as a high priority, but to consider the employment of more ecologically sustainable sanitation and waste water management solutions to meet current and future sanitation needs. In addition, these waste water solutions should aim towards achieving Green Drop certification, to minimise risk to environmental and public health (Departmet of Water Affairs, 2012)

1.1.5 Linking waste water nutrient management and food security

It is estimated that 78% to 90% of the global phosphate demand is directly attributed to the production of synthetic fertilizers and livestock feed additives in the agriculture industry (Liu et al., 2008; Kalmykova et al., 2012). Phosphate security is described as when "all the world's farmers have access to sufficient phosphorus in the short and long term to grow enough food to feed a growing world population, while ensuring farmer livelihoods and minimising detrimental environmental and social impacts" (Cordell et al., 2011). South Africa, like most countries in Africa, is experiencing a food security crisis. A 40-100% growth in food production levels is required to meet Africa's growing food requirements. The lower end percentage is to maintain current consumption rates and the higher end is required to address the MDG for hunger and poverty alleviation (IFDC, 2012). Waste water is a major nutrient sink, plant essential nutrients recovered from this waste stream have the potential to subsidize fertilizer production and use.

1.1.6 Agriculture and the fertilizer market in South Africa

The South African agriculture sector has grown by 12% per annum since the 1970s, however its GDP contribution has dropped from 7% to 2,6% by December 2012 (Department of Agriculture, Forestry and Fisheries, 2013). Despite the decline, agriculture contributes 7% to formal employment and a further 8,5 million jobs in linked sectors. (GCIS 2012); hence it is an important economic driver.

Commercial farms when including the agro-processing industry accounts for 12% of the country's GDP. The diets of rural South Africans have improved over the decades, however an integral part of the food availability relies on the 2,9 million subsistence farmers; 20% of South Africa's households (StatsSA, 2013). Subsistence farming is on the decline, rural and urban households have increased their dependence on the commercial food markets to as high as 90%, accounting for 60-80% of the total household income. Increasing subsistence farming productivity can play an integral role in ensuring food security, but this will require a significant increase in fertilizer and organic inputs. Farmers will need to pursue sustainable intensification of production by cost-effective means (Baiphethi & Jacobs, 2009). However, expansion for agriculture practices is limited; therefore soil degradation and maintenance are major issues within the agronomical sector.

Only about 13% of South Africa's surface area is available for crop production, but agriculture faces largely nutrient deficient soils. In reality only 3% of soils are fertile (Goldblatt, 2011). Crop harvesting is responsible for the excessive removal of nutrients from soils, which is four times more than what is returned naturally by fertilizers and/or manure (Morris et al., 2007). Thus, it is critical that these adverse effects are reversed to address the current food crisis. Soil fertility in many parts of South Africa has been maintained by using synthetic fertilizers; this accounts for up to 16% of farming input expenditure. The South African fertilizer market is fully affected by the international markets because the government does not regulate this sector; there are no import taxes nor fertilizer subsidizes. South Africa was initially a net exporter of fertilizer in the late 90's until a number of major fertilizer plants shut down in 1999 and the early 2000s (FAO, 2005). Since then South Africa has become a net importer of fertilizers.

The primary input for commercial fertilizers are mineral resources and the production is heavily dependent on fossil fuels for energy. The Haber Process, which is the integral part of the production of the most commonly used ammonia fertilizers, is energy intensive (Ganrot, 2005). From this perspective, harnessing locally available nutrients from municipal and human waste streams to produce organic fertilizers would not only subsidize the synthetic fertilizer shortage, improve soil fertility and help achieve food security (IFDC, 2012), but also address greenhouse gas emissions.

Organic agriculture

Organic agriculture could provide solutions to some of the world's resource-efficiency challenges; particularly for nutrient management by reducing synthetic fertilizer use. "Apart from economic opportunities, a range of social and environmental benefits can also be realised through the wider application of organic production in South Africa" (FRIDGE, 2008). The organic food market has become the fastest growing sector after baby food. This sector experienced a 300% spurt between 2005 and 2006 and was predicted to grow by 30% each year till 2010 (FRIDGE, 2008). The domestic market for certified organic goods in sub-Saharan Africa is developing slowly.

1.1.7 South African agro-mineral sector

World phosphate rock extraction was estimated to increase from 220 million tons per year (2012) to nearly 256 million tons by 2014. It is suggested that this projected increase will sustain the increase in fertilizer production due to global population growth (USGS, 2013). South African phosphate rock mining production remained constant at 2.5 million tons with the world's fifth highest reserves of 1500 million tons as illustrated in Table 2 (USGS, 2013).

Table 2: Summary of the top 8 global phosphate reserves and production rates (2012) adapted from (USGS, 2013)

Country	Production million tons	Reserves million tons	% of total global reserves
Morocco and Western Sahara	28.0	50000	75%
United States	29.2	1400	2,1%
China	89.0	3700	5,5%
Algeria	1.5	2200	3,2%
South Africa	2.5	1500	1,5%
Syria	2.5	1500	1,8%
Jordan	6.5	1500	1,5%
Russia	11.3	1000	1,1%

The agro-mineral sector in South Africa has the potential to grow substantially and the local fertilizer industry is at an advanced stage such that it should be more than capable of providing a wide range of phosphorus fertilizers. However, the development of low-cost fertilizer alternatives for subsistence farming needs to be addressed (Rocks for Crops, 2001), as long as production is based on local and overseas sources of various ingredients, particularly nitrogen, phosphate and potassium.

1.2 Problem statement

It is evident that there is a global shift towards understanding waste water as a "water-carried waste" and to reconsidering sewage treatment so as to also recover nutrients and energy in the process. With an anticipated phosphate shortage, it is estimated that approximately 15 to 20% of the world's phosphate needs can be recovered from waste water (Werner, 2006; Cordell et al., 2008).

South Africa is yet to embrace such a shift in its waste water treatment sector, let alone install sufficient sanitation infrastructure. It will therefore be beneficial for municipalities and their engineering consultants to better understand the employment of ecologically sustainable sanitation and water management solutions, which incoporates nutrient recovery.

Although some nutrient recovery technologies abroad are mature, there is little evidence to indicate that similar phosphate recovery techniques will be economically viable or socially accepted in South Africa.

1.3 Objective of study

It is thus the central objective of this dissertation to determine whether phosphate recovery technologies are likely to produce a socially acceptable product and what determines their affordability.

This dissertation forms a part of a larger study: Nutrient and Energy Recovery from sewage: Technology and exploration of possibilities in South Africa (WRC study No: K5/2218). The report by Sikosana et al. (2014) to the WRC includes a comprehensive literature review as well as case studies for various nutrient recovery technologies adopted for both small and large scale installations. In addition, the report conducted techno-economic pre-feasibility assessments on conceptual designs for two treatment plants, nutrient and energy recovery, for the case of a central city precinct in South Africa.

This dissertation expands on the knowledge presented in the WRC report K5.2218, focusing on phosphate recovery from centralised waste water treatment plants. The objective is divided into the following aims to:

1. describe sustainability within the waste water sector;
2. investigate available nutrient recovery technologies;
3. obtain the viewpoints of experts along the fertilizer produce value chain on products grown from fertilizers manufactured from waste water; and
4. present and techno-economically analyze a case study of how a nutrient recovery process could be incorporated into a biological waste water treatment works in South Africa.

To address these aims, a comprehensive literature review was conducted on the sustainability of waste water systems and nutrient recovery technologies (Chapter 2). The hypothesis, research questions and overall research methodology are developed in Chapter 3. Potential markets that could use products of nutrient recovery are identified in Chapters 4, where the views of industry experts (e.g. fertilizer advisors, organic food producers and green supply chain managers in food retail) are also presented and interrogated. These focus on trends in organic production and in particular on meeting phosphate requirements, but also on the acceptance in the food market. The supply aspects of this study are investigated in Chapters 5 through a concept design for a nutrient recovery solution at the Cape Flats Waste Water Treatment Works/Plant (WWTW/WWTP). In addition, an economic analysis of new and existing nutrient recovery technologies as well as new products is conducted.

1.4 Scope of study

This dissertation focuses on phosphorus flows and management techniques for sewage streams, in and around waste water treatment facilities. By means of an integrated and systems framework, the sustainability of the most advanced nutrient recovery methods from sewage is assessed. This will facilitate the identification of the most sustainable techniques for phosphorus recycling and reuse from various waste water streams (in the South African context) and hence the production of a market-acceptable fertilizer. Here, factors such as life cycle-costs, environmental impacts (energy and raw material consumption), as well as stakeholder viewpoints were accounted for.

There is no experimental work in this study; instead the methodology for the study focuses on data collection from various sources. The integration of the feasibility of nutrient recovery technologies at a biological WWTW in the Western Cape is investigated using available literature and knowledge. Therefore, this investigation is limited by the reliability and availability of WWTW data. In the case of the organic fertilizer market, conclusions are drawn from stakeholder opinions (excluding consumer views) as well as technology performance data from literature. The results are therefore subject to interpretation.

It is recognized that regulations in phosphate flows mainly apply to release into water bodies, however the overall management of phosphate, integrated with the recovery and re-use of phosphate from various waste streams is critical in reconstructing the urban and agricultural nutrient cycle. To ensure that a holistic approach to phosphate recovery is assessed, additional future research may be pursued in the following fields:

- nutrient management in agricultural soils;
- investigation of recovery from all possible phosphate sources and sinks;
- analysis of phosphate flows in animal excreta; and
- the effects of regulation and policy on consumption rates of phosphate on the overall cycle.

These topics are not investigated in this dissertation.

1.5 Dissertation structure

This dissertation comprises of 8 chapters.. Chapter 1 applied background information to set the scene, by identifying areas that this research may influence. This informed the research objectives, problem statement and scope of the study. A literature review in Chapter 2 follows, with a critical review of research done within this field and where the gap in research lies for further development. Chapter 3 describes the two separate research methodologies used to answer the two key research questions derived from the hypothesis. Chapter 4 and 5 present the qualitative and quantitative research findings respectively. Chapter 4 speaks to the social acceptance of fertilizers derived from human waste, whereas Chapter 5 addresses the techno-economic feasibility of phosphate recovery technologies in South Africa. Lastly, Chapter 6 reiterates and synthesizes the empirical findings in Chapter 4 and 5 as well as their implications. Recommendations are also made for further research.

2 Literature review

The following chapter investigates and describes what is already known and relevant to the objective mentioned in Section 1.3. Studies that touch on various aspects of sustainability assessments in waste water and nutrient recovery are described in Section 2.1. This is followed by a technology assessment (Section 2.2) that is largely adapted and modified based on the assessment as shown in the WRC report (Sikosana et al., 2014). Section 2.2.2 describes the deportment of phosphate in waste water streams. This is followed by an overview (Section 2.2.4) of the available phosphorus recovery processes and technologies from waste water, as well as their limits to phosphorus removal. Effective recovery and recycling of phosphorus in the form of useful products are described in Section 2.2.5, which provides a further detailed review of crystallisation technologies. These sections attempt to address the 1st and 2nd research aims listed in Section 1.4.

Section 2.3 touches on the economics of phosphate recovery from waste water. This section includes a techno-economic comparison of two case studies that have incorporated one of the most favoured processes, struvite precipitation. Conclusions drawn from this section form the basis for comparison and discussions around the fourth research aim.

Aspects of social acceptance are described in the techno-social assessment in Section 2.4.4. A description of the global market for fertilizer derived from human waste is then presented in Section 2.5. Finally, section 2.6 reviews studies that show how cumulating these techno-economic, techno-social and market assessments may result in a more holistic approach to sustainable phosphate recovery. This section informs the existing research methods and study in relation to the third research aim stated in Section 1.4.

2.1 The role of waste water in achieving sustainable development

Ecology, economics and society are the three dimensions of sustainable development (Harris et al., 2001). Today, countries are experiencing a global shift in emphasis from economic development to a more holistic approach. Matters concerning sustainable development have traditionally focused on poverty alleviation on the one hand, and on resource scarcity and global environmental issues such as climate change on the other, though not recognising the inter-linkages. More recently, it has been acknowledged that conventional waste water systems contribute to nutrient imbalances as well as excess loading by exotic chemicals such pharmaceuticals, contaminating surrounding water bodies. Such adverse effects on the environment could be addressed by more sophisticated and costly treatment systems. However, a unique opportunity has presented itself, and to use the words of Guest et al. (2009), "Waste water contains recoverable nutrients and the further development of future cost-effective treatment technologies, practices and policies will have broad geopolitical implications".

2.1.1 Review of sustainability assessment tools in waste water

Technology has impacted society, economies as well as the environment and is an integral part of larger complex systems, as illustrated in Figure 3 below. There is a wide range of nutrient recovery technologies available; however it has been argued in the past that there was a lack of socio-technology design methodologies, which bridge the science and policy gap, for the identification and implementation of the most sustainable solution in a given context (Guest et al., 2009; Motevallian & Tabesh, 2009; Cordell et al., 2011).

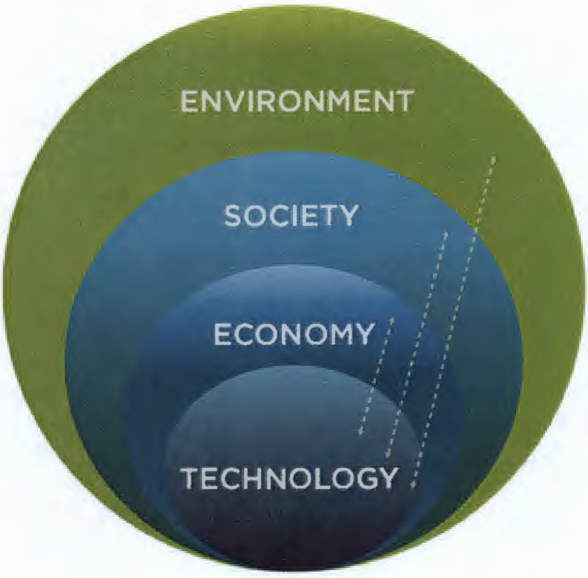

Figure 3: Technology, social and economy interaction with environment adapted from (Brent & Musango, 2011)

Since the early 2000s, studies that assess the sustainability of waste water and nutrient recovery technologies have surfaced. A sustainability assessment, in particular, serves "to provide decision makers with an evaluation of global to local integrated environment-economy and society systems from both short-and long-term perspectives" (Kates et al., 2001). Various aspects of societal, environmental and economic effects have been investigated, but mostly in isolation. Table 3 summaries the key tools that have been applied as well as the varying methodologies used.

Studies by Guest et al, (2009) and Motevalliaon & Tabesh (2009), summarized in Table 3, made contributions in an attempt to use a more holistic approach to assessing (waste) water technologies and systems. Guest et al (2009) presents a new planning and design paradigm, adapted from the Environmental Health Risk management framework (Riskworld, 1997). Similar to Motevallian & Tabesh, it advises the use of multi-criteria decision sustainability assessment (MCDA's) to "resolving trade-offs in decision-making" (Guest et al., 2009). Both studies suggest and provide planning and assessment tools that are yet to be tested.

Balkelma et al (2002) and Muga & Milhelcic (2007) presented studies that developed sustainability indicators for waste water systems, with the later concentrating on sustainable technology choices. The study by Muga & Milhelcic (2007) went a step further in testing these indicators on a range of different waste water treatment technologies. The older Balkelma et al (2002) framework, offered more technical sustainability indicators, compared to the more progressive by Muga & Milhelcic (2007), which had established key quantifiable economic-techno-social indicators. However, this study concluded that it is difficult to find a technology that meets all the sustainability criteria.

Although these studies are progressive, few have been tested. The following sections continue to address investigations of these techno-economic-social sub-systems in isolation. This is typically how sustainability research has been approached and tested in the past. Today, research has started to hone in on the importance of a more holistic approach, taking into account the links between these subsets. Muga & Milhelcic (2007) is an early sign of this critical research shift. These advancements towards achieving such a holistic research approach are described in thconcluding literature in Section 2.

Table 3 Past studies assessing the sustainability of waste water systems and nutrient recovery technologies

Research Theme	Methodology used	Reference
The past 20 years has seen an increasing interest in the sustainability assessment of urban water systems infrastructure.	• Investigated a range of general **multi-criteria decision** sustainability assessment (MCDA) tools (SAT) • Suggests a **participatory assessment approach**, whereby decision-making is assisted by input from various expert stakeholders	(Motevallian & Tabesh, 2009)
Indicators for the sustainability assessment tools for waste water treatment systems	• Investigated the possible improvements to centralized systems in contrast to decentralized waste water systems • A multi-criteria assessment was used based on a multi-objective optimization for solution selection • **Key indicators** for waste water assessment are determined (organic matter, nutrients, costs, heavy metals, land area)	(Balkema et al., 2002)
Sustainable and safe re-use of municipality sewage sludge for nutrient recovery	• The SUSAN project is a sustainable strategy to safely recover nutrients from sewage sludge, for reuse. This method was developed and its sustainability assessed, along side others. • The product market and design were assessed: **A market and agronomic analysis**	(Adam, 2009)

Table 3: Continuation: Past studies assessing the sustainability of waste water systems and nutrient recovery technologies

Description	Findings	Reference
Sustainability of waste water treatment technologies	• Environmental, societal and economic sustainability indicators were formulated and applied to different waste water treatment technologies • Used an economic analysis, Life Cycle Analysis and energy analysis • Concluded that it is difficult to design technology that meets all sustainability needs	(Muga & Mihelcic , 2007)
A New Planning and Design Paradigm to Achieve Sustainable resource recovery from waste water	• Investigation into the tools required for broad stakeholder involvement in decision-making • Suggests guiding principles for nutrient recovery systems from waste water. • Life cycle costs (LCC) must be used with an life cycle assessment (LCA) • A LCA is not sufficient and must include social assessments • After the assessments have been conducted, trade-offs must be recognized	(Guest et al., 2009)

2.2 Technology assessment: review of phosphorus recovery technologies

Sections of this technology review are derived from the WRC report by (Sikosana et al. 2014). An overview of global nutrient recovery techniques provides an essential technical platform to identify possible installation choices for the South African context. This will build a useful database of mature technologies in their relevant settings. Design parameters applied in Chapters 3-5 will refer to the database discussed in this section of the literature review.

Typical phosphate recovery processes involve a range of steps (Figure 4) including collection, storage, disinfecting treatment, phosphorus extraction by separation, transport, further refinement and reuse. Within sanitation systems, these steps can be seen as functional units, which are associated with hardware along the waste water system. A combination of these functional units alongside suitable software and skills will optimise the use of the sanitation system and potentially lead to sustainable nutrient recovery and water management solutions (Spuhler & Gensch, 2011).

Figure 4: Phosphorus recovery and reuse pathway

Phosphorus treatment and recovery techniques are dependent on the waste water source, other treatment purposes and reuse capabilities. This thesis is limited to technologies for the treatment and recovery of sewage-borne nutrients, specifically phosphorus. The following sub-sections describe the global trends in phosphate recovery techniques and technologies, from pilot scale to the most recent commercial installations.

2.2.1 Phosphate forms in waste water

Phosphorus is available in various forms of phosphates in waste water. Municipal waters contain 5-20 mg/L of total phosphorus of which 1–5 mg/L is organic and the rest inorganic (Neethling et al., 2009). The phosphates present are categorised physically into either particulate or soluble and further categorised chemically as follows:

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

The various forms of orthophosphates and their solubilities are summarised in Table 4.

Table 4: Speciation of orthophosphates in waste water (Neethling et al., 2009)

Species	pH range	Solubility
$H_2PO_4^-$	6-7.5	Soluble
HPO_4^{2-}	7.5-12.5	Insoluble
PO_4^{3-}	12.5-14	Insoluble

2.2.2 Deportment of phosphates in WWTW

Sewage treatment involves physical, chemical and biological processes to rid water of various contaminants. For a simplified overview of sewage treatment, please refer to the, please refer to Chapter 1, Section 1-5 of Metcalf & Eddy (2003), which is one of many sources. Figure 5 below illustrates sanitation system options and shows that phosphorus recovery is feasible from (A-C) liquid phase; (1-5) sludge and (6) incinerated sludge (Nieminen, 2010). Orthophosphates are present in locations A to D, the secondary effluent, anaerobic digestion side stream (also known as the sludge liquor) respectively, as well as in the source separated urine.

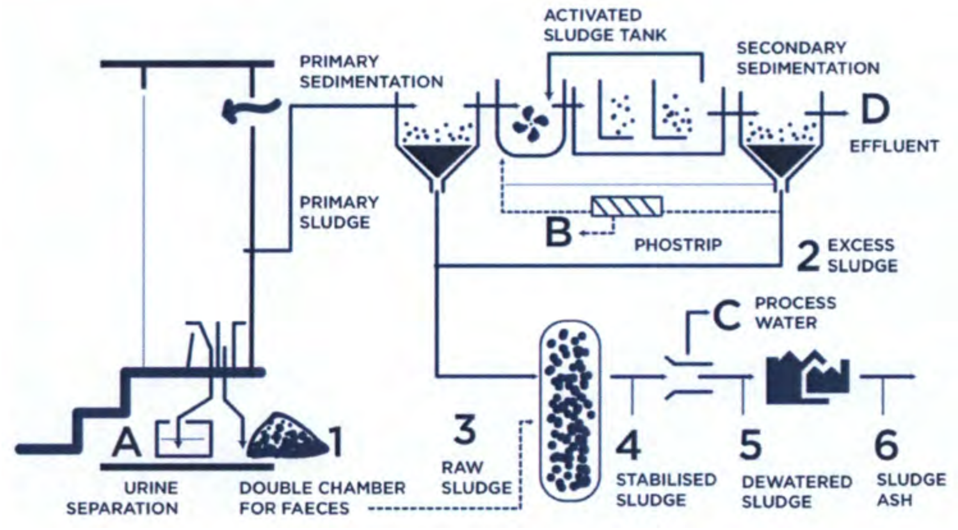

Figure 5: Locations for phosphorus recovery, modified from (Cornel & Schaum, 2009)

On average 11% of the phosphorus load in municipal waste water is removed in primary sludge settling and a further 28% incorporated into secondary sludge (Cornel & Schaum, 2009). Using the South African legislative standard of 1 mg/L of phosphate in effluent (City of Cape Town, 2014), approximately a further 50-55% of the phosphorus load must be removed by a phosphate recovery technology, if it is assumed that the influent flow is approximately 15mg/L or 1.3 gP/capita. d. Therefore, close to 90% of the phosphorus load would be incorporated in the sewage sludge in biological waste water treatment plants with a tertiary processing unit (Cornel &

Schaum, 2009). This provides several areas for potential recovery and removal of phosphates in the waste water.

For economical recovery, a minimum concentration of 50-60 mg/L of orthophosphates is required (Cornel & Schaum, 2009; Nieminen, 2010). Effluent after secondary waste water treatment typically contains < 5 mg/L of phosphates and is thus not favourable for phosphate recovery. Sludge liquor and anaerobic side streams typically have orthophosphate concentrations between 20-110 mg/L (Schick et al., 2009). For WWTWs with biological and anaerobic digestion, process side streams are typically 1% of the forward flow (Bilyk et al., 2010) and have phosphate and nitrogen loads of 15-20 % of N and 20-30% P of the influent concentrations (Bilyk et al., 2011). Source separated urine contains between 300-570 mgP/L (Putnam, 1971; Etter, 2009; Richert et al., 2010). This alongside warm (25-30 degrees) temperatures, high nutrient concentrations and relatively low flowrates usually make nutrient recovery from side-streams an economically attractive choice. (Nieminen, 2010; Wefnet, 2009; Bilyk et al., 2011). Phosphorus is either in a chemically or biological bound form in the digested sludge before and after dewatering and maybe released in the sludge liquor, under anaerobic conditions. Dried sewage sludge exiting the dewatering step contains 1-3% or about 10-34 gP/kg of phosphorus by weight (dry mass) (Schipper & Korving, 2009; Schick et al., 2009). Incinerated dried sludge ash has the highest P concentration due to the reduced volume, typically 64-180 gP/kg (Dittrich et al., 2009; Schipper & Korving, 2009; Schick et al., 2009) from primary and secondary sludge and as high as 360 gP/kg for biologically treated sludge ash (Schipper & Korving, 2009). Sludge ash may be recycled for agricultural use, however the plant availability of P_2O_5 is low (4-11%) (Scheidig et al., 2009).

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2.2.3 Past technology reviews

The earliest documented technology review, by Rybicki (1997), gives an overview of all technologies that were available in the '90s. At that time, biological treatment methods were common and chemical precipitation was an emerging technology. A more comprehensive review by Strom (2006) provides more detail and illustrates the shift to more sustainable phosphate recovery, as opposed to typical removal methods, with the turn of the century. A review by Le Corre (2009) is an intensive review of crystallisation and its technology advancements by 2009. Niemenen (2010) is the most recent technology review, which was presented in the fulfillment of a Master of Science dissertation. It is an extensive review of common recovery practices from various waste water streams and gives the best indication of the direction of phosphate recovery from waste water. There have been several advances since, hence the rest of Section 2.1, alongside the WRC report by Sikosana et., al (2014), that reiterates and syntheses information from the aforementioned reviews to form an updated database (for the 2014-2015 period).

2.2.4 An overview of phosphate recovery, removal and reuse processes technologies

There are several phosphate recovery, removal and reuse processes, which range from decentralised units to industrial scale operations. The interest in phosphate recovery is not new, and already by 1997, several technologies had reached pilot–phase. These included the conversion of soluble polyphosphates into its insoluble form, by physical, biological, chemical or physical–chemical procedures (Strom, 2006; Cornel & Schaum, 2009; Cornel & Schaum, 2009). The most common phosphate recovery, reuse and removal techniques are tabulated in Table 5 below:

Table 5: The most common phosphate recovery, reuse and removal techniques/ processes

Process	Description
Physical removal processes	This involves the removal of particulate phosphorus. These include ultrafiltration, membrane bioreactor and reverse osmosis technologies. These processes are commonly used for WWTW effluent polishing, to meet legislative standards for phosphate. They are commonly used in conjunction with biological processes to achieve phosphate levels as low as 0,04 mg/L (Strom, 2006)
Chemical removal and recovery processes	These recovery or removal methods involve the conversion of soluble polyphosphates into its insoluble form. This can be achieved by chemical precipitation; crystallization; magnetic separation; ion exchange; electrolysis or adsorption. (Strom, 2006; Cornel & Schaum, 2009)
Chemical precipitation and crystallization	Today, crystallisation and chemical precipitation with metal ions, are the most common phosphate recovery/removal method and are the preferred route to meet low phosphorus values of < 0.1 mg/L (Cornel & Schaum, 2009; Le Corre et al., 2009; Crutchik & Garrido, 2011).
Biological removal methods	Microorganisms, including bacteria and microalgae, in bioreactors perform biological uptake of nutrients. Phosphorus removal from waste water by biological means has long been in use since the 1950's (Morse et al., 1997; Bashan & de Bashan, 2004).

Table 5: The most common phosphate recovery, reuse and removal techniques/ processes

Process	**Description**
Enhanced Biological Phosphorus Removal (EBPR)	This is enhancemed storage of polyphosphates by microbial biomass in activated sludge. Polyphosphate accumulating organisms (PAOs) use polyphosphates as an energy source. In anaerobic conditions, PAOs release orthophosphates, releasing energy to absorb organics and store them as biopolymers. In aerobic conditions, the PAOs use the polymers and carbon sources as energy to grow and then absorb orthophosphates (Bashan & de Bashan, 2004).
Wet chemical processes	This involves the base or acid leaching of phosphate from sewage sludge or ash, usually after biological phosphorus removal. The resulting liquor, maybe further treated to recover struvite by crystallisation. This approach is often costly, as well as energy and chemical intensive (Sartorius et al., 2011).
Incineration	Sludge incineration effectively removes toxic compounds and most heavy metals. This resulting sludge ash can be applied directly on agricultural land (Sartorius et al., 2011). However, incineration requires gas-cleaning technologies to treat the resulting flue gas (Scheidig et al., 2009).
Combined processes:	There are several process combination options for design optimisation. For reliability and maximum phosphorus removal, simultaneous chemical EBPR is the preferred method of phosphorus removal (Neethling, 2013)
Chemical precipitation and EBPR	Chemical precipitation is used to stabilize the biological phosphate removal, which fluctuates with temperature change. The P bound to the bacteria and the phosphate precipitate, remain in the sludge solids (Strom, 2006).
Thermo-chemical treatments	Thermo-chemical processes further purify sludge ash by removing excess heavy metals. Sludge ash has limited use as a fertilizer; hence further treatment is required to convert phosphorus into a plant available form. Similar to incineration, gas-cleaning technologies are required to treat the resulting flue gas (Scheidig et al., 2009)

Table 5: The most common phosphate recovery, reuse and removal techniques/ processes

Process	Description
Direct use, phosphate recovery and reuse techniques:	Phosphate containing waste streams can be treated to recovery and reuse phosphorus.
Sewage sludge application	Sludge (and sludge ash) account for up to 25% of the phosphorus available in municipal waste water (Cordell et al., 2011). In recent years the application of sewage sludge in agriculture has been restricted in some countries, due to farmland safety and human health concerns (Werner, 2006; Adam, 2009). Policy change in South Africa will bar disposal to agriculture land by June 2015 (CDM Executive Board, n.d.)
Urine sterilisation and application	When stored, urine degrades to ammonium and urease, altering the pH. and sterilizing the solution. This urine has plant available nutrients and can be used in crop production on a local level (particularly in developing countries), if the health risks and application procedures are fully understood (Ganrot, 2005; Richert et al., 2010).

2.2.5 Chemical precipitation

Chemical precipitation involves the addition of divalent or trivalent metal salts to waste water calcium (lime), aluminium and iron, as chlorides or sulfates) in well mixed regions 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). Aluminium is the least toxic and corrosive as well as is easiest to handle of the metal options. Furthermore, compared to the same dosage of ferric chemicals, aluminium is more effective at removing orthophosphates (Szabo et al., 2008). Often spontaneous chemical precipitation may occur within waste water treatment plants (esp. in sludge liquors after anaerobic digestion) under specific conditions causing pipe blockages and other issues (Kroiss et al., 2011). Chemical precipitation involves the following steps (Kroiss et al., 2011):

- dosing: the introduction of metal ions into solution;
- precipitation reaction: formation of precipitates;

- coagulation: the destabilisation of colloids and the coagulation into micro-flocculants;
- co-precipitation and flocculation: separable macro-flocculants are formed alongside particles and flocculants bound to organic matter; and
- separation: the different separation methods include sedimentation, filtration, floatation and adsorption (deBarbadillo et al., 2012)

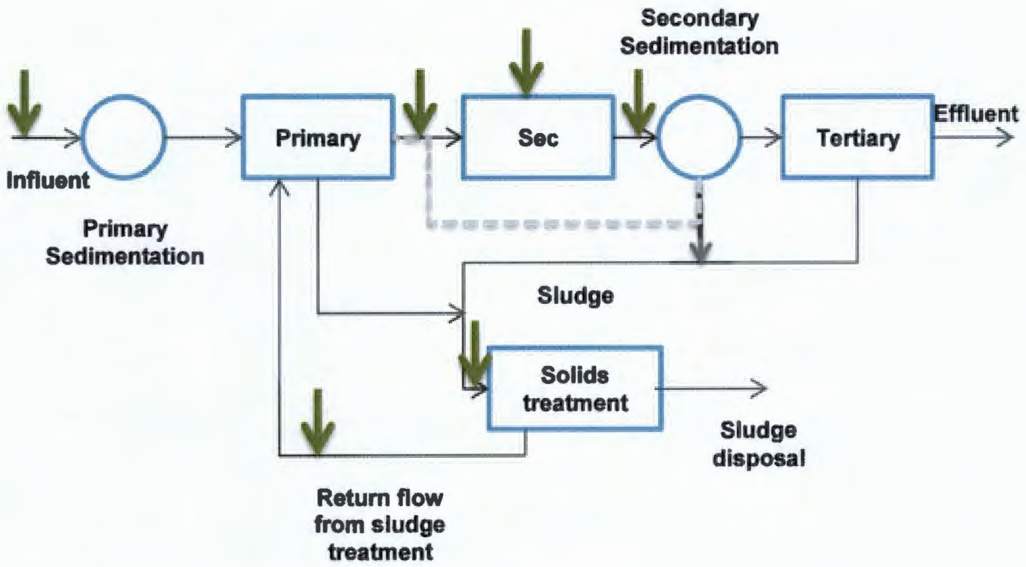


Figure 6: Illustrates all possible chemical precipitation dosage points

As shown in Figure 6, a plant may implement primary, secondary or tertiary precipitation:

- **Primary**: Metal salts are dosed prior to primary sedimentation and the phosphate removed in the primary sludge (Morse et al., 1997; Rybicki, 1997; Bashan & de Bashan, 2004). This process may achieve a removal efficiency (RE) of 90% and is dependent on the efficacy of the primary clarifier (Lenntech, 2005; Wefnet, 2009).
- **Secondary:** is the most frequently applied method and involves either the dosage of chemicals (usually metallic reagents) into the aeration tank of an activated sludge process or just before secondary sedimentation (Rybicki, 1997; Morse et al., 1997; Bashan & de Bashan, 2004). Co-precipitation is suitable for activated sludge plants, as the recirculation, flocculation and adsorption reduce chemical consumption and hence cost. Only iron and aluminium reagents are used, with calcium for pH control. A effluent recovery (RE) of >85% and effluent phosphate concentration (EPC) of 1-0.5 mg/L is expected (Wefnet, 2009).
- **Tertiary:** metal salts are dosed in the effluent following the secondary sludge (Bashan & de Bashan, 2004) or to process side streams as a removal enhancement step. This process enhances the phosphate effluent recovery of the biological process and the

converted P will be a constituent of the biomass and extracted with the secondary sedimentation biomass sludge (Wefnet, 2009). With a ferric dosage of 1.5-2.5 times the P ions in solution, the expected effluent recovery is about 95%, while an effluent phosphorus concentration of <0.5 mg/L can be achieved (Lenntech, 2005).

Although a very flexible P removal approach, chemical precipitation is rare in newer WWTW 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 & Garrido, 2011; Giesen et al., 2009). Precipitation technologies have a high carbon footprint due to the additional 3 steps involved which include: coagulation, flocculation and an energy intensive separation process (Giesen et al., 2009). In addition, the metal bound metal-P complex has little to no bioavailability, hence pushing research for alternative technologies that produce more useful products (Morse et al., 1997). One such technique is crystallisation.

This technique speaks towards more sustainable phosphate recovery and is covered in more detail in the following sections.

2.2.6 Crystallisation

Crystallisation is a versatile alternative to chemical precipitation. This is due to the economic and environmental benefits offered in combining water treatment and product recovery (all four steps of precipitation are combined into one step) (Giesen et al., 2009).

Both chemical precipitation and crystallisation undergo the same basic process of supersaturation, nucleation and crystal growth. Where the equilibrium imbalance maybe induced by evaporation, temperature or pressure changes or more commonly the addition of seeding material (Wefnet, 2009; Gordon, n.d.)

Differences between chemical precipitation and crystallisation

Although the principles are similar, the main difference between crystallisation and precipitation are, namely, speed of reaction, size and shape of the particles produced. Precipitation refers to rapid formation of indistinctive amorphous particles, which are difficult to separate (Nieminen, 2010). Whereas crystallisation processes result in more crystalloid solids which give distinct x-ray diffraction peaks and are easily filtered from solution and purified. (differencebetween, 2011). Secondly as described above, chemical precipitation is a chemical reaction that results in an irreversible change in chemical compounds in contrast to crystallisation products that are formed through solubility variations. This aspect of crystallisation enables products to be easily dissolved and recrystallized (Gordon, n.d.; Le Corre et al., 2009). The comparison of chemical and crystallisation products is summarised in Table 6.

Table 6: Comparison of precipitation and crystallisation products, adapted from (Giesen et al., 2009)

	Crystallisation pellets	**Precipitation products**
Morphology	Round pellets 0.8–1.0mm	Sludge
Water content	1–5 %	60-85% after dewatering
Seed material content	< 5%	

Crystallisation technologies in phosphate recovery

The fluidized bed reactor was the earliest crystallisation technology, developed in 1938 (Zhou & Tang, 2008), originally applied to water softening. This reactor was then industrialised in 1972 within a Dutch municipality. The Crystalactor® developed in the 80's and 90's penetrated the water treatment market as a technology for heavy metal, fluoride and phosphate recovery (Giesen et al., 2009). This technology is well established in a range of different applications, but it is not widely used in South Africa in full plant engineering and operation (Giesen et al., 2009; Burger, 2011). The Crystalactor® pilot plant at the Gold Fields Driefontein mine, is an example of a pilot plants running in South Africa (Giesen et al., 2009). Studies have modified the fluidized bed into single, agitation, inner circulation and FBR struvite crystallisation reactors. Modern crystallisation reactors differ from older crystallisers in the following manner (reference):

- reduced energy consumption;
- conditions are easy to implement, therefore reactions are accelerated;
- purification methods have a high selectivity;
- high purity of product; and
- large particles are recovered by precipitation and smaller ones continue to grow.

There are several variations of the crystallisation reactor, which include the single columnar; the gas agitated or mechanically stirred; the double groove; internal recycle; and the better-known Fluidized bed reactor (FBR). A summary of available, bench, pilot and full-scale crystallisation installations are summarized in Appendix B, Tables B.1.

The Crystalactor®

The Crystalactor® was developed by DHV Water BV in the Netherlands and has been used since the 90's to recover phosphate from waste water treatment plants. In a Crystalactor® unit, as shown in Figure 7, water is pumped up the reactor column through the seeded material that maintains a fluidized state. PH adjustment and reagent injection initiated crystallisation of the desired product. Process conditions are controlled to achieve high-purity crystals .Larger crystals move towards the bottom of the reactor and are discharged at regular intervals. An influent of < 100 mg/L of phosphate results in a high crystallisation rate with a short retention time and may take place is smaller reactors (Liberti et al., 2001; Giesen et al., 2009).

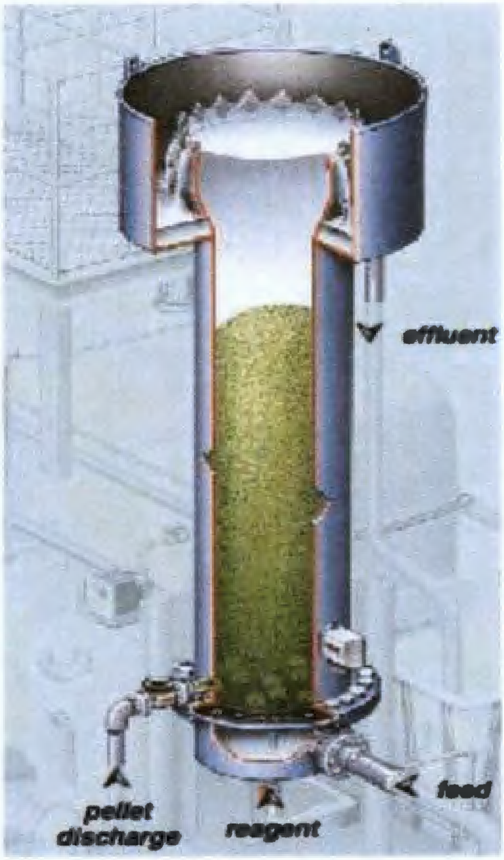


Figure 7: Typical Fluidized bed reactor (Giesen et al., 2009)

Crystallisation products: calcium phosphate and struvite

Crystallisation produces high purity, water–free and marketable final products, namely struvite and calcium phosphates, which can be used directly as fertilizers (Le Corre et al., 2009; Wefnet, 2009; Nguyen, Ngo, Guo, & Nguyen, 2013). With the growing global food security crisis, phosphorus recovery for fertilizer use and production will be the main motivator for phosphate recovery and reuse. If the future driver for recovery is for fertilizer use, then the quality and usefulness of the final phosphorus recovered product is essential. The crystalline structure of the fertilizer particles produced, is an important quality criteria in determining the rate of nutrient release into soils. However, for industrial processes it is the purity of phosphate compounds produced that is important. It is therefore essential to understand the different forms of crystallisation products.

Calcium phosphate

Calcium phosphate, particularly hydroxyl apatite is comparable to virgin phosphate rock (Cornel & Schaum, 2009). It is therefore an attractive product that has both industrial and agricultural uses. Calcium does not spontaneously precipitate and must be separated from solution using a seeding material such as sand and calcium silicate hydrate (Nieminen, 2010) Calcium phosphate pellets are formed when calcium is added at a pH of about 8.

Struvite

In WWTP with high concentrations of soluble ammonium, magnesium and orthophosphates, struvite may precipitate spontaneously (Bashan & de Bashan, 2004). Struvite precipitates as a crystal with a repeating pattern in all three spatial dimensions. It comprises of magnesium (Mg^{2+}) ammonium (NH_4^+) and phosphate ions (PO_4^{3-}) and is known as magnesium ammonium phosphate hexahydrate, $MgNHPO_4 \cdot 6H_2O$. It is a white solid with a unique orthorhombic crystal structure with a density of 1 710 kg/m^3 (Crutchik & Garrido, 2011). Crystals can grow within 3 hours, with natural aging within a few days with varying amounts of both struvite and hydroxyapatite. Table 7, compares the theoretical compositions of key struvite chemical components, to struvite produced on two separate studies.

Table 7: Percentages by mass of Mg, N and P in struvite

	Theoretical value	**Struvite from Oxley Creek**	**Struvite from Phosnix (nava 2009)**
Mg	9.90%	9.10%	9.90%
N (NH_4)	5.70%	5.10%	5.90%
P (PO_4)	12.6%	12.4%	12.6%
6 H_20	44,0%	39,0%	

Phosphate recovery in the form of struvite, has shown to be profitable and is recommended for process streams with high orthophosphate concentrations (Bashan & de Bashan, 2004; Le Corre et al., 2009; Crutchik & Garrido, 2011). De Bashan and Bashan (2004) and Gell et al., (2011) concluded that the best-feed stream for struvite formation is the supernatant of EBPR sludge and source separated urine. The question of obtaining a sustainable and economical magnesium source will affect the feasibility of the process. Ranges of factors that affect struvite crystallisation include, namely, pH, supersaturation, type of seeding material, mixing energy and temperature

(Le Corre, Valsami-Jones, Hobbs, & Parsons, 2009). Hence, the research focus continues to investigate the potential for struvite precipitation at WWTW.

Factors affecting struvite production

Waste water treatment plants have a Mg concentration of between 3-10 mg/L, which coupled with favourable pH conditions will result in struvite formation in pipes (OSTARA, 2013). Struvite precipitation may occur during anaerobic digestion due to the presence of orthophosphates and Mg ions from the biomass as well as some ammonium compounds (Nieminen, 2010). Additional factors and their affects are summarised in Table 8 below.

Table 8: Summary of the factors affecting the struvite production and costs

Factors	Effect
pH	
(Le Corre et al., 2009)	Solubility decreases from 3000 mg/L to 100 mg/L with a rise in pH from 5 to 7.5
(Green et al., 2004)	PH affects the uptake of ammonia and hence the Mg: N: P ratio
	Optimum pH for maximum yield between 8.5 and 9.5
Super saturation ratio	Affects crystal growth
Temperature	Affects the saturation and hence the solubility constant
(Le Corre et al., 2009)	Optimal conditions: 25 °C to 35 °C
Mixing	High turbulence releases CO_2 and affects pH
	High mixing quickens nucleation and results in brittle crystals
Impurities	Sodium, sulfate and bicarbonates and calcium have adverse effects
(Le Corre et al., 2009)	Calcium carbonate increase the induction time for crystal formation
(Crutchik & Garrido, 2011)	Sludge liquors have high Ca levels and will have a high selectivity for calcium carbonate instead of struvite.
(Green et al., 2004)	Ratios of Ca:Mg of 1:1 inhibits struvite crystallisation and induces CAP growth
	Sodium, sulfate and bicarbonates and Ca have adverse effects
	Inhibited by total suspended solids (TSS) over 1000 ppm
Concentrations of Mg and N	High ammonia concentrations increase struvite production (1: 9.4)
(Gell et al., 2011)	When Mg is adequate and the levels of Ca are high and N low, the precipitation of CAP is favoured
	Mg: Ca must be less than 1:1
	High levels of ammonia affects struvite kinetics

2.2.7 Review of commercial crystallisation processes

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. The Seaborne process and the Crystalactor that produce calcium phosphate experienced difficulties. All these processes are located on WWTPs with anaerobic digesters and produced final marketable products. The Seaborne process is the first industrial–scale wet chemical process, yet it is due for re-evaluation, as it is experiencing feasibility issues associated with chemical input and fertilizer prices (Nieminen, 2010). Typically, 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). Table 9 summarizes some of the successful industrial scale crystallization processes.

Table 9: Summary of industrial scale processes, adapted from (Nieminen, 2010)

Process	**Location**	**Feed material**	**Influent flow and P concentration**	**Product**	**Production rate kg/d**
Crytalactor	Geestmerambacht the Netherlands	Supernatant from anaerobic digester	12 000 m³/d 50-80 mg/L	CAP	4600
Phosnix	Shimane prefecture Japan	Sludge liquor, Industrial process water, side streams	45 000 m³/d 100-110mg/L	Struvite	500-550
Seaborne	Gifhorn, Germany	Leached Digested sludge, then centrifuge liquors	6500 m³/d 600 mg/L Ptot	Struvite	680
Ostara Pearl	Edmonton, Canada	Sludge liquor	100-900 mg/L	Struvite	500
AirPrex	Berlin, Germany	Digested sludge/ sludge liquor	180 000 m3/d 300 mg/L	Struvite	2500

2.2.8 Crystallisation case studies: Ostara and Multiform Harvest

Two industrial scale installations and one community–scale pilot project were investigated in the larger WRC Report (No: K5/2218) by Sikosana et al. (2014). In all three cases the final product, mainly struvite, is sold for fertilizer use. These case studies illustrated both centralised and decentralised phosphate techniques as well as solid and liquid phase phosphate recovery. Two of these centralised large-scale systems are summarised below. Here, the Ostara, Multiform Harvest and the Seaborne processes are centralised and are located at WWTPs with anaerobic digester units, treating the sludge liquor and sewage sludge respectively. It is increasingly evident that phosphate recovery from biological WWTW side streams from anaerobically digested sludge is an attractive option.

Case study: Ostara installation by Hampton Roads Sanitation District (HRDS), at the Nansemond Treatment Plant, Suffolk, Virginia. 2010

The Ostara process installed at the HRDS Nansemond WWTP, Virginia (United States) is a full-scale nutrient recovery facility with a maximum capacity of 416 m^3/day producing 1650 kg/day of struvite at a 85% phosphate recovery rate. The installation recovered excess nutrients, which mitigated severe blockages in the digested sludge pipelines, whilst also increasing biological stability. The struvite produced is packaged onsite and is distributed and sold by the service provider Ostara. The process is summarized in the Figure 8 below.

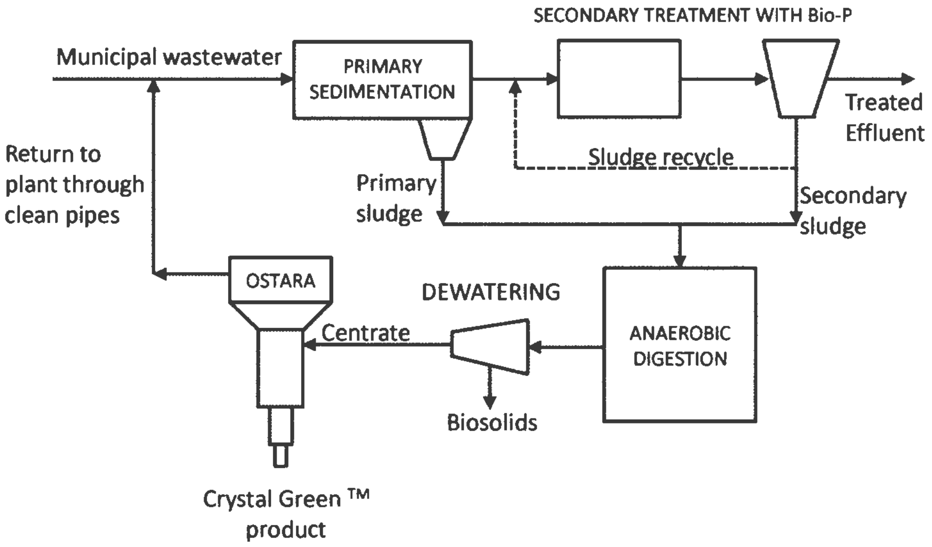


Figure 8: Process diagram describing the Nansemond WWTP

Case study: Multiform Harvest in Yakima WWTW, USA, 2012

The Yakima WWTW is an activated sludge treatment works with enhanced phosphorus removal that treats approximately 52 ML/day of waste water and has a design capacity of 75 ML/day. Yakima is within an industrial area that results in high total phosphate concentrations between

July and August, which may cause eutrophication in the Yakima River. The Multiform process comprises of conical fluidized bed reactors, with no recycle and short retention time, which recovers 90% phosphorus. These reactors are currently operating at 832 kL/day and producing about 453 kg/day of struvite. Table 10 below summarises the main differences between the two commercial processes.

Table 10: Muiltiform harvest compared to OSTARA costs 2010 for same capacity adapted from (Bilyk et al., 2010)

Service provider	**OSTARA**	**Multiform Harvest**
Installations	8 full-scale installations	1 full-scale and 1 pilot
Land requirements	Needs a new building Significant space needed for struvite processing	Maybe installed into existing buildings
Reactors	Larger than Multiform (m^3) Require recirculation pumps Reactor effluent recycled several times 80-90% recovery Set reactor sizes	Conical shaped reactors No recycle Shorter retention time 80-90% recovery
Struvite processing	Drying and bagging equipment requirement Good quality crystal struvite is sold	No bagging or drying required Low quality (often powdery) struvite is collected wet
Product ownership	OSTARA has selling rights to the struvite produced	Multiform Harvest has selling rights to the struvite produced
Maintenance and repair	High maintenance costs associated with struvite processing units	Low due to reduced equipment

It is evident from the technical assessment 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. Therefore, crystallisation technologies to recover struvite from anaerobic side streams at a WWTW is the main focus of the following sections and the dissertation as a whole.

2.3 Techno-economic assessments

This section reviews past techno-economic assessments to provide a useful basis for the 4th research aim, which is, namely, to present and techno-economically analyze a case study of how a nutrient recovery process could be incorporated into a biological waste water treatment works in South Africa.

Phosphorus recovery and elimination costs are subject to regional variations. They have to reflect the chemical input costs as well as the sludge treatment and disposal costs and they are therefore subject to local conditions.

2.3.1 Cost estimates and implications

Kroiss et al. (2011) estimated the removal of phosphorus by chemical and biological methods to be between €6-14/kg Premoved (R90-210/kg Premoved); and €2.5-9/kg Premoved (R90-140/kg Premoved) respectively. These have cost implications of about €3.5/capita.·year (R53 /capita.·year) and €4-9/capita.·year (R60-R135/capita.·year) for biological and chemical removal respectively.

The unsubsidized costs for phosphorus recovery were calculated using mass balances and are summarised by Balmer (2003). It is estimated that the cost of combined phosphorus recovery and elimination from waste water is about €3,6/kgP (R54/kgP) (Balmer, 2003). At a South African phosphate load of 1.3 gP/capita.·day or 475 gP/capita.·year the cost implications of waste water removal is R26/capita.·year. The same report quotes the recovery cost of phosphorus from sewage sludge as €8,8/kgP (R132/kgP) which incurs a cost of R63/capita.·year (Kroiss et al., 2011). More specific phosphate recovery estimates are quoted in Petzet and Cornel (2013) and are summarised in Table 11. However, these do not account for the cost saving that comes with reduced sludge disposal and chemical and maintenance. The concentration of orthophosphates also affects the rate of struvite formation and hence the cost of production with predictions of R42000/t of struvite (at 50 mgP/L) and R7800/t of struvite (800 mgP/L) (Crutchik & Garrido, 2011; The Money Converter, 2014).

Kroiss et al. (2011) estimated phosphate recovery from sewage sludge and sewage ash to be about €5-20 /kg Precycled, which is R74-300/kg Precycled. This translates to €5-20/capita.·year and R23-75/capita.·year; which are similar to values quoted by Petzet and Cornel (2013).

The price of phosphate rock is approximately US$0.1/kg (R107/ton) (Infomine, 2014). The European market price for 1kg P recycled is €0.5-1 (R7.5-15) (Kroiss et al., 2011), which is higher than the current phosphate rock market price. On this basis, phosphate recovery is yet to be cost effective.

Table 11: Summary of cost estimations for phosphorus removal and recovery processes[1]

Treatment process	Costs	Reference
Biological	R90-140/kgP removed	(Kroiss et al., 2011)
Chemical	R90-210/kgP removed	(Kroiss et al., 2011)
Sewage sludge and ash	R75-300kg/P recycled	(Kroiss et al., 2011)
Sewage sludge only	R40-380 kg/P recycled	(Petzet & Cornel, 2013)
Sewage sludge ash only	R40-113kg/P recycled	(Petzet & Cornel, 2013)
Sludge liquor	R140-230kg/P recycled	(Petzet & Cornel, 2013)
Sludge liquor (50-900mg/L)	R7,80-42 kg/ kgstruvite	(Crutchik & Garrido, 2011)

2.3.2 Techno-economic assessment studies: prefeasibility

According to Cordell (2011), a life cycle (cost) analysis serves as a basis for comparison between current business-as-usual practices and the proposed nutrient recovery/removal technologies. Various comparative prefeasibility studies have been conducted on potential phosphate recovery technologies and removal techniques. These studies and their key findings are summarised in the proceeding in this Section 2.3.2.

West Boise WWTF Use of Struvite Crystallisation Technology as Part of the Phosphorus Removal Plan by Barbeau et al. (2009)

A comparative techno-economic assessment was conducted in their report. Metal iron precipitation and crystallisation to form struvite, using the Multiform Harvest set-up were considered for high strength filtrate treatment.

The main findings from their report were as follows:

- ferric chloride was the cheapest chemical at the time;
- struvite precipitation operating costs were within 10% of the chemical precipitation costs;
- the Multiform Harvest pilot plant was tested on the process side stream and sometimes produced a dusty product (low grade struvite) which may not be suitable for high end agricultural and other chemical processes;

- the struvite market was not adequately developed at the time of the study (2009);
- struvite was predicted to sell at R1 080 per ton of struvite;
- capital cost of the Multiform Harvest set-up was estimated to be R36,6 million (size not specified); and
- a positive cash flow is only feasible when struvite is sold at a minimum of R6 650 per ton of struvite.

Process and economic benefits of side stream treatments (Bilyk et al., 2010)

Side stream phosphate loading in anaerobically digested centrate, the anaerobically treated sludge liquor, in biological WWTWs accounts for 20-30% of the influent load. Dewatering occurs as a batch process and results in peaks in nutrient concentrations and may cause issues downstream. Two case studies were evaluated, on a techno-economic basis, to demonstrate the economic benefits of side stream treatments (Bilyk, Pitt, Taylor, & Wankmuller, 2011). Ostara and Multiform Harvest installations were discussed and compared to traditional chemical precipitation techniques. The cost comparisons are summarized in Table 12. In addition, the following observations were made:

- theoretical phosphate removal up to 90%;
- higher temperatures and concentrated nutrient loads of side streams result in faster kinetics;
- although it had the lowest capital expenditure (CAPEX), chemical precipitation (with Aluminium) was found to be less cost effective than two struvite production options explored
- Ostara CAPEX costs are significantly higher than that of Multiform Harvest as it requires a new building;
- there are variations in service provider business models for struvite production; and
- business models will adjust to allow for more reactor sizes and preference over processed and unprocessed products.

Table 12: Cost estimates for Ostara, Multiform Harvest and Chemical precipitation units at two plants

	Ostara		**Multiform Harvest**		**Aluminium ppt.**	
Plant (flow rate not specified)	A	B	A	B	A	B
CAPEX ZAR million	43,8	47,0	11,6	14,8	-	7,65
OPEX ZAR million	0,154	0,43	0,51	0,51	2,00	3,60
Present Worth Cost (20 years)	41,8	42,2	18,0	21,3	27,7	52,3

A disadvantage of the Bilyk et al. (2010) assessment is that no information was given on the specifics of the two WWTPs. As the flow rates, nutrient loading or business-as-usual data have not been disclosed, it is difficult to establish the relationship between the above mentioned plant parameters and the 3 phosphate extraction techniques.

Nutrient and energy recovery from sewage: Technology review and exploration of possibilities in South Africa.

The WRC report by Sikosana et al. (2014) included a conceptual design for two treatment plants (nutrient and energy) and the techno-economic pre-feasibility assessments for the case of a central city precinct in South Africa were investigated. The initial techno-economic results of this report were encouraging; although four times higher than the outmoded disposal options. However, it was concluded that "this decentralised nutrient-recovering method over a 20-year period is still well within the envelope for standard treatment. The main findings from the report included:

- diverting urine from male urinals can produce about 75 kg/d of struvite;
- this could recover R42250 p.a in operating costs;
- the co-digestion of primary sludge can generate a surplus of 27kW, at a feed tariff of R1.00/kWh this presents a cost recovery of R509000; and
- 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 costs incurred by the existing scheme (waste water to ocean outfall and food waste to landfill).

2.4 Techno-social assessments

Historically, technology development and innovations were viewed to be independent of society. It is now argued that any technology can be analysed sociologically, therefore technology assessment tools should encompass a variety of societal driven design factors (MacKeinzie & Wajcman, 1999; Franks, Cohen, McLellan, & Brereton , 2010). The following section gathers information from past studies that are themed around the fourth research aim.

2.4.1 Society shaping technology

Economic calculations are a mechanism of social shaping of technologies. This feedback situation arises when labour costs, job creation and benefits to society associated with the project and technology in question, are considered. Likewise government and its policies form an important part of society that has a strong effect on cost patterns and hence the "technology" trajectory.

Social acceptance and technology transfer

Technologies have the ability to improve the livelihoods of many; however, not all emergent technologies are accepted by society. Across different countries, cultures and geographical boundaries, varying environmental types, health and social risks associated with new technologies may result in failure to penetrate a new or existing market (Franks, et al., 2010). Hence, some technologies are more compatible to certain social groups than others; adopting a new technology can come with more economical, cultural and political effects than initially perceived. By ignoring these factors, transfer of inadequate, unsustainable, unsafe, or "bad", but perhaps cheaper technology and equipment can take place. (Franks, et al., 2010).

An alternative perspective on technology transfer is the process conceptualising and then the consequent implementation of new application of an existing technology (Reisman, 1989). Understanding technology transfer is particularly important in the context of climate change. Technologies are the main sources of greenhouse gases, therefore rapid technology innovation is essential in allowing for the global transfer of adaptable, mitigation technologies that are environmentally sound (Marter, 2000). Programmes such as the Global Environmental Facility (GEF) and the Intergovernmental Panel on Climate Change (IPCC) facilitate the deployment and acceleration of low emission technologies in developing countries, to foster the transition to a green economy. But most importantly, collaboration initiatives with stakeholders must be developed to better adapt these technologies to user needs (IPCC, 2000; GEF, 2013).

Social and environmental impacts

The ethics to be considered around the sustainability of a process or technology have recently started to reflect more strongly in societal views and expectations. However, most views are personal and criticism regarding some emerging technologies appears to be based on perceived threats or factors of personal importance (Franks, et al., 2010). Scientifically based regulations enforced by government are no longer sufficient to meet the needs of the public or their concerns. "A more effective approach is needed to design technologies that are reflective of stakeholders." (Franks, et al., 2010). As such it is necessary to communicate with and understand the community and cultural context as part of a technical risk evaluation.

With this backdrop, sustainability assessments must encompass all necessary aspects of sustainability, including the all the social interactions described.

2.4.2 Investigating consumer attitudes towards the nutrient recovery technologies

Urine separation and nutrient recovery technologies that yield useful products such as fertilizers are increasingly becoming innovations to improve the sustainability of urban waste water management (Pahl–Wostl, et al., 2001). The social acceptance of these innovations will play a major role in their potential implementation. Stakeholders will have to consider their participation as consumers of urine fertilised produce and as tenants or house owners. There is an increase in decentralised technologies at a household scale, hence the viewpoints and involvement of stakeholders is starting to play a major role. Pahl-Wostl et al (2001) used a focus group approach to assess the acceptability of NoMix toilets in Nepal. The following was concluded:

- NoMix (urine diversion) technology was generally accepted, if the innovation offers a similar level of comfort and affordability as conventional technologies.
- Nutrient recycling in relation to long-term sustainability were not of high importance compared to concerns around micro-pollutants on humans and the ecosystem health.

Another survey conducted by Sartorius et al. (2011) assessed the acceptability of various waste water treatment technologies, by means of expert interviews. It was found that the success of struvite derived from human waste was based on quality. The same study also concluded that phosphate recovery from source separation would be better suited for developed rather than developing countries (Sartorius et al., 2011).

Investigating social acceptability of urine diversion technologies in South Africa

Roma et al. (2013) investigated the user perceptions of urine diversion toilets in eThekwini municipality district, South Africa. The study referred to user feedback to highlight several key post-implementation challenges, 10 years post-installation. In contrast to the Pahl-Wostl (2001) study, perceived risks associated with smell, alongside problems such as poor maintenance contributed to the 70% of the sample of users interviewed being unsatisfied with this technology (Roma et al., 2013). It was concluded that education activities to tackle the negative perceived risk, alongside monitoring and maintenance of these installations, would help overcome the negative perception of closed-loop excreta/nutrient recycling.

2.5 Product and technology marketability

As has become evident from the described studies, nutrient recovery technologies that yield high quality fertiliser products from waste water are being explored and implemented globally. However, once a promising innovation is discovered how is it introduced to the market (Munch et al., 2001)? In research, this commercialisation step is often overlooked and may result in the proposed innovation not reaching its full potential. Marketability considerations can assist in the development of technology design and implementation frameworks within a given context.

2.5.1 Struvite markets

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

- replacement for secondary phosphate ore;
- industrial grade phosphate;
- slow release fertiliser;
- animal feed additive; and
- fire proof agent and cement adhesive (Zhou & Tang, 2008).

Although it has been suggested that struvite could be ideal for industrial processes, it is argued by Schipper et al. (2001) that it has limited applications in electro–thermal processes due to its ammonia content. Ammonia would cause serious gas scrubbing and emission issues in the sintering stages of industrial processes (Schipper et al., 2001). As a fertiliser, struvite could be used directly if harvested properly or as a specialty fertilizer in nurseries as well as a component for agricultural fertiliser production. Small amounts are being tested as fertilisers in Japan (Bashan & de Bashan, 2004), Switzerland and South Africa (VUNA, 2013). Studies by Nawa (2009), Kern et al. 2008, Gell et al. (2011) and VUNA (2013) illustrated that struvite has low concentrations of heavy metals and other pollutants. The slow release of struvite nutrients minimizes the risk of leaching and root damage and is favoured in grasslands, forests, where fertiliser application is minimal (Trenkel, 1997). Struvite can be mixed with phosphoric acid to produce a fertilizer superior to and more cost effective than di-ammonium phosphate (de Bashan & Bashan, 2003). Also, the magnesium content of struvite is an attractive characteristic for sugar beets, as they require high amounts of magnesium. Phosphate rock is purified and used as an additive for detergents, food and cosmetics (Bashan & de Bashan, 2004). However as no purification method for struvite is known, these are not viable markets for struvite use as a raw material.

2.5.2 Nutrient recovery market assessments

Munch et al. (2001) describes a market research conducted for an undisclosed Australian "Company X", which intended to provide phosphate recovery services. This report outlined a commercialisation business plan (in 2001) for struvite as well as its potential investors and customers. Piggeries and biological domestic waste water plants with anaerobic digestion were identified as potential clients for Company X. A more general and recent study by BlueTech (2012), explored the global market dynamics of nutrient recovery products, in relation to the USA (American) market.

Making a business from struvite crystallisation for waste water treatment: turning waste into gold (Munch et al., 2001)

Munch et al. (2001) identified primary and secondary markets in Australia with the aim to: recognise potential customers; determine the market dynamics as well as market size. The study used a participatory approach, by evaluation of the viewpoints a range of industrial experts. A questionnaire was distributed to understand:

- the key driver for the service;
- suitability to the potential client's operations;
- technical aspects of the precipitation process; and
- potential policy changes in relation to current WWTW effluent regulations.

Results of this questionnaire are summarised in Appendix C, Table C.1. Furthermore, a strength, weaknesses, opportunities and threats (SWOT) analysis revealed that although the pig industry is in need of effluent disposal solutions, the lack of working capital and their slow adoption to new technologies might hinder Company X's penetration into this niche market. It was postulated that MAP production from waste water streams is such a good opportunity, that Company X was expecting immediate government backing. This support would grow their predicted 2 % market penetration to 10% in the pig industry as legislations begin to change. Furthermore, Company X anticipated that larger WWTW are more likely to invest in such a technology over smaller industries. In addition, the following observations were made:

- The predicted selling price of struvite will have to be a minimum of R4850/kg struvite for agricultural use
- Company X will charge a service fee of R5200/ML reacted
- Predicted payback period of 5 years

Nutrient removal and recovery: market and technology overview (Algeo & O'Callaghan, 2012)

This more general study explored the current and future global nutrient recovery market. Key market drivers, barriers and market trends were investigated.

Market drivers: Similar to the Munch (2011) study, the main market driver for nutrient recovery in Europe, USA and China is attributed to waste water treatment plant regulatory compliances and government legislation. In addition to this:

- It is estimated that the revenue contribution potential of struvite is R39 000/ton (of magnesium and orthophosphate combined).
- It is noted that for many cases phosphorus recovery may not cover the CAPEX, but it will offset treatment costs to meet environmental regulations.
- Land use of sewage is sludge increasingly coming under pressure

In South Africa, the water research commission and the CSIR formulated the "sludge to land application decision support (SLADS) software. This software is based on the "Permissible utilisation and disposal of Sewage Sludge" guide, which was formulated by the collaboration of thirteen concerned groups from the government and private sector (Water Research commission, 1997). The document was compiled to assist relevant stakeholders in the safe disposal and application of sewage sludge in the agriculture sector. It also serves an open source document to address real and perceived risk at a community level.

Market Barriers: Although MAP has been in production for 50 years, quality assurance requirements may hinder its market penetration. It was speculated "regulators in some jurisdictions might take the view that since waste water is a 'waste' anything derived from it must be a 'waste' by definition, unless 'end of waste' criteria are established" (Algeo & O'Callaghan, 2012). Also:

- There is uncertainty in which American market avenue to pursue
- Struvite may be sold as a premium fertilizer to niche markets (if 2-4mm in size)
- The best use may be to sell struvite to fertilizer blenders, however the production rate of struvite is too small compared to industry fertilizer throughput
- There is a slow buy in for struvite production technologies by companies, which will make it difficult to convince municipalities of the benefits of struvite production
- Money will have to be spent on packaging and marketing.

Market trends: A more recent development in phosphorus trading is nutrient trading programs. Similar to the carbon credit system, the Nutrient Credit Trading program in the USA serves to keep compliance costs down while meeting or exceeding water quality regulations. If compliance is exceeded, WWTP may be able to sell their excess nutrient credits to another smaller facility. Alternatively, some countries such as China have restricted exports of phosphorus to protect reserves. As expected, the price of nutrients in the US will increase as reserves run out. In addition in coming years, agricultural waste streams will increasingly becoming a niche market for energy and nutrient recovery.

2.6 Technical, economic and social assessments

The above techno-economic, techno-social and marketability assessment tools over-simplify interactions between systems, limiting the ability of technologies to adapt to disturbances (Alexandra & Limnios, 2008). Also, these studies use techno-economic and social-techno assessment tools in isolation. However, the complexities between technology and sustainable development cannot be reduced to linearity. Hence, dynamic assessment tools must be developed that allow for predications of internal and external changes across sub-systems Brent & Musango, 2011). This in turn will reduce the risk of selecting expensive and high energy consuming phosphate recovery technologies that do not address the key issues of the entire system in a sustainable manner (Cordell et al., 2008).

This is known a systems approach and goes beyond the combination of techno-economic-socio assessments. It is an interdisciplinary approach that includes the totality of elements of a system structure (de Rosnay, n.d.). Studies are being conducted towards adjusting existing or developing new sustainability frameworks to incorporate complex system dynamics. These include Brent and Musango (2010) and Cordell (2011). Cordell (2011), proposed a systems framework that investigates the applicability and challenges associated with phosphate recovery and recycle techniques. Although progressive, these studies go beyond the scope of this thesis. Therefore, this dissertation only considers a holistic (yet linear) technological, social and economic assessment.

2.7 Summary of literature review

Waste water systems have increasingly become pivotal in addressing water-related issues of sustainable development. Since the early 2000s, studies that assess the sustainability of waste water and nutrient recovery technologies have surfaced. Various aspects of societal, environmental and economic effects on technology development have been investigated globally, but mostly as isolated sub-systems. This chapter has presented a structured review of studies related to the sustainability assessment of waste water nutrient recovery systems, particularly those focused on phosphate recovery.

2.7.1 Technology assessment

A comprehensive technology review identified that the phosphate recovery technologies can include physical, biological, chemical and physical–chemical procedures. The focus has shifted from chemical processes in the 1980s to biological processes in the 1990's and more recently to crystallisation. Crystallisation methods typically achieve a recovery of > 90% and a final effluent of 0.3-1 mg/L, whilst producing a marketable final product in the form of the phosphate rich mineral struvite or calcium phosphate. A concentration of 50-60 mg/L of orthophosphates is required in a feed stream for economically feasible recovery. It is becoming increasingly evident that phosphate recovery from biological WWTW side streams from anaerobically digested sludge is an attractive option.

2.7.2 Techno-economic assessments

Phosphorus recovery and elimination costs are subject to regional variations. Comparative techno-economic assessments revealed that metal precipitation has the lowest capital expenditure (CAPEX), however was found to be less cost effective (no marketable product and high chemical costs) than other struvite production options explored. However, to be profitable, struvite prices must exceed the current market nutrient prices and sell at a minimum price of US$570/ton within the American market. Capital expenditure costs for the Ostara technology that produces high-grade struvite is significantly higher than the Multiform Harvest technology, which produces low-grade struvite. This is attributed to the new infrastructure and additional struvite processing units associated in producing a more refined product onsite.

2.7.3 Techno-social assessment

Historically, technology development and innovations were viewed to be independent of society. It is now argued that any technology can be analyzed sociologically and therefore that technology assessment tools should encompass a variety of societal driven design factors. Life cycle cost assessments are not sufficient for a holistic sustainability assessment and must include social aspects (Guest et al., 2009). Post installation social acceptance studies have been conducted in two developing countries, Nepal and South Africa, with starkly contrasting observations. Unlike in South Africa, the Nepalese people generally accepted urine diversion toilets. However, there were concerns with the health and safety associated with fertilizer use from human waste, a view shared with waste water industry experts interviewed by Sartorisu et al (2011). This illustrates how geographical, cultural and regional differences can affect the success of technology transfer and implementation. South African cultural differences and large post-apartheid class disparity may make it difficult to implement any further decentralized units. Hence, centralised phosphate recovery units may be the most feasible option in this context.

In research, commercialization steps are often overlooked and may result in a proposed innovation not reaching its full potential. Marketability considerations can assist in the development of technology design and implementation frameworks, within a given context. Struvite markets vary from industrial grade to direct use in agriculture. However the lack of a known purification method and the low throughput of recovered struvite from waste water are market barriers that must if struvite is to be considered as a raw material alternative to phosphate in industrial processes. Munch et al (2001) studying struvite product prospects in the USA, used a participatory approach in the form of expert interviews, to identify potential customers and to determine the market dynamics as well as market size. A key observation made was that support through government policy changes would more than double the potential market penetration. No such study has been done in the South African context.

2.7.4 The gap: techno-economic-social assessment

The technology, techno-economic and techno-social sustainability assessments described above have often been done in isolation and have over-simplified interactions between these sub-systems. Research by Balkema (2002) and Muga & Mulchelci (2008) show progress towards a more holistic approach to technology assessments. These frameworks are conceptual and have been applied to existing nutrient recovery case studies, but are yet to be applied in the prefeasibility step of phosphate recovery techniques, yet alone in the South African context.

These considerations for a more holistic approach, which include both a social and techno-economic assessment, have shaped the aims described in Section 1.3 and have informed the methodology for this research, which will be described in the following chapter.

3 Research approach

As a continuation to the WRC Report No: K5/2218 by Sikosana et al (2014), this study is a technological, social and economic investigation of the sustainable development contributions that a phosphate recovery installation would have at a centralized biological WWTW with existing anaerobic sludge stabilization units. Findings from case studies with similar installations in other parts of the world, described in Sikosana et al. (2014) and Section 2.2.8 are referred to and form the basis for the concept designs that are then subjected to the social and techno-economic assessments presented in the preceding chapters.

Section 3.1 describes the hypothesis and the resulting key questions that form the basis of the research approach. The work presented in this dissertation attempts to answer these questions by combining evidence obtained by means of two different methodologies. Section 3.2 describes a qualitative approach used to better understand the market potential for fertilizers derived from human waste in South Africa. A techno-economic assessment conducted on three concept designs for phosphate removal at the Cape Flats WWTW, follows in Section 3.3.

3.1 Hypothesis and key questions

The literature review has shown that mature phosphate recovery technologies that produce high quality struvite for use in food production are often costly. Furthermore, there is little evidence that indicates that these phosphate recovery techniques will be economically viable or socially accepted in South Africa. Therefore this dissertation proposes that:

The South African market is better suited for low quality struivte for use in secondary (non-food) markets. This will be cheaper than both traditional chemical precipiation (phosphate elimination) methods and high-quality struvite production.

3.1.1 Key questions

Based on this hypothesis and considering the current sanitation backlog, economic state and agricultural fertilizer constraints in South Africa, the following key research questions arise:

1. What space is there for fertilizer production (such as struvite) from human waste in the South African markets?
    a. What are the viable market avenues?
    b. As such, what are the socio-techno dynamics that one can use to develop a framework to base technology design and implementation on product marketability within a given (South African) context?

The second aim explores the possibility of an advanced crystallisation technology at a WWTW in the Western Cape. Hence:

2. Would the installation of a centralized nutrient recovery technology at a biological WWTW coupled with anaerobic sludge stabilization, be an economically viable sludge liquor treatment technique in the South African context?

This dissertation continues to answer these questions by means of two separate methodologies described in Section 3.2 and 3.3. A qualitative approach is used to assess the socio-techno viability of phosphate recovery, with these findings presented in Chapter 4. A quantitative techno-economic assessment to answer key Question 2 is developed in Section 3.3 and its results will be presented in Chapter 5.

3.2 Social sssessment: methods

This Section and its corresponding results Chapter 4 attempts to address the first research question. This methodology is reproduced from the WRC report by (Sikosana et al., 2014). Chapter 1 and 2 gave some background into the social aspects of phosphate recovery from various waste streams and served as a starting point for this social assessment. Relevant to this social assessment, the following was established:

- Life cycle cost assessments are not sufficient for a holistic sustainability assessment and must include social aspects (Guest et al., 2009)
- Social aspects are often overlooked; there are a few studies on the social acceptance of user-end technologies, but are non-existent for the marketability of the final fertilizer product in South Africa
- The struvite market is not well established and is dependent both on geographical location and context.
- Phosphate recycling and organically grown produce are both informed by sustainability concerns, so it is of interest to determine whether these two changes to food production systems can be co-implemented.

3.2.1 Overview

The overall aim of Section 4 was to investigate the social-techno dynamics in developing a technology design and implementation framework based on product marketability within the South African context. The question explored is: **What space is there for fertilizer production (such as struvite) from human waste in the South African markets?**

The marketability assessment used literature and a qualitative approach to:

- Identify viable market avenues for struvite both premium and low end.
- Understand the potential for market penetration of phosphate fertilizers derived from human waste in the organic food market (a premium market).
- Identify the social-dynamics and key stakeholders.
- Conceptualize a framework to base technology design and implementation on product marketability within a given (South African) context?

3.2.2 Qualitative research approach

A qualitative approach was employed to ascertain the societal influence on the entire nutrient recovery system, along the waste water to agriculture value chain, from fertilizer product to potential consumer. The overall aim was to understand and interpret existing rules as well as the views of various stakeholders. This study did not include the views of any potential consumers due to time constraints, as well as the inappropriateness of the qualitative methodology used for larger sample groups. Therefore, conclusions made pertaining to consumer needs and predicted behaviours are limited to what may be inferred from the experts.

Interpretative phenomenological analysis (IPA) is a detailed exploration of how the interviewee makes sense of their surroundings, through their personal experiences, free from the perceptions of the interviewer. This research methodology tries to find homogenous samples, by using purposive sampling rather than random or representative selections. IPA studies can be done by the collection of data via email, diary and personal accounts; however, semi-structured interviews are the preferred method and were the method of choice for this study. . There are several studies published that use a standard IPA methodology, this study draws on the generic phenomenology approaches described by Kvale, (1996) and Smith and Osborn, (2007). The left hand side of Figure 9, illustrates a summary of the qualitative methodology used. Stakeholders were identified along the agriculture chain and are illustrated on the right hand side of Figure 9. The main steps involved in an IPA are:

Data collection: semi-structured interviews: The semi-structured approach maximizes an interview experience, as it gives the opportunity for new ideas and issues to be identified, that were not previously thought of by the interviewer. An interview schedule was developed to guide (but not direct) these semi-structured interviews to be consistent with the overall research question, as stated above.

Sample: A defined group of experts down the recovery phosphate to agriculture value chain were the sample pool for this research. Three academic experts in struvite production, an organic farming expert, an organic farmer, one representative from retail, one representative from the fertilizer industry as well as two representatives from two different organic certification boards were interviewed for an overall total of 9 participants.

The interview schedule and interview process: Semi-structured interviews with non-explicit open-ended questions were drafted to assist in predetermining ways to deal with possible difficulties (Smith & Osborn, 2007). Interviews ran for a non-determined period of time, within the respondents' method and/or venue of choice. Questions in the interview schedule fell under the following themes:

- Current local and global agriculture practices (past, present and future)
- The South African fertilizer industry (phosphate industry)
- Socio-technical risks: waste water and phosphate technology
- Human waste as a fertilizer; is it viable?
- Agriculture value chain

Analysis of results and data of semi-structured interviews: The aim was to attempt to understand the complexity of the meaning of the respondent's views by making links between the IPA findings, own experiences and findings in literature. Some parts of interviews were more useful than others and required more commentary in the form of paraphrasing as well as summaries and are thus open for interpretation (Smith & Osborn, 2007). Using the summaries, it was then necessary to identify similarities and differences, contradictions and amplifications within the respondent's response and that of other interviews. This is in order to catergorise the statements made by the stakeholders, into themes. From this initial script, theme titles were formulated, for use whenever similar themes emerged in other interviews and interpretations.

Thereafter the themes were clustered and tabulated as follows:

- Fertilizer quality and quantity
- Organic practices
- Organic certification
- Phosphate fertilizer from human waste
- Market channel and value chain
- Health and safety
- Prediction of societal views

These were further grouped into four subheadings: Organic fertilizer and food security, Alternative market routes, Quality, health and safety and Social acceptance.

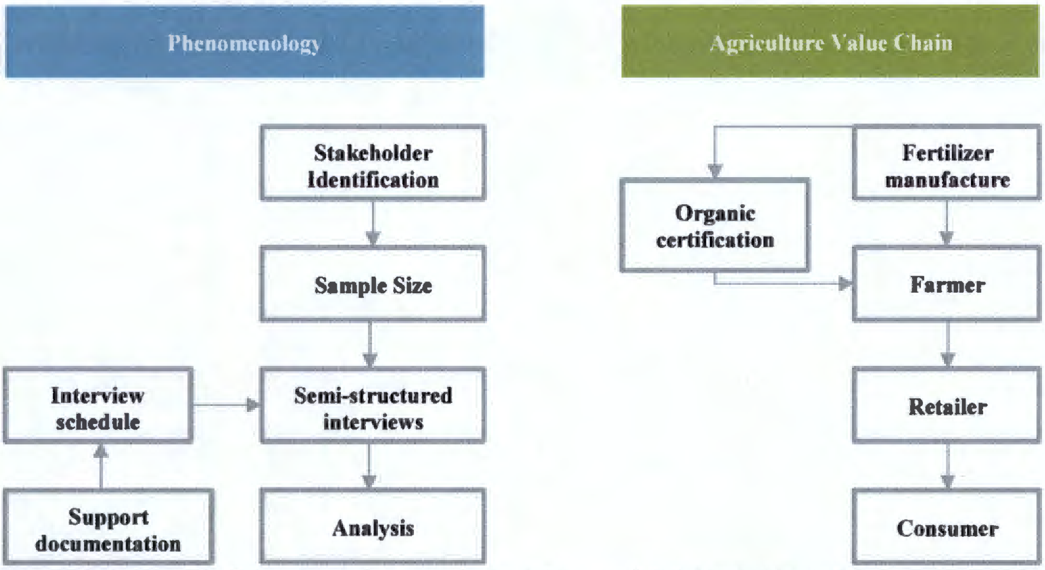


Figure 9: Summary of the phenomenology methodology used (left hand side) and the Agriculture value chain identified (right hand side)

3.2.3 Research ethics

A range of ethical issues was considered for the purposes of Chapter 4 and 5. Acknowledgement of these in stakeholder interviews is summarized in the approved ethics clearance form appended. Mostly importantly, none of this research was presented without the written consent of the interviewees. All findings described are subject to interpretation.

3.3 Techno-economic assessment: methods

This section and its corresponding Chapter 5, present the methodology and results for the techno-economic assessment of phosphate recovery treatment at a biological WWTW with anaerobic sludge stabilization. This serves to address the second research question. Chapter 1 and Chapter 2; the 1st results; Chapter 4, as well as the WRC Report No: K5/2218 by Sikosana et al (2014), gave some background on the potential of phosphate recovery from various side streams and served as a starting point for this prefeasibility investigation. Relevant to this assessment the following was established:

- Crystallisation and wet extractive phosphate recovery processes, from both liquid and sludge process streams, have been built at full-scale globally
- Phosphate recovery from side streams of biological WWTWs with anaerobic digestion is the most promising practice.
- Crystallisation methods are chemical treatments that produce high purity, anhydrous and marketable final products and are becoming the most common and ecological choices to recover phosphate from waste streams
- Crystallisation 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.
- Struvite production units have been installed successfully on small, medium and industrial scale for various reasons, which include: effluent polishing and spontaneous struvite precipitation in pipes and fertilizer shortages.
- Flowrate to phosphate loading ratio is the most important factor affecting the feasibility of profitable struvite production
- Based on case studies: The OSTARA process produces high-grade whereas Multiform Harvest produces low grade, unprocessed struvite (Bilyk et al., 2011; Multiform Harvest, 2014)
- The OSTARA process installed at the HRDS Nansemond WWTP, Virginia (United States) appears to be a sustainable process, which is both fully operational, and economically sound. The nutrient recovery facility treats digester centrate with 140-900 mgPO_4-P/L and recovers 85% of the phosphorus in the digestate. Approximately 1650 kg/day (up to 500 tons per year) of Crystal Green® (struvite) is produced.

3.3.1 Cape Flats WWTW

Based on literature gathered in Chapter 2, treatment of sludge liquor streams in biological WWTWs with anaerobic digestion are the most promising practice for nutrient recovery. In the South African context and more specifically in the Western Cape, the Cape Flats WWTW is a good example of such a treatment facility and forms the basis of this analysis. This 200ML/day facility in Athlone is generally in good condition with upgrades in the past 5 years. However according to the COCT (2010), the sludge handling and maturation ponds need attention. In terms of effluent compliance, the plant achieved 100% compliance to the Ammonia (N) regulations in 2005 and predicted to meet only 33% compliance in 2010 (COCT, 2010). This report forecasted 75% compliance to the phosphate effluent concentrations. Currently, the CFWWTW phosphate effluent averages a value of 5,1 mg/L, 5 times the legislative value. A more detailed description of the CFWWTW is available in Appendix E, Section E.3.

Biological nutrient removal at the Cape Flats WWTW is achieved using the modified 5-stage PhoRedox (Bardenpho) process (Van Rensburg et al., n.d.). Since 1980, thickened waste activated and primary sludge streams are stabilized in 3 anaerobic digesters (operating at temperature of 32-38 degrees, an alkalinity of 2000-3000 mg/L and pH 6.5-7.4). The digestate is supposed to be degritted, mechanically dewatered in a centrifuge and then pelletized in the Thermal Drying plant (TDP) (CDM Executive Board, n.d.; Van Rensburg et al., n.d.), but this privately operated add-on facility to the CFWWTW has experienced frequent technical breakdowns. Therefore the digestate is alternatively lagooned behind the WWTW. When operational, the TDP reduces the sludge volume from 2000 m^3 to 50 m^3, forming pellets that may be used as a fertilizer (Matthews, 2003). Figure illustrates a basic mass balance performed over the plant using literature values as well as the CFWWTW data summarized in Appendix E, Table E.1.

The Cape WWTW has experienced issues with mineral precipitation (mostly struvite) that has led to the poor performance of the digestate centrifuge, as well as blockages in the pipes leading to the Thermal Drying Plant. Batch dewatering processes cause nutrient peaks and instability in secondary processes, hence causing effluent nutrient spikes and spontaneous struvite precipitation (Bilyk et al., 2011). Excess phosphorus in the waste activated sludge (WAS) as well as the loss of CO_2 (which increases pH) along the sludge treatment line are the main causes of struvite precipitation (Van Rensburg et al., n.d.). An additional nutrient sink would recover these excess nutrients to mitigate blockages in the AD sludge centrifuge and pipeline. In addition, based on plant data provided for the period 2012-2014, the TP concentration (July 2014) in the plant effluent is 5,1 mgP/L, which is 5 times the legislative limit of 1mgP/L. The calculated value of 2,44 mgP/L presented in Figure is expected if all plant equipment is working up to design specifications. Where orthophosphate levels are depicted as 0 mgTP/L, they are off neglible magnitude. The plant data secondary treatment effluent is 1,8 mgTP/L, which is still exceeds the legislative amounts. If phosphate removal is implemented, a dccrease in the plant phosphate effluent concentrations will be experienced; whereas phosphate to the TDP is assumed not to be drastically affected. This is because minimal amounts of dissolved orthophosphates enter the TDP unit.

It is important to note that the proposed City of Cape Town (COCT) waste water treatment improvements 7 year Master plan (2012) states that the Cape Flats has a scheduled upgrade in the form of centrate treatment for the period 2012-2013. The current budget for this is between R 3 and R 5 million. A further R4 million per year is to be injected into equipment upgrades for a period of 3 years (COCT, 2012).

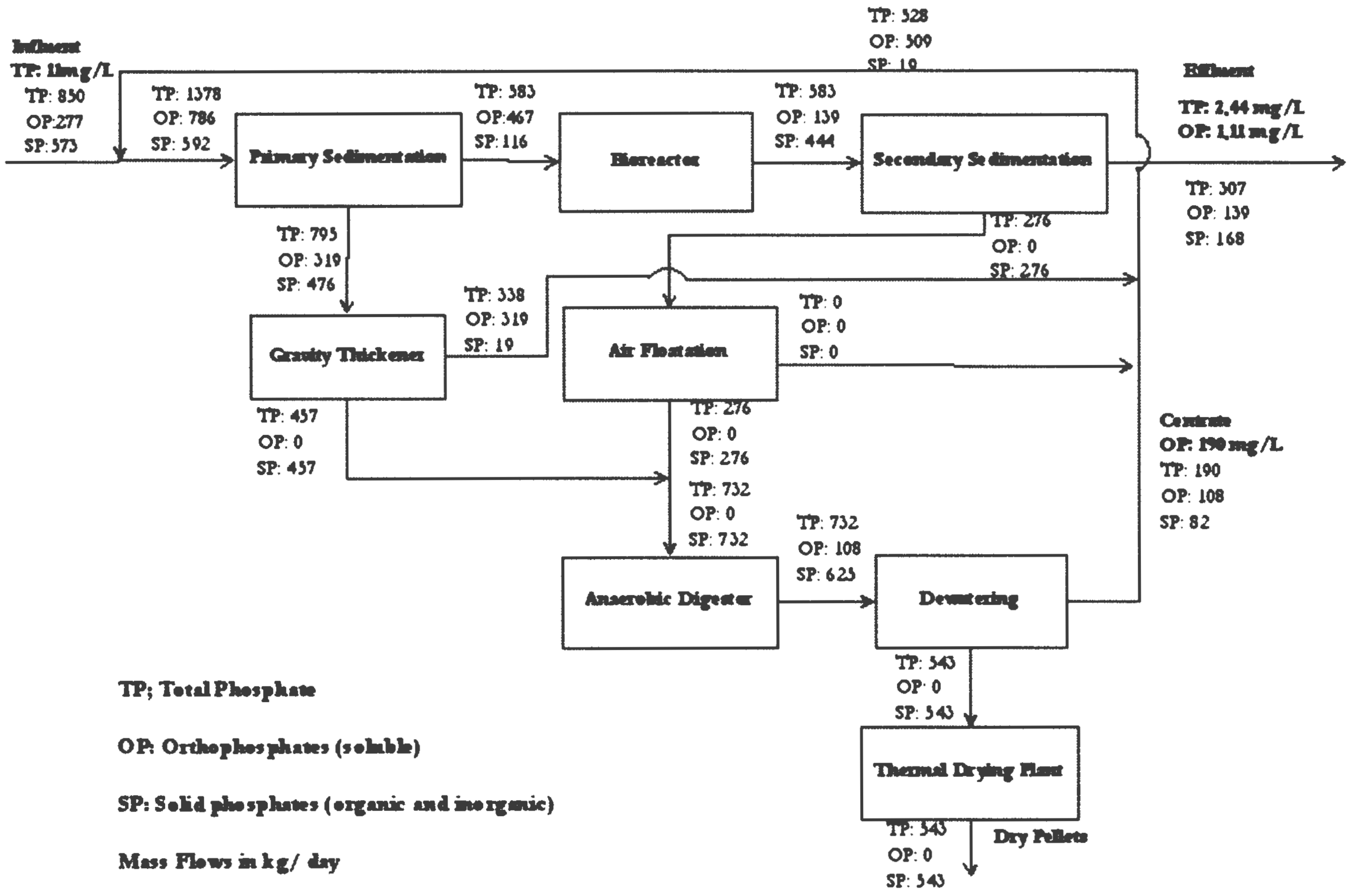


Figure 10: An overview of the Cape Flats WWTW and mass balance calculated based on average flowrates and nutrient concentration

On visiting the Cape Flats WWTW, significant fluctuations in process operations were observed. Therefore, irregularities in plant operations and nutrient concentrations were considered in this study. The following plant inconsistencies were observed as of July 2014:

- Only 2 of the 3 of anaerobic digesters were functioning,
- 2 of the 8 bioreactors were out of commission,
- The air flotation unit was not operational,
- 2 of the 3 gravity screws were operational,
- Digester effluent had a pH of about 4.8, which is low for anaerobic digestion processes,
- The centrifuge is currently out of commission and has been replaced with a belt press,
- Accumulation of water has been observed within the biodigesters, and
- The WWTW is not currently receiving additional sludge from Athlone and Mitchell's Plain WWTW.

Due to these plant irregularities, the process modeling and techno-economic assessment were performed over theoretical, (maximum dry season) plant data and literature with available information for this plant in question and not current plant da

3.3.2 Research approach

This techno-economic assessment consists of the following steps:

- Development of concept designs for three phosphate-focused project interventions at the CFWWTW: the approach to generation of the concepts is discussed in Section 3.3.3 and the concepts themselves are described in Section 5.1. The options involving recovery of marketable fertilizer were linked to the potential South African market routes summarized in Section 4.4.
- Both mass and energy process models, for side-stream treatment at the CFWWTW: methods in section 3.3.4 and results in section 5.2.
- Financial assessment of the three proposed installations: methods in section 3.3.5 and results in section 5.3.

3.3.3 Concept design

The objective of this part of the study is to assess the potential for struvite production as a viable side stream treatment option at the Cape Flats WWTW. Comparison is then made with the more traditional tertiary chemical precipitation.

Conceptual designs for these three options were developed for the purposes of techno-economic pre-feasibility criteria. The approach to conceptual design involved:

- Generation of three distinct alternatives, informed by the technology review and case study analysis (in Sikosana et al. 2014) as well as knowledge of the configuration of the CFWWTW;
- Development of process flow diagrams and process summaries;
- Linking the potential products to the market routes identified in Section 4.4.

Three process options

Two struvite production nutrient recovery systems, to produce high quality and low quality struvite, respectively, were considered. These concept designs for high- and low-grade struvite production were based on case studies of the OSTARA and Multiform Harvest installations respectively mentioned in Section 2.2.8 and described in the WRC report K5/25114 (Sikosana et al., 2014). These were then related and integrated into the various market routes accessible in South Africa (Section 4.4). The third option is that of a more traditional chemical precipitation process to reduce phosphate levels.

3.3.4 Technical evaluation

Option 1, 2 and 3 were then evaluated based on the following key technical criteria:

- Production rate of solid products (kg/d and kg/year)
- Energy use (kWh/d)
- Chemical consumption rates (kg/d)
- Land requirements (m^2)
- Additional labour requirements (over and above the needs for the existing WWTW)
- Additional maintenance requirements (over and above the needs for the existing WWTW)

Process modeling: material balance

For all three-side stream treatment options, an excel worksheet model was developed to simulate the potential recovery processes and struvite as well as excess sludge production potential of the waste water treatment plant. These sheets are summarized in Appendix F, Section F.1 and F.2. Process models were based on the design basis and criteria presented in Table 13, Table 14 and Table 15 below. A maximum theoretical conversion of 90% for all three options was used for comparative purposes.

Table 13: Summary of design basis used for calculations

Description	**Unit**	**Value**	**Comment / Source**
CFWWTW Flowrate	ML/day	125	Plant data (average)
Side stream DS %	%	3,5	Plant specifications
Side stream flowrate	m^3/day	1060	Calculated from maximum design capacity of dewatering centrifuge
Side stream pH		4.8	Plant data
Phosphate concentration	mg/L	89-190	Used highest loading (Van Rensburg et al., n.d.)
Magnesium concentration	mg/L	29-67	Used highest loading (Van Rensburg et al., n.d.)
Ammonia concentration	mg/L	In excess	Assumed
Option 1 conversion	%	90	(Rahman et al., 2013)
Option 2 conversion	%	90	(Rahman et al., 2013) and (City of Yakima, 2014)
Option 3 conversion	%	90	(Strom, 2006); (Minnesota pollution control agency, 2006)

Table 14: Conceptual design criteria for process options 1 and 2

Description	Unit	Value	Source/comment
Molar feed ratio PO4:Mg	mol:mol	1:1,2	(Rahman et al., 2013)
Reactor conversion	mol%	90%	(Rahman et al., 2013) De-Bashan & Bashan (2004) (Quintana et al., 2008)
Reaction Kinetics	h^{-1}	7,9	(Rahman et al., 2013) (Ohlinger et al., 2000)
pH		8,7	(Ohlinger et al., 2000)
Moisture content of filtered struvite	g/g (Water dry Solids)	1.5	Assumed
Temperature		25 °C	Ambient

Table 15: Conceptual design criteria for all process options 3

Option 3			
Molar feed ratio PO_4:Al (orthophosphate: aluminium)	mol:mol	1:1	(Strom, 2006) (Minnesota pollution control agency, 2006) (Lenntech, 2005)
Reactor conversion	mol%	90%	(Strom, 2006); (Minnesota pollution control agency, 2006)
pH		Maintain	(Lenntech, 2005)
Residence time	min	5	(Mohammed & Shansool, 2009)
Temperature		25 °C	Ambient
Clarifier effluent DS	%	5	(UNEP, 2001; Bowers, 2011)
Dewatered sludge DS	%	25	(Turovskiy & Mathai, 2006)
Excess TSS removal	%	25	(WEF, 2005)

Equipment sizing

The results of the material balance, presented in Section 5.2.1, determined the design capacities for all three process options and allowed for the sizing of key plant equipment which includes:

- the struvite precipitation reactor;
- feed and effluent storage tanks;
- auxiliary plant equipment (pumps and driers); and
- struvite processing equipment

Storage tanks, pumps, driers and other processing equipment were designed based on heuristics for chemical engineering plant equipment presented in Turton et al (1998), chapter 8 and 9. Detailed sizing calculations are summarized Appendix F, Section F.5.

Existing onsite waste water clarifiers, air flotation and centrifuge units can serve as flowrate equalizers. For the purposes of this prefeasibility study, it was assumed that all process units for the proposed nutrient recovery facility would be purchased and installed.

Reactor sizing and reaction kinetics

Reaction kinetics and an average influent range described in Table 13 were used to estimate the reactor sizes for option 1 and 2 at various recovery rates. The anticipated reactor size at various process conditions was established. This was compared to the OSTARA Pearl© reactor sizes on the market and the costs estimated accordingly (see Section 5.3). The following design criteria and major assumptions were used:

- The Fluidized bed reactor can be modeled as a non-ideal plug flow reactor with a dispersion factor (Sinnott, 2005).
- Decrease in conversion due to axial dispersion was ignored and therefore modeled as an ideal PFR.
- The reaction rate was taken to be 1st order in respect to magnesium.
- The reactor zone and volume of OSTARA Pearl© reactors are preset (Bilyk et al., 2010; OSTARA, 2013).
- Multiform reactor sizes and volume are based on plant design criteria (Barbeau et al., 2009; Bilyk et al., 2010).
- Both Option 1 and 2 are designed to produce the same mass of struvite per pass, but will differ in product quality. Option 1 has a recycle system and an additional drying step.

Energy use

The process model presented in Section 5.2.3, alongside chemical engineering heuristics in Turton et al (1998) were used to calculate energy consumption in kWh/year.

Land requirements

Land footprints were calculated based on the space requirements of predetermined OSTARA Pearl© 2000 reactor set-ups described in the OSTARA product brochure presented in Appendix F, Section F.7.

Operations and maintenance

Considering the size and automated nature of the plant, various assumptions were made in determining plant operations and labour requirements.

3.3.5 Financial analysis

Based on the struvite production rates and chemical input requirements, engineering economic calculation methods were used to evaluate the financial feasibility of struvite production at the CFWWTW. These are described in Section 4.3. Current market prices for caustic soda and magnesium (both magnesium oxide and chloride) were taken into account. Additional cost estimates used are summarized in Table 16. The potential selling price of struvite was established using current phosphate fertilizer prices on the market. The economic viability of struvite production was assessed based on the following economic indicators:

- Plant establishment costs: Capital expenditure (CAPEX)
- Operating expenditure (OPEX)
- Cost recovery from struvite production (revenue)
- Net present value/net present costs (NPV/NPC) costs over a 20 year investment period

Table 16: Economic assessment criteria for all options

Description	Unit	Value	Source/comment
Price of magnesium chloride	R/kg	8.30	Protea Chemicals, 2014
Price of aluminium sulfate	R/kg	1,16	
Price of electricity	R/kWh	1.00	Within range of peak/off-peak charges from COCT for commercial users
Wages	R/h	80.00	Assumed
Water	R/kL	12.51	COCT website
Transport and disposal of solid biosolids	R/kg	0.5	(Sikosana et al., 2014)
Maintenance costs		4%	chemical precipitation (Tetra Tech, 2013)

Estimation of Struvit prices

Struvite prices were calculated using a least-squares regression on phosphate and nitrogen concentrations against current South African fertilizer prices (MAP, MAPZ, DAP, Palfos, FMP) summarized in Appendix G, Section G.4.This technique was similar to what was reported in the WRC report by (Sikosana et al., 2014), but use more phosphate fertilizer and more recent market prices. These costs do not include, packaging, water content or delivery costs and are representative of the absolute dry cost of struvite.

CAPEX estimations

Option 1 and 2 capital costs were estimated using the flow capacities of existing OSTARA and Multiform Harvest setups. CEPI indices were accounted for and the capital costs scaled using the sixth tenths rule. These calculations are summarized in Appendix G, Section G.1.

For Option3, chemical costing information available in the Tetra Tech (2013) cost estimate of phosphorus removal at waste water treatment plants report was used for the CAPEX estimates. This document uses cost data from various case studies with expansion and retrofit projects for phosphate removal. Costs were generated through a cost estimating software, CAPDETWorks, which estimates WWTW CAPEX and corresponding OPEX for phosphate removal equipment (within a 20% range of the actual plant costs). A linear relationship between phosphate loading, reactor size and cost was assumed. Parameters used for the CAPEX calculations are summarized in Appendix G, Section G.2.

OPEX estimates

For all three options, variable costs associated with electricity and chemical use were calculated based on the mass and energy balances presented in Section 5.2.1 and 5.2.3

The OPEX for Option 3 was compared to the operating costs calculated using the Tetra Tech (2013) estimates. The USEPA (1997) report describes non-linear costing CAPEX and OPEX equations for chemical precipitation treatment technologies, based on data available in the USEPA (1989) design manual for phosphorus removal. The CAPEX and OPEX generated from these costing equations (Appendix G, Section G.2, Table G.5 and Figures G.1 and G.2) were investigated in the sensitivity analysis section 5.4.

3.3.6 Sensitivity analysis

Baseline techno-economic evaluations were done on a 1st order basis. Therefore, it is necessary to consider to what extent variations in process parameters would affect the techno-economic analysis. This will aid in identifying which parameters have the highest effect on the economic performance and hence feasibility of the nutrient recovery facility as well as how best it can be controlled. This section varied and assessed the impacts of the following key parameters: on the NPV costs and hence the proposal feasibility:

- reactor sequence and choice (Option 1- OSTARA);
- maintenance costs (as a percentage of CAPEX);
- retail price of struvite fertilizer (Option 1 and 2);
- CAPEX (all options);
- pH and corresponding reaction rate (in the same reactor);
- plant equipment availability for Option 3 operations;
- sludge disposal Options and price; and
- discount rate

All of these parameters, with the exception of sludge disposal, struvite selling price and discount rate, were varied over a range from -50% to 100% increase and their effect on NPV compared to the base case.

4 Social assessment: results and discussion

Chapter 4 is one of two chapters of results, which addresses the first research aim: an assessment of the marketability of fertilizers derived from human waste in the emerging South African markets. These observations provide a basis for technology selection, potential market avenues and struvite selling prices within the South African context. Essential information used in techno-economic assessment of nutrient recovery treatment technologies is presented in Chapter 5.

Section 4.1, gives an overview of the organic agriculture scene in South Africa. Findings from the expert semi-structured interviews were summarized into the following themes: Quality, Health and Safety (Section4.2.) and Social acceptance (Section 4.3). Combining literature and interviewee statements, viable market routes were mapped for the South African context and are summarized in (Section4.4).

4.1 Organic fertilizer and food security

Potential in the organic market

FRIDGE (2008) identified organic agriculture as the fastest growing market, after baby food in the South African food industry. Entry of fertilizers from human waste into premium markets, which are typically more expensive than conventional inorganic fertilizers, could increase the economic viability of phosphate recovery and reuse from waste streams. Views of the organic accreditation expert A, verify that farmers will continue to opt for organic practices due to "bad experiences with agri-chemicals". However it is believed that this practice may only be sustainable for smallholder farmers and that large-scale organic farming is not sustainable. In the same breath, both the Agronomical expert A and B identify organic certification as a hindrance to smallholder farmers.

Organic and inorganic phosphate fertilizers from waste streams

Animal manure and human excreta have been used extensively as an organic fertilizer on a global scale (Liu et al., 2008). Urine and faeces streams are source separated and stored for further use. Phosphorus, nitrogen, potassium and other micronutrients in faeces are returned to the soil organically by composting, whereas urine is either converted into struvite or used directly as an organic fertilizer (Ganrot, 2005; Etter, 2009). Phosphate fertilizers from wastewater are comparable to soluble inorganic fertilizers on the market (Gell et al., 2011). Studies done by the local agronomical expert A, revealed that struvite is indeed comparable, more so to triple super phosphate TSP with a 6% Phosphorus content. According to the Organic Certification expert A, phosphate rock, an inorganic input, is acceptable in organic agriculture. Therefore, struvite may be an acceptable inorganic input, in organic agriculture practices, but it is dependent on the source of magnesium used in the processing step. It is however argued by the organic certification board member B, that struvite production is an agro-chemical rather than organic farming input. Therefore, the placement of struvite in the fertilizer market is not fully known.

What is the organic agriculture scene in South Africa?

Both the agriculture and organic certification boards confirmed that South Africa does not have any set organic agriculture policies in place. Therefore, organic certification standards in South Africa are registered through a private bureau of standards. All fertilizer products are to be registered under ACT 36, but must be approved for use in organic agriculture by a registered certification board. This contradicts a statement by the Department of Agriculture, Forestry and Fisheries (2005) that there are no legal requirements for organic produce to be certified in South Africa. There are 8 private organic certification companies in South Africa, the largest of these is African Farms Certified Organic (AFRISCO) (Rundgren & Lustig, 2005). According to an AFRISCO member, 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. Although the IFOAM basic standards under the Codex Alimentarius Commission Guidlines (CAC/GL) 32 (Kilimohai Organic, 2007), have guidelines for use of human excreta as organic fertilizer, (Section 4.4.5: **Human excrement shall be handled in a way that reduces risk of pathogens and parasites and shall not be applied within six months of the harvest of annual crops for human consumption with edible portions in contact with the soil.**), the compliance to the EU standards (Section 5(2) (e): **Manures containing human excrement (faeces and urine) shall not be used** (AFRISCO, 2012)) does not allow the use of human waste of any form; therefore organic certified farming for food production is not a viable market route for fertilizers derived from human waste. The AFRISCO member and the organic farming expert stated that the biological farmers association of South Africa (BioSA) may be an alternative market opportunity as they have less stringent organic standards, with a larger emphasis on holistic farming practices. However, contrary to this statement, a BioSA member indicated that similar standards are observed and will not endorse human waste as a fertilizer source for food production.

According to the agricultural expert, human waste derived fertilizer may enter the food production industry via participatory guarantee systems (PGS); networks of farmers and customers with a trusted and transparent set of standards, for small-scale food markets. However, it was argued by the AFRISCO member that this route is limited to the local market and may bar produce from any future organic certification, hence limiting exportation opportunities. This is not favourable, since the domestic market price policies have been described to be such that it is more profitable to sell organic produce overseas (UNEP, 2007). Overall, most parties agreed that community scale gardens are the most viable food production routes, if economically feasible.

4.2 Quality, health and safety

All respondents highlighted, regardless of the market avenue chosen, that health and safety is their top concern. According to the fertilizer expert interviewed, if the commercial production route is chosen, the source of phosphate would not be important, however purity as well as health and safety are important considerations. Also, farmers would be willing to use struvite if the necessary guidelines are stated. The phosphate recovery expert A and organic expert A believe that the same could be said for the direct use of sterilized urine. 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 (Johnson & Richards, 2003; Cabeza Perez et al., 2009; Gell et al., 2011). Despite health and safety concerns, it is likely that struvite will pass toxicity, pathogen and metal content regulations (Gell et al., 2011). In terms of quality, struvite is comparable to most phosphate fertilizers on the market (Barak & Stafford, 2006; Gell et al., 2011; VUNA, 2013).

4.3 Social acceptance

Although most stakeholders recognized the importance of phosphate recycling in tackling food security and achieving sustainable water and nutrient cycles, the South African markets and retail consumer may not to be ready for fertilizers produced from human waste least of all the organic production route which might well bar them. As stated by a Biodynamic association member *"There is also an issue with local belief systems and ethical systems, where human waste is seen as unacceptable, while animal waste is not."*

This illustrates that acceptability may be subject to the source of recovered phosphate, whether it is wastewater, sludge or urine. The organic farming expert A and phosphate expert A, are fully accepting of the direct application of urine and urine derived struvite as a source of phosphate. However, not much commentary was made by the other stakeholders as to whether the source from which struvite is derived urine and wastewater) would affect social acceptability.

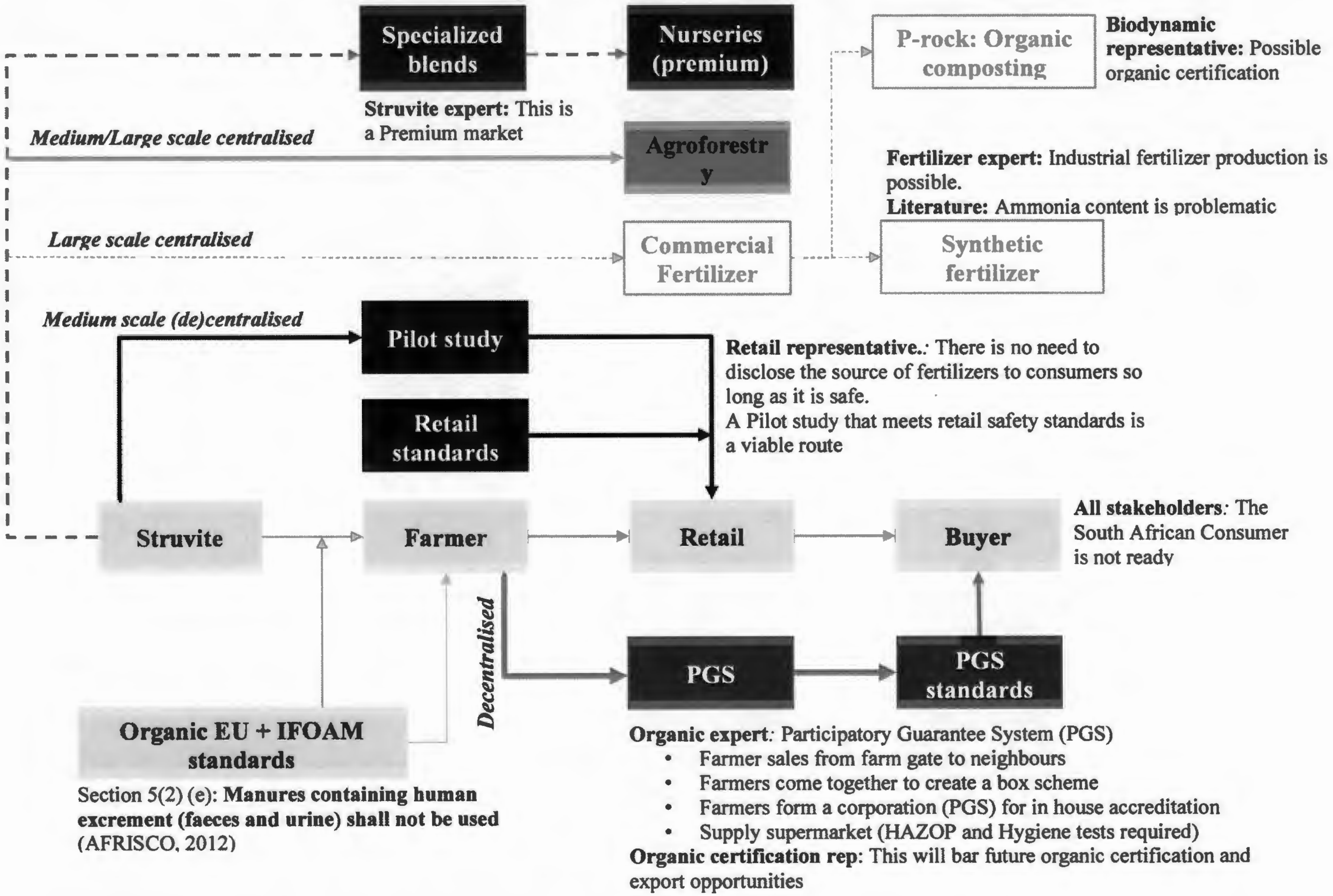
It is believed by the fertilizer production expert, that acceptability in the fertilizer processing industries would be good, as the source will not be important to the manufacturing companies, if it is proven to be safe. Therefore, social acceptability will vary between the organic and inorganic industries and their target consumers.

4.4 Alternative market routes

According to the fertilizer experts and academics interviewed, phosphates recovered from the various sources (specifically struvite) may enter the following markets:

- As a source for industrial commercial fertilizer production;
- Small community garden projects / Participatory Guarantee System (PGS);
- Specialized ornamental plant (non–food products) fertilizer blends and
- Replacement of phosphate rock for organic composting

Studies by Nawa (2009), Kern et al. 2008, Gell et al. (2011), illustrated that as a fertilizer, struvite could be used directly or as a specialty fertilizer in nurseries as well as a component for agricultural fertilizer production. However, the phosphate recovery expert B feels it is not possible to sell phosphorus as a stand-alone fertilizer constituent as the quantities are too small for the commercial market. Although it has been suggested that struvite could be ideal for industrial processes, it is argued by Schipper et al. (2001) that it has limited applications in electro–thermal processes due to its ammonia content. Ammonia could cause serious gas scrubbing and emission issues in the sintering stages of industrial processes. These processes include detergent, fire retardant and fertilizer production processes. Figure 11 summarizes the possible market avenues 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.



Struvite expert: This is a Premium market

Biodynamic representative: Possible organic certification

Fertilizer expert: Industrial fertilizer production is possible.
Literature: Ammonia content is problematic

Retail representative.: There is no need to disclose the source of fertilizers to consumers so long as it is safe.
A Pilot study that meets retail safety standards is a viable route

All stakeholders: The South African Consumer is not ready

Section 5(2) (e): **Manures containing human excrement (faeces and urine) shall not be used** (AFRISCO, 2012)

Organic expert: Participatory Guarantee System (PGS)

- Farmer sales from farm gate to neighbours
- Farmers come together to create a box scheme
- Farmers form a corporation (PGS) for in house accreditation
- Supply supermarket (HAZOP and Hygiene tests required)

Organic certification rep: This will bar future organic certification and export opportunities

Figure 11 Summary of feasible market avenues based on expert interviews and literature, in the South African context

4.5 Conclusions

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. A participatory guarantee system was suggested as an alternative route to enter the food production market, but was disputed 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 lie within ornamental plant and commercial inorganic fertilizer production, and possibly also in community scale gardening. This shows that there is potentially a larger market for lower grade fertilizer derived from Human waste, for use in secondary, non-food markets. This is in line with what was hypothesized.

5 Techno-economic analysis: results and discussion

Chapter 5 is the second of the two results chapters and serves to address the second key research question: **Would the installation of a nutrient recovery technology at a centralized biological WWTW equipped with anaerobic sludge stabilization, be an economically viable side stream treatment technique in the South African context?** To answer this question, a techno-economic feasibility analysis was performed on three concept designs for meeting the phosphate discharge specification of a typical large WWTW. The Cape Flats WWTW in the Western Cape is the basis for this study. Linking to the social-techno-economic assessments, vital information pertaining to the marketability of struvite and the corresponding market routes in South Africa context described in Chapter 4 was used for the initial part of this assessment.

Section 5.1 describes the concept overview of three proposed side stream treatment options, which include: high and low-grade struvite production (Options 1 and 2) as well as conventional chemical precipitation (Option 3). The potential market routes of products from Options 1 and 2 are assessed in accordance with the research findings of the emerging South African markets summarized in Section 4.5.

Based on the concept designs in Section 5.1, technical assessments, for Option 1 and 2, are presented in Section 5.2. These include estimates of expected struvite and sludge production, major plant equipment sizes as well as land and energy requirements. Based on these findings, the cost implications of all three options were investigated and are compared in Section 5.3. The financial assessments consider CAPEX (Section 5.3.1), OPEX (Section 5.3.2), projected cash flows (Section 5.3.3) and life cycle costs in the form of an NPV (section 5.3.4). This is in line with the economic assessment criteria described in the methodology section 3.3.5. In Section 5.4 the sensitivity of the NPV for all three process pptions are tested against a range of variable process parameters. In closing, Section 5.5 discusses and summarizes the main findings of this assessment.

5.1 Concept design

5.1.1 Concept design overview

The CFWWTW anaerobic digester liquor stream has a phosphorus concentration of 89 to 190 mg/L and Mg from 29 to 67 mg/L (Van Rensburg et al., n.d.) as well as a design flowrate of approximately 1060 m^3/day. Given that struvite production will lower recycled phosphate amounts, a lowered steady-state concentration will be experienced at the CFWWTW. This phosphate concentration can only be lowered and will be within the phosphate loading limits of the reactors which are designed at worst case scenario (highest possible loading). Figure illustrates the potential product market routes in relation to the findings in Section 4.

Option 1: Similar to the OSTARA model described in Section high quality struvite may be formed by incorporating a recycle stream within the reactor. The produced struvite granules are dried (pelletized) and packaged onsite (to 92% DS) before distribution to viable markets for agronomical use. High quality struvite may be suitable for use in specialized blends for nurseries, a premium market as shown in Section 4.4.

Option 2: The Multiform Harvest process produces a less refined product (40wt% DS), which is collected from the bottom of the reactor into a skip (with a filter). This skip is collected weekly from the WWTW and may be further treated off-site before sale in secondary markets. The conical fluidized bed reactors are typically smaller than the OSTARA installations, with a lower retention time and do not require recirculation pumps. In addition, no drying or bagging equipment is required which drastically reduces capital costs.

Option 3: Tradition chemical precipitation is an efficient method of phosphorus removal. In this case, the addition of aluminium sulfate as a coagulant in the side stream was considered and compared to the above Options on an economic basis. Aluminium was used, as it is non-toxic, easy to handle and the least corrosive of the metal Options. The typical post precipitation set-up involves the installation of a flash tank and clarifier for solids separation. The sludge produced would be filtered, dewatered and either transported to landfill or treated further.

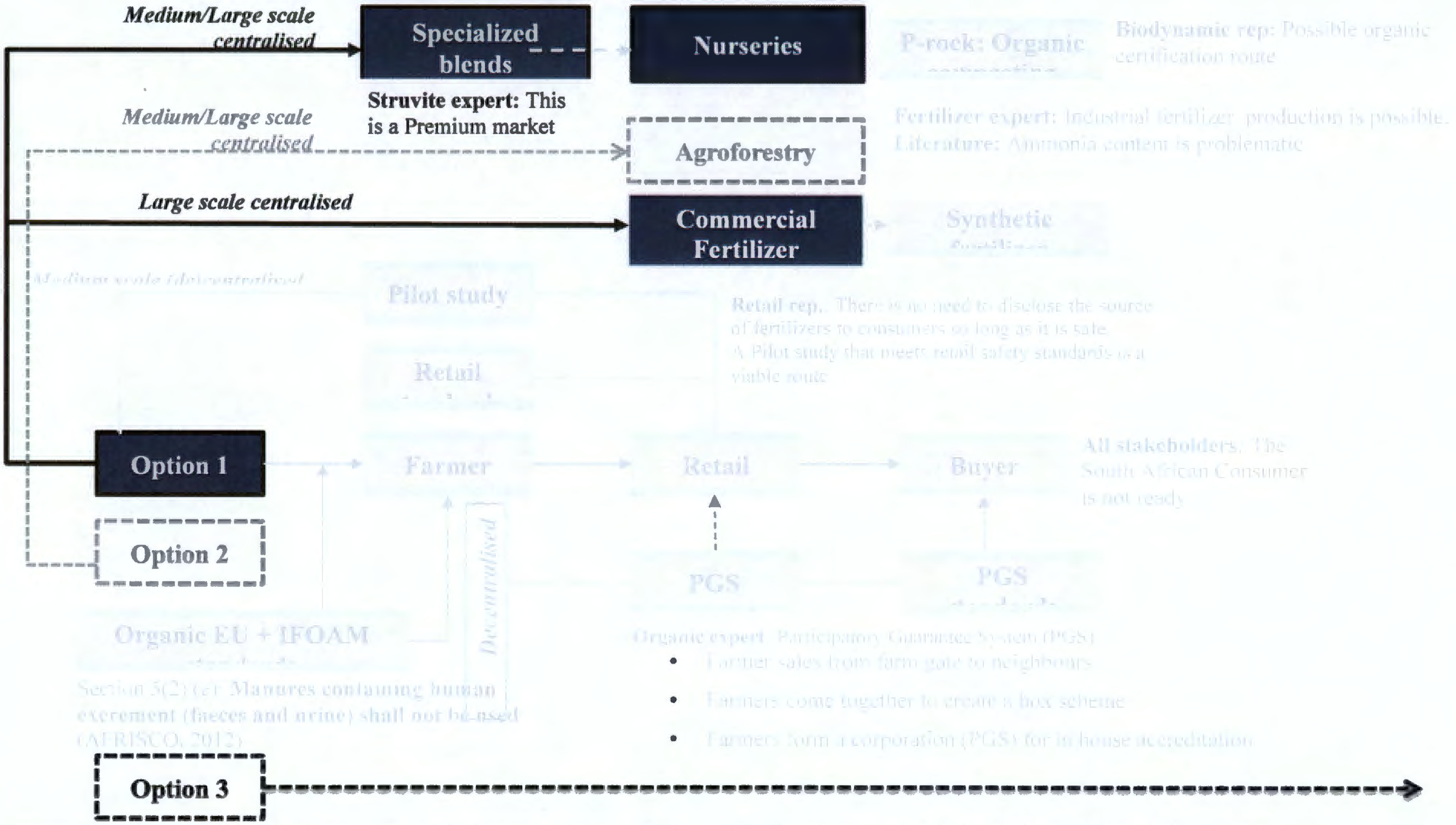


Figure 12: Illustrates the viable market routes of the treatment process Options 1, 2 and 3, based on the grade and form of phosphate produced

5.1.2 Flowrate analysis: side stream design flow

The feed ntering the CFWWTW fluctuates between 115-134 ML/day. The max design capacity for the plant is 200 ML/day at a typical phosphate concentration of 11 mg/L. This translates to a total daily phosphate loading of 1378 kg/day.

Due to the current plant inconsistencies theoretical and literature information was used to estimate relevant concentrations and flowrates. Based on the theoretical design specifications of the dewatering centrifuge and the average plant flow rate, a design side stream flowrate was calculated to be 1060 m^3/day, which is about 0,8% of the current influent flow. Process streams, particularly liquor from anaerobically digested sludge are typically 1% of the plant influent flowrates (Bilyk et al., 2010).

5.1.3 Process summaries

In the case of Option 1 and 2, the process side stream is diverted to a precipitation reactor via a buffer storage tank. Magnesium in the form of MgCl, together with NaOH (caustic soda) for pH control, are fed into the struvite precipitation reactor. In Option 1, Figure 13, struvite is dried and bagged for distribution, while the filtrate is recycled back to the plant head with the rest of the WWTW supernatant.. In the case of the simpler Option 2's recovery system, Figure 14, the drying step onwards can be ignored and the struvite is sold wet and unprocessed to secondary markets. Option 3, demonstrated in Figure 15, requires a mixing tank, into which aluminium salt, and lime for pH control, are fed for precipitation. The sludge produced is dewatered and then disposed of. The liquid effluent is recycled back to the primary treatment section of the plant.

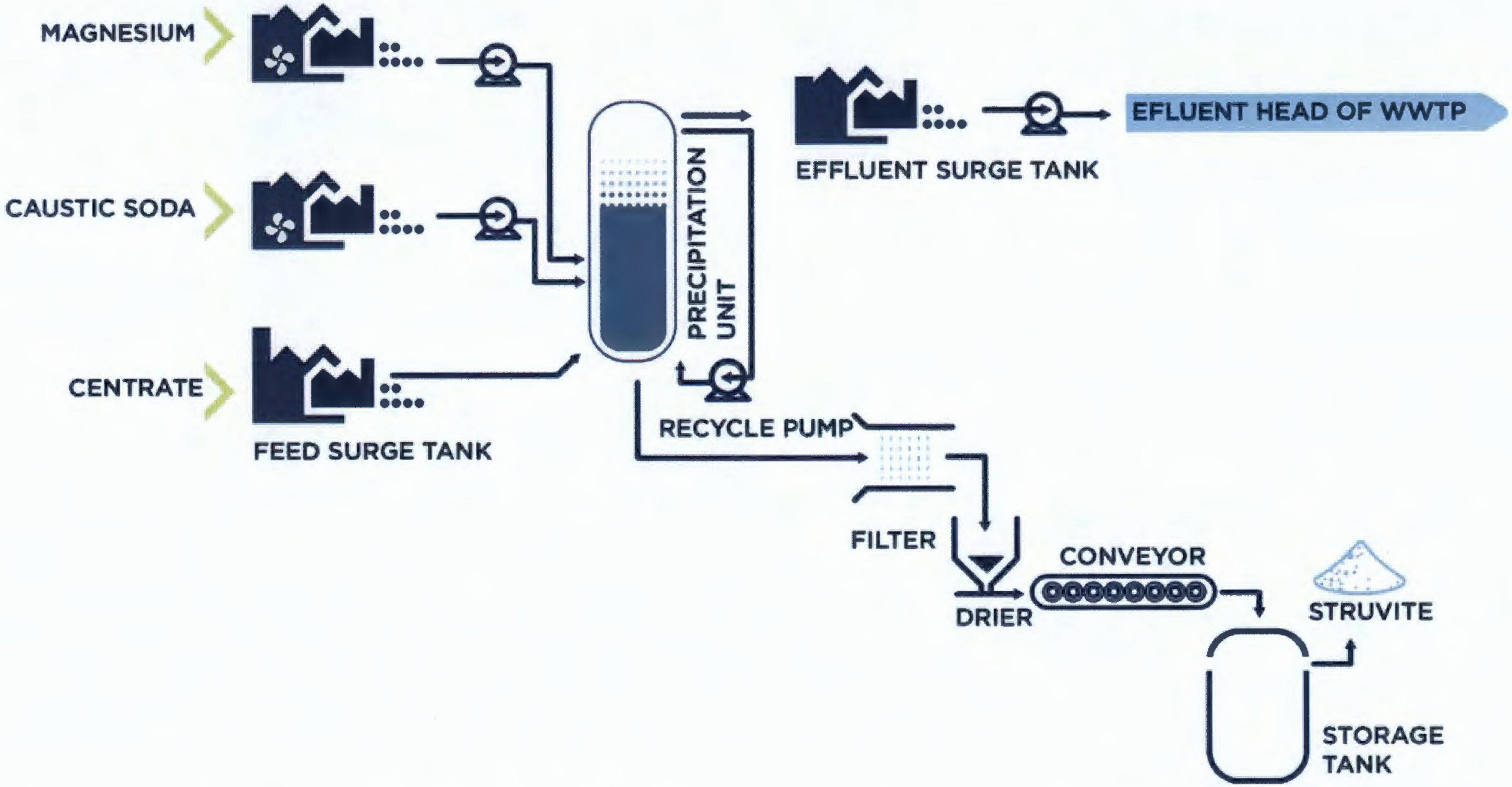


Figure 13: Process description of nutrent recovery facilitty to form high quality struvite prodcution that is processed and packaged onsite

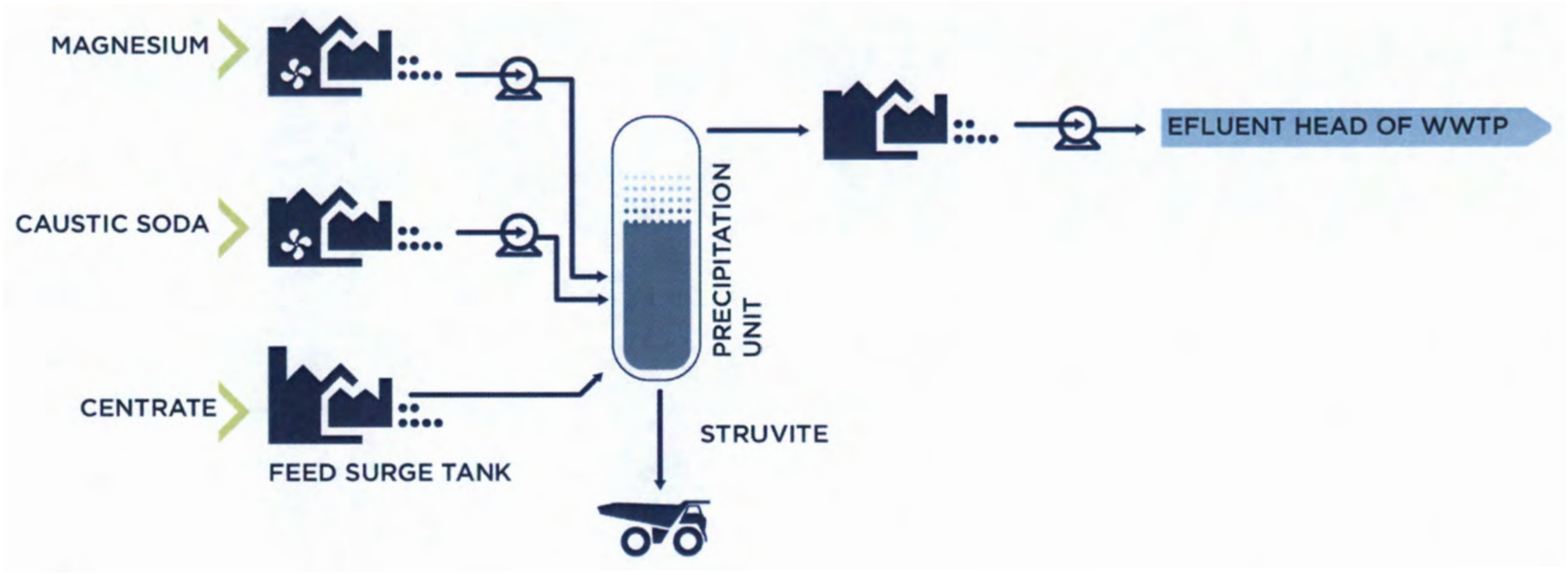


Figure 14: Process description of Option 2 to produce low quality struvite that is transported offsite unprocessed

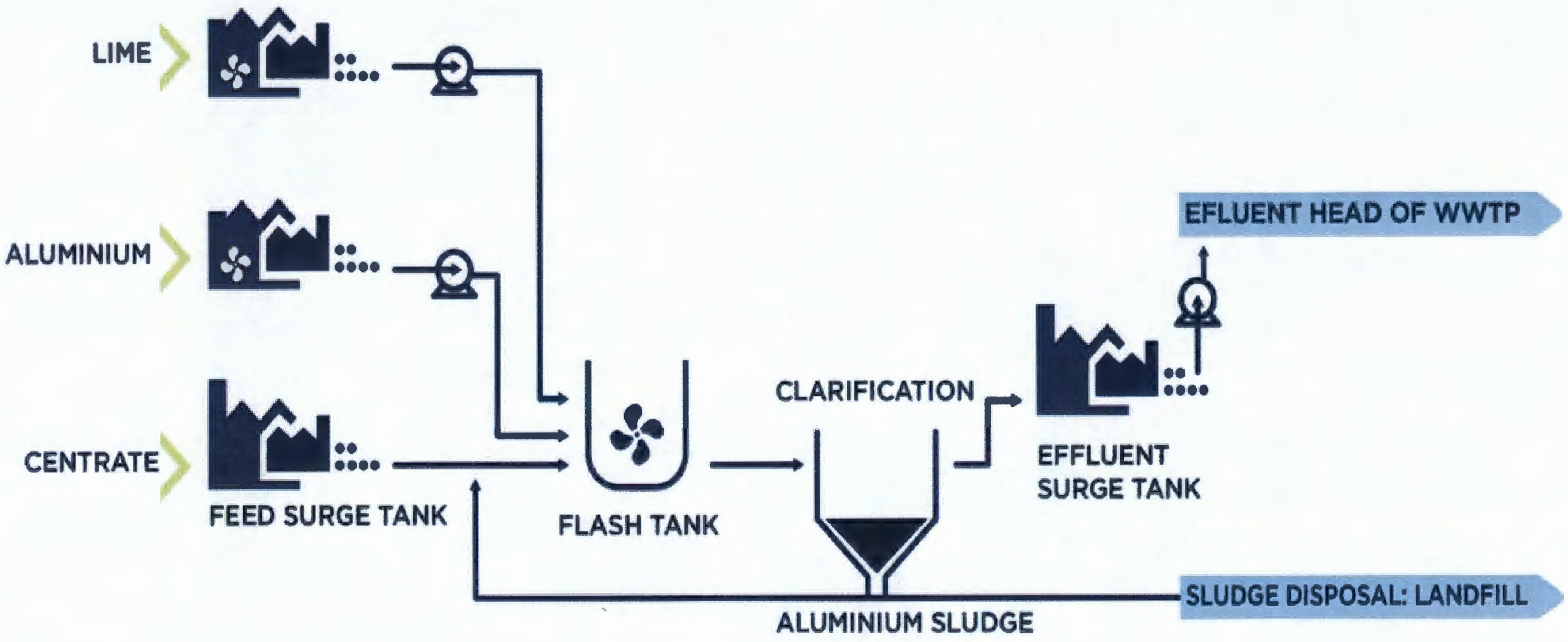


Figure 15: Process summary of traditional tertiay chemical precipitation

5.2 Technical assessment

5.2.1 Process model (material balances)

Mass balances were performed across the proposed nutrient recovery and removal set-ups and are based on the design criteria presented in Table 13 - Table 15. The process models used a design flowrate of 1060 m3/day and maximum loading rates of 190 mg/L of phosphate and 67 mg/L magnesium respectively. Table 17 summarizes the material balance results for the three process models.

Table 17: Summary of material balance done over the three process options

	Unit	**Option 1 and 2**	**Option 3**
Struvite production dry	kg/day	469	N/A
Struvite production wet (40% DS)	kg/day	1173	N/A
Packaged struvite dry	kg/day	510 (92% DS)	568 (80% DS)
Aluminium phosphate	kg/day	N/A	233
Aluminium hydroxide	kg/day	N/A	9,34
Sludge production (wet: DS 25%)	Kg/day	N/A	2400
Ortho-phosphate recovered	kg/day	182	182
Phosphorus recovered	kg/day	59,0	59,0
Dosing			
Aluminium sulfate (dry)	kg/day		1260
Alum solution (48 wt%)	kg/day		2630
Magnesium chloride	kg/day	162	N/A
Magnesium solution (30wt%)	kg/day	540	N/A
Magnesium oxide	kg/day	69	N/A

For both Option 1 and Option 2, approximately 469 kg/day of struvite is produced (on a dry basis), recovering 58 kg/day of phosphorus at a 90% conversion rate. This will require approximately 162 kg/day of magnesium chloride or 69 kg/day of magnesium oxide. When packaged and dried, this amounts to 510 kg/day (92% DS) high-grade struvite and 568 kg/day (80% DS) low-grade (wet) struvite. Magnesium oxide would be preferable but as described by Rahman et. al (2012), magnesium chloride results in high efficiencies in phosphate and ammonium removal.

Chemical precipitation results in 242 kg/day of chemical sludge (aluminium hydroxide + phosphate) and an additional 25% suspended solids removal (WEF, 2005), to give 601 kg/day of dry sludge. Once mechanically dewatered to 25% dry solids, 2400 kg/day excess sludge is to be disposed of. This is an 0,2 % increase in the overall Cape Flats sludge production. Aluminium solution dosage is about 2630 kg/day, 5 times that of magnesium dosing material. These mass balances form the basis for the equipment sizing and the subsequent CAPEX and OPEX calculations. Corresponding phosphorus and elemental balances were performed on the process models and are summarized in Appendix F, Section F.1.

5.2.2 Equipment sizing; Option 1 and 2

Reactor sizing: Option 1 and Option 2

For Struvite formation, the fludized bed reactor (FBR) was modeled as an ideal plug flow reactor. The Cape Flats WWTW centrate has half the maximum orthophosphate loading and a volumetric flowrate 2.3 times larger than that processed in the OSTARA Pearl unit in the case study described by Sikosana et al. (2014) (WRC K5/ 2218). Based on first order kinetics, the following design Equation 5-1 was used to evaluate reactor size.

$$\partial V = \frac{\vartheta_0}{k(1-X)} \partial X \qquad \text{Where } k = 7{,}9 \text{ hr}^{-1} \quad \vartheta_0 = 40 \text{ m}^3/\text{hr} \qquad \text{Equation 5-1}$$

Where: V = reactor volume; ϑ_0 = volumetric flow rate (m^3/hr); X = conversion and k= reaction constant

In the case of a first order reaction rate, reactor size is a factor of volumetric flowrate and conversion, and is independent of orthophosphate loading. A reaction constant of $k=7{,}9\ hr^{-1}$ was used to generate the reactor design graph in Figure at pH 8,7 and ambient temperature. To achieve 90% conversion, a 50,3 m^3 reactor is required, with a 75 minute retention time. Literature stipulates that full crystal growth can occur in under 3 hours. The resulting reactor design curve is illustrated in Figure 16.

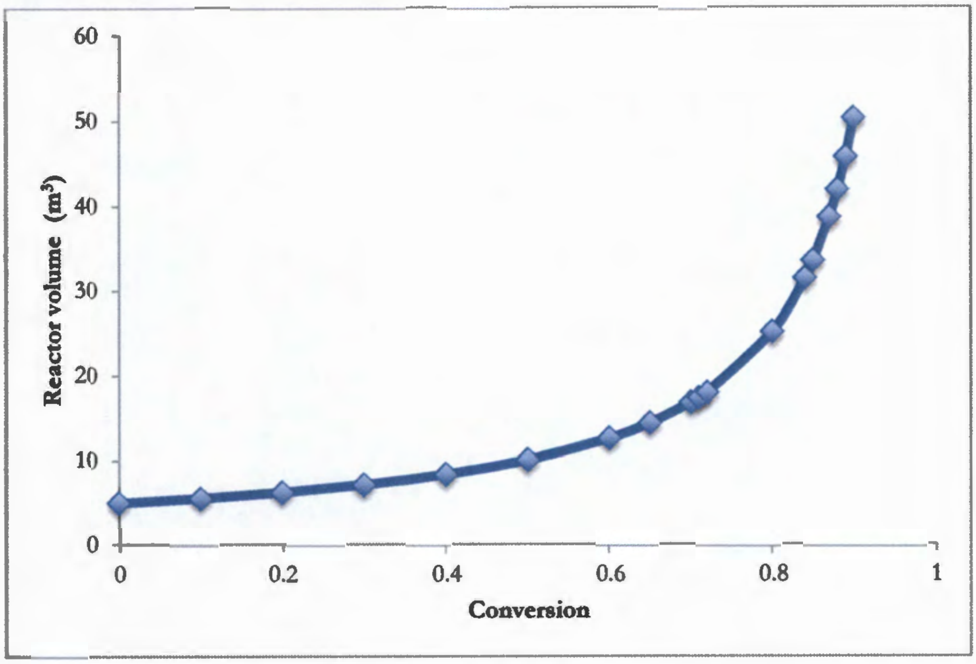


Figure 16: Reactor volume as a function of conversion for the Cape Flats specifications

The OSTARA reactors (Pearl 500, Pearl 2000, Pearl 10000) come in set reactor sizes. However not all reactor specifications are accessible to the public. Using information from the OSTARA Pearl 2000 technical brochure presented in Appendix F, Section F.7, the reactor zone volume for the Pearl 2000 reactor was estimated to be 43 m^3. Company specifications imply that one larger Pearl 2000 reactor can achieve about 4 times the orthophosphate recovery rate as compared to the smaller Pearl 500 reactor. This linear relationship contradicts the exponential trend demonstrated by the PFR graph illustrated in Figure 16 above. Therefore, Equation 5-1 was modified using the maximum loading information of the Nansemond WWTP case study and estimated the Pearl 500 reactor size to be approximately 12 m^3. If installed at the CFWWTW a maximum conversion of 60% can be achieved.

To achieve close to 90% conversion four Pearl 500 reactors or one Pearl 2000 reactor may be used. The hydraulic retention times are based on phosphate conversion and are per pass. However, to achieve high quality struvite (larger crystalline granules), the Pearl reactors are installed with recirculation pumps that recycle a portion of the effluent into the reactors.

As there is no available sizing information for the Multiform Harvest reactors, similar calculations were performed and estimated the reactor sizes to be between 20-25 m^3. Reactor volumes and sequence selections as well as their corresponding conversions are summarized in Table 18. These sizing Options will have a significant impact on the plant CAPEX, based on whether the City of Cape Town decides to locally produce the precipitator or order standard size reactors from a service provider such as OSTARA.

Table 18: Summary of reactor choice and corresponding volume and expected conversion based on first order kinetics

Reactor Selection	**Volume/m^3**	**Conversion**
1 x locally constructed reactor	50	90% (theoretical)
OSTARA Pearl reactors		
1 x Pearl reactor 500	12	60%
4 x Pearl 500 reactors	48	89%
1 x Pearl 2000 reactor	43	88%
Multiform Harvest reactors		
2 X 25 m^3	25	90%

For the purposes of this techno-economic assessment, the reactor size was chosen to be a locally constructed 50 m^3 reactor.

Other major plant equipment

For struvite production, other than the precipitation unit itself, additional major plant equipment include magnesium chloride dosing equipment and the feed buffer tank for flow regulation. Chemical precipitation requires a stirred flash tank for the precipitation, a clarifier/settling tank for solid/liquid separations and a belt press (on-site) for dewatering. Major plant equipment are summarized in Table 19.

High quality struvite pellets, at 92% DS (500 kg/day), can be bagged and stored in 70 or 50 kg bags for weekly collection. In the case of Option 2, 6 m^3 /day of 40% DS struvite, will collect in a 10 m^3 skip with a filter. This skip will be collected weekly and the partially dry product can be delivered to the secondary market. In both cases transport will be at the expense of the service provider or client. A similar logistical model was observed for the collection of belt press sludge and the TDP ash.

Table 19: Summary of other major equipment sizes for the three phosphorus recovery/removal options

Description	**Size (m^3)**	**Residence time**
Option 1 and 2		
Precipitation volume	50,3	75 mins
Feed buffer tank volume	283	5 hrs
Effluent storage volume	14,8	15 mins
Magnesium chloride tank	17,0	30 days
Caustic soda dosing tank	0,34	180 days
Filtering skip (standard)	10,0	7 days
Option 3		
Clarifier /Settling Tank	590	10 hrs
Reactor	7,37	5 mins
Lime dosing tank	43,8	180 days
Alum solution	80	30 days

5.2.3 Energy requirements

The centrate stream is assumed to be at ambient conditions, hence there is no need for any heating/cooling demands. Pumps, dryers and conveyor belts are the main consumers of energy for Option 1. Option 2, which produces a raw, unrefined product, excludes major plant equipment such as recycling pumps, driers blowers and heaters. Option 3's main utility use is due to pumps and sludge dewatering.

A centrifugal pump directs stored feed to the fluidized bed reactor for struvite production. Caustic soda as well as the magnesium salts are dosed using metered diaphragm pumps, to ensure correct stoichiometric ratios are meet. In the case of high quality struvite production (Option 1), fluid is recycled through the reactor to induce crystal formation. Reactor effluent flows into a storage tank and is returned to the main WWTW system via a centrifugal pump. If the struvite is to be purified onsite, the filtered struvite (Option 1) is dried using a blower and heater in a drying chamber. The energy requirements are summarized in Table 20.

As mentioned in literature chemical precipitation has a higher footprint, but only slightly higher than that of low-grade struvite production. High-grade struvite production carries a significant electrical/carbon footprint, which can not be ignored.

5.2.4

Table 20: Energy use for side stream treatment Option 1 and 2

Description	Unit	Value		
		Option 1	Option 2	Option 3
Feed pump	kW	1,57	1,57	1,57
Recycle pump	kW	3,16	-	-
Magnesium dosing pumps	kW	3,52	3,52	-
Alumimiun sulfate dosing	kW	-	-	1,31
Lime dosing pump	kW	-	-	2,31
Caustic soda dosing pump	kW	2,69	2,69	-
Effluent discharge pump	kW	0,70	0,70	0,7
Blower (2 atm and 200 m3/hr)	kW	0,10	-	-
Heater	kW	18,5	-	-
Conveyors	kW	0.2	-	-
Solid -liquid separation (belt presss)	kW			0,74
TOTAL	kW	30,3	8,48	6,63
Total	kWh/year	265000	74300	58100
	kWh/day	727	204	159

5.2.5 Land requirements

Based on the OSTARA Pearl 2000 technical brochure, a plant with one 43 m^3 Pearl 2000 reactor has a land footprint of about 325 m^2 and an extra 45 m^2 for every additional reactor. This includes 45 m^2 for a reactor, 78 m^2 for the drying and processing of struvite and the rest for a control room and struvite storage bags. Hence Option 1 and 2 have footprints of 325 and 250 m^2 respectively. Option 3 has a footprint of approximately 77 m^2, estimated using the equipment sizes and the standard spacing of 3,5 m between equipment items (Turton et al., 1998).

5.2.6 Operations and maintenance requirements

For all three options the nutrient treatment facilities will require extensive monitoring and control equipment. The plant will therefore need to be mostly automated, but will require 1-2 employees to receive dosing chemicals, load packaged struvite/sludge and supervise operations working 8 hour shifts. The sludge handling would be done via the same means as the current WWTW operations. Mechanical equipment including: pumps, reactors, driers and feeders will require continuous maintenance. Furthermore, control and monitoring equipment will significantly increase plant maintenance costs.

5.2.7 Summary of Technical assessment

The above technical assessment considered: reactor size, major plant equipment sizes, land requirements, plant utilities (energy) and maintenance. The technical assessment for the three process options is summarized in Table 21.

Table 21: Summary of the two struvite production Option technical assessments

	Option 1	**Option 2**	**Option 3**
Technology	Crystallisation: Fluidized bed reactor	Crystallisation: Fluidized bed reactor	Chemical ppt.
Objective	Form high quality struvite for premium markets	Form low quality struvite for sale in low end markets and processing plants	Removal and disposal of excess orthophosphates in side stream
Process summary	• Use of large reactor unit with recycle for high quality crystal formation • Struvite filtered, dried (92 % DS)	• Use of smaller reactors to produce low quality unprocessed struvite • Collected struvite is (20% DS)	• Chemicals dosed to induce precipitation • Sludge is dewatered (25% DS)
Phosphate recovery %	90	90	90
Orthophosphate kg/day	178	178	178
Struvite (kg/d) (40% DS)	Wet: 1173 Dry: 469	Wet: 1173 Dry: 469	-
Package struivte (kg/d)	(8% DS): 510	(20% DS): 568	-
Excess sludge (kg/d)	-	-	Dry: 601 Wet: 2400
Utilities (kWh/day)	727	204	159
Land requirements (m²)	325	250	77
Chemical dosing (kg/d)	MgCl: 540	MgCl: 540	Alum: 2630
Employees	2	2	2
Major equipment m³			
FBR reactor	50,3	50,3 or (2X25)	Flash tank: 7,37
Feed buffer tank	382	382	382

5.3 Financial Assessment

The three options were evaluated based on capital expenditure (CAPEX); operating expenditure (OPEX); recovered costs (struvite sales) and project cash flows. In addition, the net present costs (NPC) were evaluated over a 20-year period.

5.3.1 CAPEX

Preliminary CAPEX estimates were calculated using the flow capacities of existing nutrient recovery facilities. Any of the three options could be built on land within the CFWWTW; hence it was assumed that there were no extra costs associated with land use. The CAPEX estimations are shown in Appendix G, Section G.1 and G.2. The sixth tenths rule and CEPI indices were used to estimate plant set-up.

In the case of Option 1, a separate nutrient recovery facility equipped with struvite processing units is required. Although, the plant size is relatively small in comparison to the WWTW, it carries a significant capital cost as shown in Table 22.

Table 22: CAPEX estimates for proposed options

Description	Unit	Option 1	Option 2	Option 3
CAPEX	R million	72,6	20,6	2,41

For Options 1 and 2, the significant capital costs of R72,6 million and R20,6 million are mainly due to the reactor size, which is a function of volumetric flowrate and conversion. High-grade struvite production costs were scaled up (using the sixth-tenths rule and relevant costing indices) from existing OSTARA installations. These facilities included advanced struvite processing units resulting in the significantly higher CAPEX. Similarily option 2 used available Multiform Harvest information from case studies, resulting in a lower CAPEX which is however, 8 times higher than that of chemical precipitation. The less sustainable chemical precipitation option, falls within the R3-5 million budget for centrate treatment proposed by the COCT waste water 7-year improvement plan (2012). This may poses as an obstacle to sustainable phosphate recovery.

Options 1 and 3 can have various installation set-ups, including preset units or the use of existing plant equipment. Various equipment set-ups for these options were investigated and are presented in the sensitivity analysis Section 5.4.

5.3.2 OPEX

Variable costs associated with electricity and chemical use were calculated based on the mass and energy balances in Section 5.2.1 and 5.2.3. Magnesium, caustic soda and aluminium sulfate costs were estimated using current market prices and electricity using 2014 industry rates.

Operating costs of R3,97 million, R 1,51 million and R5,18 million per annum were calculated for Options 1,2 and 3 respectively. Figure 17 shows the contribution of the variable and fixed operating costs in relation to the overall operating expenses for the proposed options. Using data provided by the COCT (2010) report, the projected budget for OPEX for the CFWWTW was calculated to be R62,5 million for financial period 2013-2014 (COCT, 2010). Subsequently a 6,35%, 2,42% or 8,66% increase in operating costs is expected with the implementation of either Options 1,2 or 3 respectively. Chemical precipitation, despite the lower CAPEX, is economically less attractive from a per annum OPEX stand point.

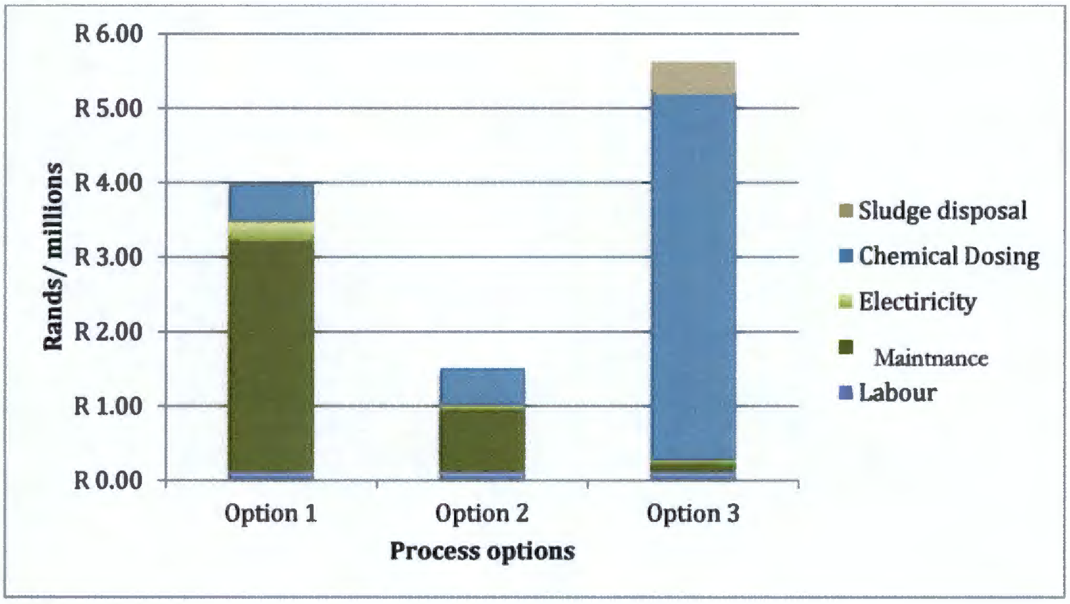


Figure 17: Operating costs and their respective contributions for Options 1,2 and 3

Option 1 has an OPEX 15% less than the Nansemond OSTARA facility, which treats a centrate flowrate 2,3 times less than the proposed Cape Flats process stream, at a treatment fee equivalent to ZAR4,82 million/year. However, there is no available documentation on the cost breakdown of this treatment and whether the CAPEX has a significant effect (in terms of repairs and maintenance) on this amount. In the case of Option 2, an economic assessment conducted by Bilyk et al (2011) estimated the operating costs of a plant with a R14,8 million CAPEX to be R0,51 million (3,3% of the CAPEX). Again, there is no available cost breakdown. These OPEX approximations have a high degree of uncertainty, as the cost calculations are based on heuristics, literature and assumptions. The effects of varying repair and maintenance costs and other operating cost parameters on OPEX are investigated in Section 5.4.

The operating costs for Option 3 calculations were based on mass and energy balances performed over the process. An OPEX of R5,18 million/year is double the operating cost of R2,15 million peryear calculated using Tech Tetra (2013) cost estimates and slightly higher than R3,60 million quoted by Bilyk et al (2011). However, these are incomparable, as neither the nutrient loading nor the centrate flowrate was specified in that report.

It is also important to note that the cost of MgCl at R8,30/kg and caustic at R3,00/kg are local costs. Alum traders on an international platform sell Alum for the competitive price of R1,15/kg. If similar international vendors could be found, both MgCl and caustic costs would be reduced substantially. These cost implications are tested within -50% to 100% increase (Section 5.4).

Chemical dosing and utilities

For both Options 1 and 2, chemical-dosing costs, particularly magnesium, contribute highly to the overall variable costs. De Bashan and Bashan (2004) and Gell et al., (2011) emphasized how obtaining a sustainable and economical magnesium source will affect the feasibility of the process. However, this is not the key variable OPEX. According to literature reports, magnesium chloride is the preferred reactant for the recovery process (Rahman et al., 2013). Magnesium chloride dosage is equivalent to R6,38/mol struvite produced. Bittern and magnesium oxide are cheaper sources, but this will not significantly affect the overall operating costs of Option 1 as maintenance costs contributed highly to the overall OPEX. In the case of Options 2 and 3, dosing chemicals (pH adjustment and precipitation chemicals) are key operating expenses, accounting for 33% and 95% of the costs respectively. Tetra Tech (2013), assumed that chemical dosing, sludge handling and disposal costs account for about 70% of the OPEX costs.

The major cost saving of Option 2 over Option 1 is due to the reduced power usage, which in the case of Option 2 is 28% of option 1 at R74000/year. On site processing of high quality struvite incurs the significant electricity cost.

Maintenance

At a rate of 4% of the CAPEX, Option 2's maintenance costs are R0,822 million/ year and are about a 1/3 the cost of Option 1 at R3,12 million. For chemical precipitation, both the Tetra Tech (2013) and EPA (2000) reports estimate the maintenance costs to be 4% of the overall CAPEX, resulting in R96000/year for option 3. Maintenance and repair costs for Options 1 and 2 will incur a 313% and 10% increase in current business as usual repair budget (R750000).

However, it can be argued that the various plant irregularities described in Section 3.3.1 may be as a result of this low budget allocation for the CFWWTW maintenance and repairs.

Additional costs: sludge handling and delivery costs

If chemical precipitation were the treatment option for the process side stream, overall plant sludge would increase by 0,2% and would still have to be disposed off site and will incur an additional cost of R44000/year. The sludge is gravity-thickened to 3% dry solids (DS) and further dewatered to 25% DS. This cost could be avoided if safely mixed with the TDP treatment stream.

If consumers are charged a 50 c per kilogram of struvite delivery fee, then this will account for the water in the packaged struvite mass. This cost is believed to be at the cost of the buyer and will be added to the cost of the packaged product. It is therefore not factored into the calculations, as the cost will cancel out. It would cost approximately R92 800/year for 510 kg/day (92% DS) struvite. If the water content is decreased even further to 80% DS (no excess process water) the struvite revenue would be about R117000/year for 568kg/day (80% DS) struvite.

Recovered costs

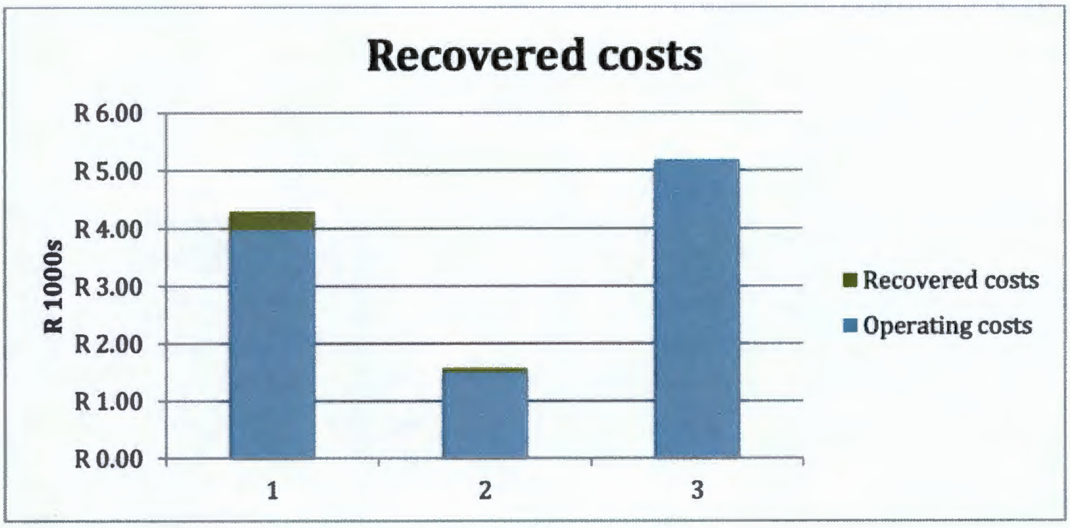
Struvite prices were calculated using a least-squares regression on phosphate and nitrogen concentrations against current South African fertilizer prices (MAP, MAPZ, DAP, Palfos, FMP) summarized in Appendix G, Section G.4. Low-grade unprocessed struvite was forecast to sell at the low-end market value, R0,37/kgstruvite (dry basis, pure struvite) and the processed product at the higher end, R1,35kg/struvite. This cost is not inclusive of packaging, water content, and delivery costs. These costs (Table 23) will be factored in but it is assumed that this will be paid off at the expense of the client.

Table 23: Estimated market price of struvite

	Price of struvite (R/kg)
Average (MAP, MAPZ, DAP, Palfos)	1,35
Low end fertilizer (Palfos)	0,37
High end fertilizers (DAP)	1,84

The Multiform installation at West Boise is designed to produce low quality struvite similar to Option 2, selling at R2,12/kg struvite. In addition, Barbeau et al (2009) projected that the selling price, for struvite as a proeess raw material, will have to be above R6,68/kg to be profitable in the American market. The same study suggested the market value for unprocessed struvite to be about R1,10/kg; this is closer to the estimated average struvite market value calculated for South Africa. This is 6 times the selected selling price of struvite produced by option 2; hence this selling price may need to be adjusted to generate more revenue, if the goal is to be profitable. However, pricing flexibility is limited, as market value is subject to the South African and international phosphate fertilizer prices, which at the moment, is not regulated by government. Therefore, struvite may need to establish its own market value within the South African fertilizer industry.

The costs recovered relative to the current operating costs for the Options 1 and 2 are summarized in Figure 18. These are insignificant compared to the overall operating costs of the plant and only recover 7,98% (Option 1) and 4,21% (Option 2). Despite the low market value of struvite (relative to the case studies investigated), the high flowrate to phosphate loading ratio of the CFWTWW process stream, amplifies capital costs and minimizes struvite production rates. Therefore not enough income is generated. In the case of the Nansemond OSTARA set-up which produces 1650 kg/day of R4,15/kg processed struvite, achieves a yearly income of R2,5 million This not only recovers up to 50% of the annual operating costs but is predicted to pay back investment within 6 years. Overall, a R6,43 million annual cost saving is achieved, with R4,82 million/year in maintenance costs savings from previously experienced spontaneous struvite precipitation. It would therefore be useful to have a cost breakdown of the CFWWTW maintenance and repair costs, especially in relation to spontaneous struvite precipitation currently experienced. From this perspective, it may be easier to justify the cost of installing a nutrient recovery facility, not only as a means to meet legislative effluent levels and mitigate eutrophication, but with the possibility to cut down on plant maintenance costs.



.Figure 18: Recovered costs due to yearly struvite sales for all options

Treatment costs

All three process options will only marginally increase the CFWWTW treatment costs from the projected cost of R1,37/kL for the year 2015. Option 1,2 and 3 will increase the treatment costs by R0,09, R0,03 and R0,12/kL respectively. In comparison to recovering water for re-use at a cost of R7,00/kL, and basic sewage treatment costs at R2,90/kL, all options are within an acceptable range. The associated operating costs per kg of PO_4 and P recovered as well as per kg struvite and sludge produced are summarized in Table 24.

All three options fall under the OSTARA's treatment cost (Section 2.3), at between R180-240/kgP recycled, which may show an underestimation in process costs. These are heavily dependent on the process stream phosphate loading. Option 1 is within the literature chemical precipitation treatment range of R90-210/kg P removed. From this perspective, the not-for-profit treatment of the process stream by means of struvite production could be justifiable. Option 3's treatment cost of R265/kgP removed is only slightly higher than the literature treatment cost range for chemical precipitation. These costs are subject to precipitating metals used and the disposal method of the excess sludge produced.

Table 24: Operating and net operating treatment costs per kg PO4, P recovered and struvite

Operating costs		**Option 1**	**Option 2**	**Option 3**
Cost/kg struvite	R	21,1	8,90	N/A
Cost/kg PO_4 recovered (removed)	R	56,6	22,2	85,2
Cost/kg P recovered (removed)	R	172	72,0	261
Cost/kg sludge	R	N/A	N/A	33,6
Treatment cost/kL (influent)	R	0,05	0,03	0,12

5.3.3 Projected cash flow and net present value (costs)

Project cash flow analysis was conducted over a 20-year investment period and for a discounted rate of 10%. The Fixed capital depreciation period was set to 20 years.

Net present costs

Figure 19 illustrates the cumulative operating and recovered costs for all 3 options, over a 20 year period, discounted to a present value at 10% per annum.

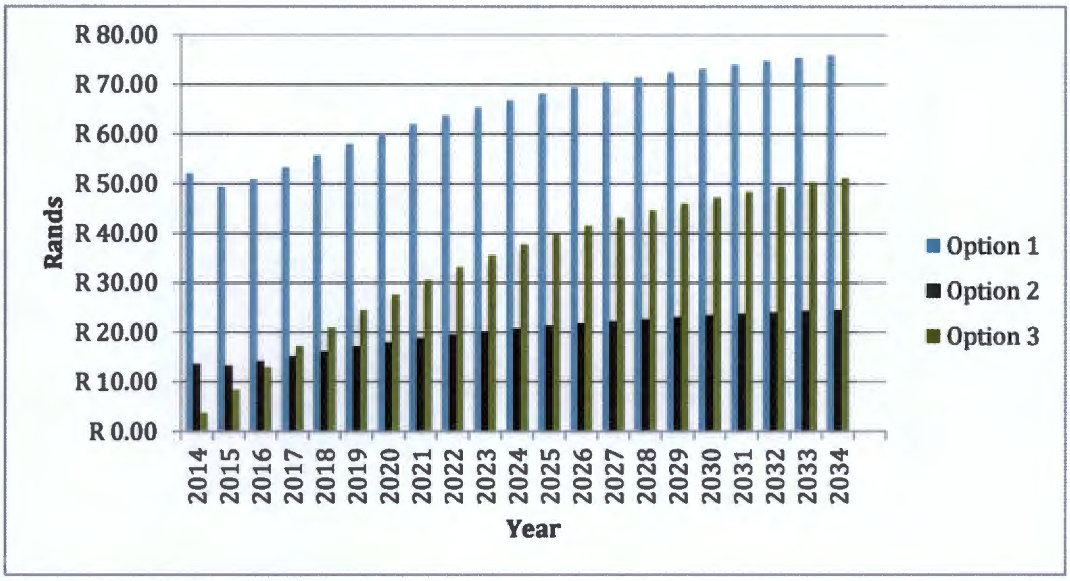


Figure 19: Cumulative costs and the resulting net prsesent costs for the three options

The net present costs for option 1, 2 and 3 are R76,2 million, R 24,7 million and R51,2 million respectively. As hypothesized, despite the higher capital investment and unprofitable operations, unprocessed struvite production is cheaper than traditional chemical precipitation, over a 20-year period. Higher operating costs due to chemical dosing and sludge disposal amplify Option 3s net present costs. The high flowrate to phosphate loading ratio, makes the high capital cost associated with on-site processing of high-grade struvite impractical. Despite the higher market value, low production rates of high quality struvite will not generate enough revenue to recover the cost of production let alone the investment.

A useful economic comparison for the two phosphate recovery options are life cycle costs. This is the operating costs per kg struvite produced. Option 2 at R8,90/kgstruvite comes in close to the OSTARA installation with a process cost of R 8,09/kgstruvite. Option 1 comes in at 4 times this cost at R23,20/kg struvite produced, but comes somewhere within the feasible range R7,80-R42,0/kgstruvite (for 50 mgP/L to 900mgP/L). (Crutchik & Garrido, 2011) at 61 mgP/L.

5.4 Sensitivity analysis

Thus far, the techno-economic assessment had been on basic approximations, which rely on basic assumptions, heuristics and literature data. Therefore it is useful to assess the sensitivity of this assessment to changes in key parameters. This is will account for uncertainty in the design criteria and assumptions made. In addition, this will identify the main design parameters that can positively affect the feasibility of the proposed options.

The variation in the following key parameters were investigated:

- reactor sequence and choice (Option 1- OSTARA);
- maintenance costs (as a percentage of CAPEX);
- retail price of struvite fertilizer (Option 1 and 2);
- CAPEX (all options);
- pH and corresponding reaction rate (in same reactor);
- plant equipment availability for Option 3 operations;
- sludge disposal costs; and
- discount rate

5.4.1 Option 1 and 2: CAPEX, Maintenance costs and struvite selling price

Option 1 reactor sequence

OSTARA provides preset reactor sizes the Pearl 500, Pearl 2000 and Pearl 10000. In Section 5.2.2, it was established that 3 or 4 pearl 500 reactors and 1 Pearl 2000 reactor may achieve conversions within 10% of the proposed 90% conversion. The CAPEX costs (excluding import costs and duty) and their corresponding NPV costs over a 20-year period are summarized in Table 25. Investing in a single Pearl 2000 rector would decrease the maximum conversion slightly to 88% but will decrease the CAPEX by up to 35%, resulting in a 30% decrease in net present costs. This makes the production of high quality struvite more economically feasible and possibly more comparable to Option 2's proposal.

Table 25: Reactor sequencing and corresponding NPV values

Reactor Selection	Conversion	Price/ R million	NPV costs/ R mill
1 X locally constructed reactor	90% (theoretical)	72,6	76,2
1 X Pearl 500 reactor	60%	33,3	36,1
3X Pearl 500 reactor	82%	53,2	54,1
4 X Pearl 500 reactors	89%	68,4	63,8
1 X Pearl 2000 reactor	88%	47,2	48,6

Maintenance costs

Maintenance costs were calculated as a percentage of CAPEX in all instances. The base case was set at 4% for all options however there is much uncertainty associated with this figure. The current business as usual budget allocates of R784000 which is 1,4% of CAPEX for maintenance and repair (COCT, 2010). If the maintenance and repair costs were comparable to the business as usual rates, there will be a significant decrease in the NPCs to R56,4 million and 19,7 million for Option 1 and 2 respectively. However Option 3 at R53,3 million does not change significantly.

Selling price

Revenue is subject to prices on the South African fertilizer market and, as it stands, the selling price of struvite is significantly lower than the cost of recovery.

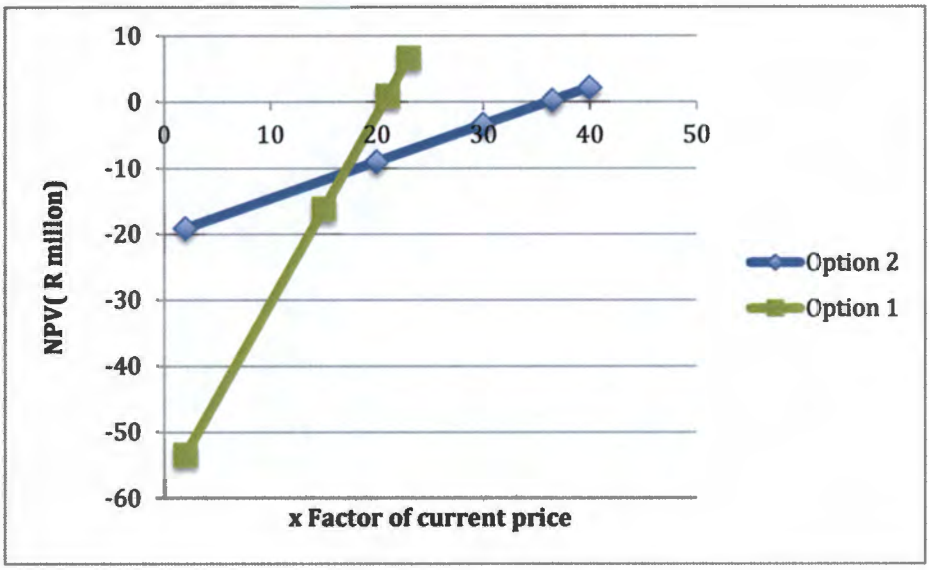


Figure 20: Effects of change in struvite selling price

As illustrated by Figure 20, doubling the struvite selling price will not make the proposed options economically viable for either process option. For the base case costs of Option 2, a selling price of R13,50/kg struvite would be needed to show a positive cumulative cash flow after 18 years. A further increase to R14,80/kg struvite would result in a pay back time within 12 years. To create a higher selling price for struvite a high-end niche market has to be created (Barbeau et al., 2009). The prefeasibility assessment for a Multiform Harvest installation in the United States predicted that unprocessed struvite could sell for R1000/ton (R1,08/kgstruvite) unprocessed and at highest R6,60/kgstruvite as niche market raw material. High grade struvite produced by Option 1, will have to sell at 6,5 times this amount, R39,00/kgstruvite to be profitable within 20 years.

Reaction kinetics: pH and conversion

A change in pH and the corresponding reaction kinetics has little effect on the conversion and hence net present costs if the same reactor size of 50 m^3 is considered. If the set point of the operating pH is changed to 8,4 and 9, reactor sizes reactor sizes of 119 m^3 and 33,8m^3 are required respectively, to achieve a 90% conversion. A drastic change in the design reactor size and hence CAPEX is experienced over a small operating pH range. The optimal pH range is for struvite production is between 8,3-8,,7. Although a pH of between 9 and 11 achieves higher reaction kinetics, this pH range results in a decreased struvite crystal size (Matynia et al., n.d.).

A drop in phosphate recovery would have a similar effect to a decrease in struvite selling price. Hence fluctuations in the phosphate removal efficiency of the between 45-90% will not drastically affect the plant OPEX. However, this decrease in removal efficiency will increase the effluent phosphate loading and as such cause plant effluent as well as maintenance and repair issues elsewhere on the WWTW

Comparing Option 1 and Option 2

Figure 21 shows the effects of a -50% to 100% increase in selling price, CAPEX and maintenance costs on the NPV of both option 1 and 2. If compared to Option 2, changes in Option 1's CAPEX and maintenance drastically influences the net present costs. Changes in selling price have very little effect on the overall profitability of the plant in both instances. With the base case design criteria, Option 2 will always have an NPV lower than that of Option 1.

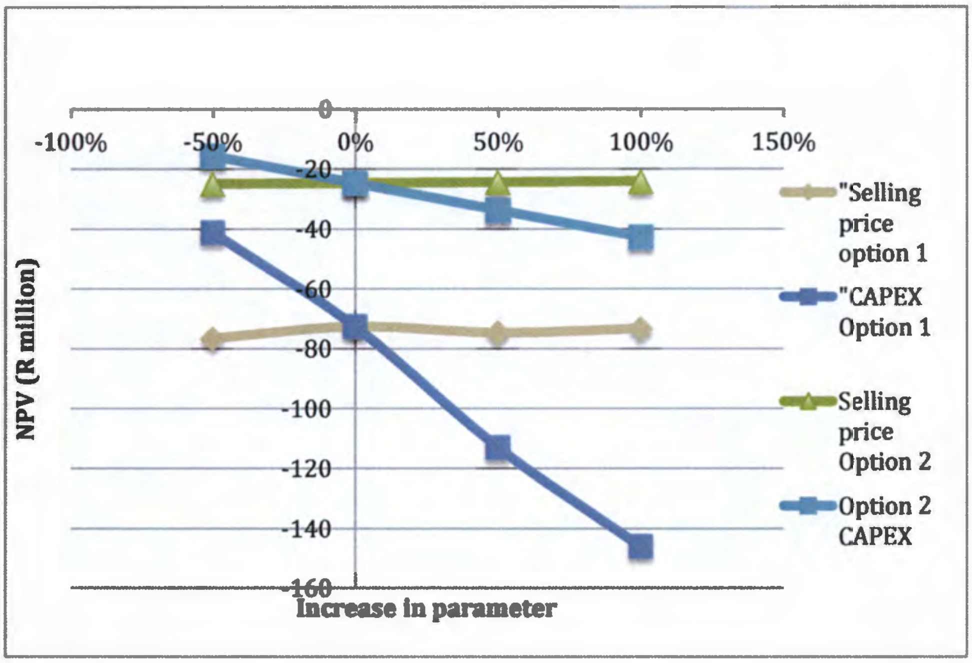


Figure 21: Plot of varying process parameters (selling price and CAPEX) to identify key parameters for Option 1 and 2

Best case Option 1 vs. base case Option 2

If the municipality were to consider the production of high-grade struvite over the unprocessed low-grade, key process parameters may need to change to yield a lower NPV. The key parameter that affects Option 1's NPV is CAPEX. If a Pearl 2000 reactor is used the NPC may reduce to as low as R48 million. At best the high-grade struvite can sell at the literature value of R6,60/kgstruvite, resulting in an NPC of R41,4 million; just over 1,6 times greater than Option 2s NPC. To come in even lower at R32,5 million, maintenance can be lowered to the business-as-usual amount of 2%. It is evident that unless the phosphate loading in this stream increases, Option 2 will always come in cheaper than Option 1 in the case of the CFWWTW centrate.

5.4.2 Option 3: equipment set up and chemical use

Chemical precipitation typically includes the installation of a flash tank, pH tank, clarifier and filter. However depending on plant set up, this side stream treatment process may use existing plant filters and clarifiers, hence reducing CAPEX costs to values lower the R1 million. Using costing information provided by Tetra Tech (2013); if the chemical precipitation process is to use existing solid-liquid separation units, the resulting capital cost reduces to approximately R787 000 and a corresponding net present cost of R50,7 million (2% decrease). However there is much uncertainty in these capital cost estimations, as the Tetra Tech (2013) considers the CAPEX to increase linearly with an increase in flowrate.

The USEPA (1997) report describes capital and operating costing values for a range of case studies as well as estimations from a chemical precipitation-costing program CAPDET. This software interprets the non-linear costing equations for chemical precipitation treatment technologies, based on data available in the USEPA (1989) design manual for phosphorus removal. Cost estimates for various chemical precipitation set-ups using the non-linear costing equations available in both reports are summarized in Table 26. For a set-up similar to the above base case results in a capital cost of R8,97 million, which is 3,5 times higher than the base case. There must be considerable uncertainty in these figures, using CEPI from 1997 to 2014.

Table 26: CAPEX investments and their resulting net present values for various chemical precipitation set-ups

Equipment	CAPEX investment	NPV costs (R mill)
Flash + clarifier + filter	9,9	54,4
Flash tank only	2,57	51,2
Flash tank +clarifier	3,54	51,7
Flash tank + filter	8,97	53,9

Chemical usage

Chemical dosing has the highest effect on the Option 3 OPEX, therefore chemical choice and dosage considerations are important parameters to consider. Calcium maybe used for chemical precipitation but the most common metal salts are ferric chloride and aluminium sulfate. For the base case, aluminium sulfate was chosen as it is easier as well as safer to use and does not cause as much corrosion (Minnesota pollution control agency, 2006). In South Africa, ferric chloride has been installed for chemical precipitation for effluent polishing; an example of this is the

Wildevoelvlei WWTW in the Western Cape (Muzanenhamo & Sikosana, 2012). However, ferric chloride comes in at close to 4 times the cost (R4 500/Ton) of Alum solution.

Sludge handling cost

Sludge collection was estimated at a rate of R0,5/kg. However, chemical precipitation sludge may require specialized removal. At R3 000/ton, the chemical precipitation net present costs increases from R51,2 million to R70,9 million. If this excess sludge can be sent to the TDP for processing, no additional cost is incurred for removal and a NPC of R47,1 million is achieved over the 20 year period.

5.4.3 Comparing Option 2 and Option 3

Figure 22 compares the effects of Option 2 and 3 NPC with the change in chemical dosing costs and CAPEX. Chemical dosage costs has the highest effect on NPC in the case of Option 3, but has little effect on Option 2s NPC. However even with a 50% drop in chemical price Option 2 is more affordable than Option 3 as a phosphate removal method at the CFWWTW.

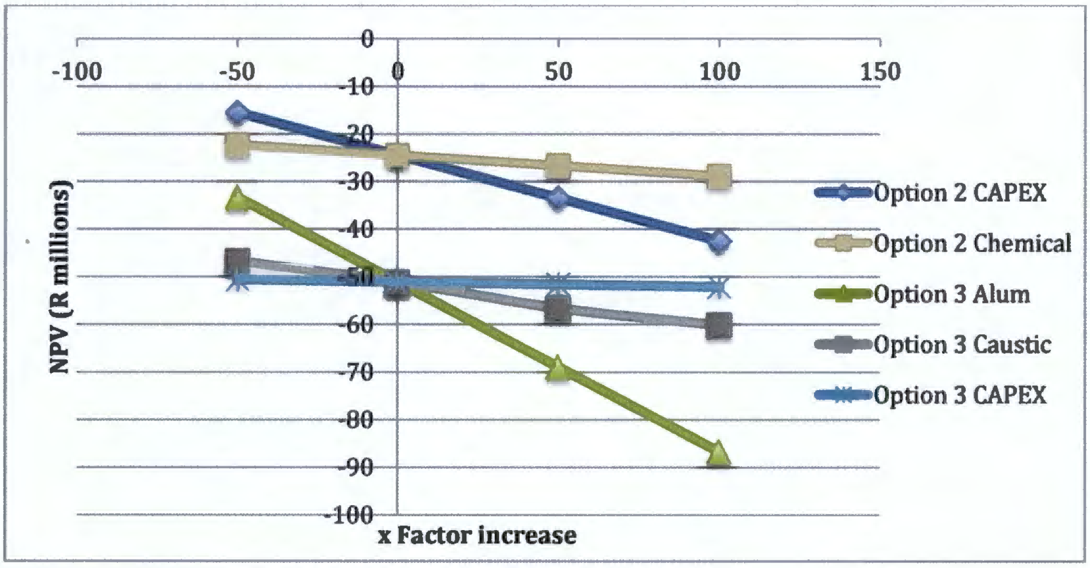


Figure 22: Sensitivity of NPVs to varying chemical costs

Best case Option 3 vs. base case Option 2

Key process parameters can vary in a number ways and may make these two Options even more comparable or at the very best with NPVs within 10% of each other. If Option 3 can use an existing clarifier and belt press for dewatering, the CAPEX value can drop to R0,78 million and the NPC to R50,7 million. At best alum sells for R1,08/kg, this results in a NPC of R38,6 million, 1,5 times that of Option 2. If possible, the excess sludge may be treated in TDP, eliminating sludge disposal costs and reducing the NPC to R34,6 million. Even then, the base case design of Option 2 comes in cheaper than Option 3 over a 20-year period. However as illustrated by Table 27, with these parameter changes, Option 3 comes within 10% of Option 1s best-case scenario. In this case option 1 can come in cheaper than Option 3.

Table 27: Comparing the 3 options with a change in key parameters

Option	Best case option 1	Base case Option 2	Best Case Option 3
NPC R millions	32,5	25,4	34,6

5.4.4 Discount rate for all three options

Comparing NPVs is an effective way of comparing costs benefits for a range of options; a key parameter in this assessment is the discount rate. This rate applies to and may differ for public, private and public-private partnership (PPP) investments. Typically public sector discount rates are lower and range between 3% and 10% and represent long-term project investments. Private investment or PPP schemes discount rates have been quoted to be as high as 15%, which usually accounts for capital financing (P.Burger & J. Hawkesworth, 2011). According to both J.Leighland (2007) and Philippe Burger & Ian Hawkesworth (2011), there is no real concensus on the appropriate discount rate for any investment route. When comparing public to private sector investment options, South Africa uses the same economic discount rate for ex ante cost estimations (P.Burger & J. Hawkesworth, 2011). Figure 23 shows how the net present costs of all three options vary with a change in discount rate from 3-20%. Option 1 experiences the greatest drop in NPC from R100 million to under R63 million at 20%. At higher discount rates Options 2 and 3 become more comparable, at a little over R15 million differences in NPV between 15 and 20%. At 5%, rates more representative of public sector investment, Option 1, 2 and 3 increase to R90,5 ,R30,5 and R73,4 million respectively.

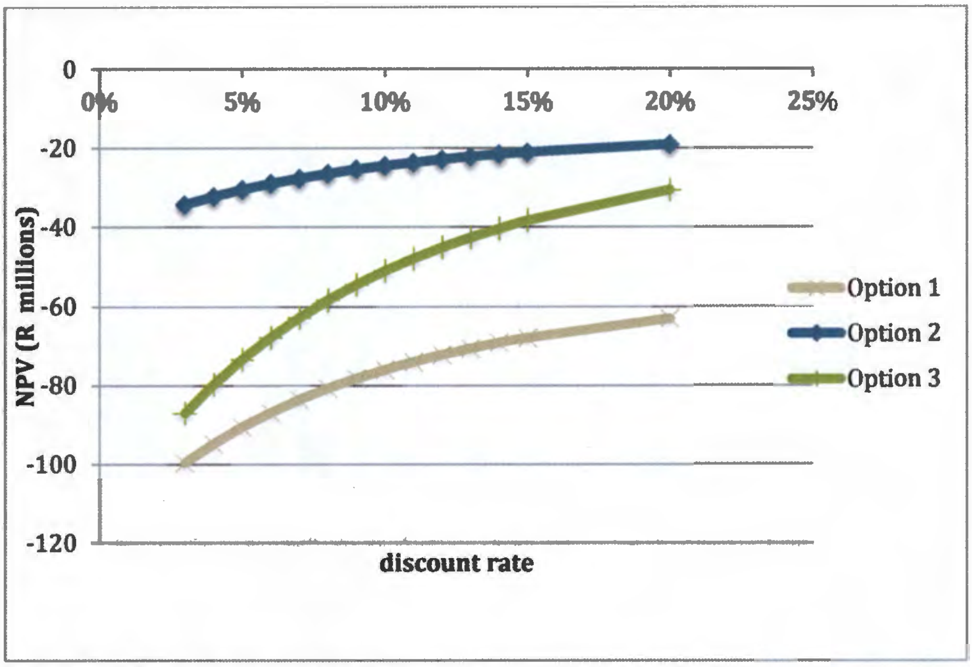


Figure 23: NPV costs with varying discount rate

5.5 Summary of technical and financial Assessment

At 90% conversion, 470 kg/day of dry struvite can be produced at a cost of R22/kg struvite for high-grade and R8,90/kg struvite for unprocessed fertilizer. This production rate recovers a mere 4,21% and 7,98% of the operating costs for Options 2 and 1 respectively. Chemical precipitation produces 2400 kg/day (25wtd% DS) excess sludge for landfill disposal. Phosphate removal at the CFWWTW will incur additional treatment costs of R0,05, R0,03 and R0,12 to the business-as-usual rate, for Option 1,2 and 3 respectively. In comparison to recovering water for re-use at a cost of R7,00/kL and sewage costs at R2,90/kL, all options fair well. The ex ante NPV costs are R76,2-, R25,4- and R51,1 million for option 1,2 and 3 respectively. CAPEX has the highest effect on NPV for both option 1 and 2, whereas chemical dosing cost significantly affects chemical precipitation NPC. Option 2 can be profitable within 19 years if the price of struvie increased to about R14,00/kgstruvite. Despite changes in key design parameters for both Options 1 and 3, the Option 2 base case design criteria at the CFWWTW, will always come in cheaper. The technical and economic assessments for all three options are summarized in Table 28..

Table 28: Summary of Tech-economic assessment done on the process side stream treatment options

	Option 1	**Option 2**	**Option 3**
Technology	Crystallisation: Fluidized bed reactor	Crystallisation: Fluidized bed reactor	Chemical precipitation
Objective	Form high quality struvite **for premium markets**	Form low quality struvite for sale in **low end markets** (agroforestry) and processing plants	Removal and disposal of excess orthophosphates in side stream
Process summary	• Use of large reactor unit with recycle for good crystal formation • Struvite filtered, dried and packaged	• Use of smaller reactors with less retention time to produce low quality unprocessed struvite	• Chemicals dosed to induce precipitation • Sludge is separated and disposed
Technical assessment			
Phosphate recovery %	90	90	90
Orthophosphate kg/day	178	178	178
Product struvite kg/day	469	469	N/A
Package struvite (kg/d)	(8% DS): 510	(20% DS): 568	
Product excess sludge kg/day (25wt%)	N/A	N/A	2400
Utilities kWh/day	727	141	182
Land requirements	325	250	77
Employees	2	2	2
Major equipment m^3			
FBR reactor	50,3	50,3 or (2 x 25)	73,7
Feed buffer tank	382	382	382
Total chemical storage	17,3	17,3	124
Economic Assessment			
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	315 000	63 300	0
Cost/kg struvite	22,1	9,01	N/A
Cost/kg PO4 recovered (removed)	56,6	23,5	86,2
Cost/kg P recovered (removed)	173	72,0	263
Treatment cost/kL (influent)	0,05	0,03	0,12
Net projected costs (R million)	76,2	25,4	51,2

6 Conclusions and recommendations

This study set out to investigate the technological, social and economic dimensions of phosphate recovery from sewage in South Africa. It builds on knowledge presented in the WRC Report No: K5/2218 by (Sikosana et al., 2014); with a particular focus on phosphate recovery potential from large centralised waste water treatment works, which had not been covered in that report. Both pieces give effect to analyses suggesting that alternatives to conventional waste water treatment are crucial in addressing water related issues of sustainable development in South Africa.

This concluding chapter reiterates and complies the findings of the previous 5 chapters. The methodologies used are reviewed in Section 6.1 and their suitability to the current study assessed. The degree of fulfillment of the research objectives set out for this dissertation is described in Section 6,1 and 6,2. Section 6.3 draws conclusions by reviewing the hypothesis and key questions, as well as the considering the practical, theoretical and policy implications of the study. Finally, Section 6.4 gives recommendations for further research.

6.1 Methodological review

Two separate methodologies were used in attempting to answer the key questions posed by the hypothesis. A qualitative methodology explored socio-technical issues by means of expert interviews. The second research component used standard engineeirng techno-economic methods to assess and contrast three conceptual retroft designs for phosphate recovery/removal.

In the case of the expert interviews, conclusions were drawn from stakeholder opinions as well as technology data from literature. The results indicate the "likelihood" of market direction, which is partly based on conjecture and is therefore subject to interpretation. In addition, the study was limited to experts and did not collaborate across other stakeholder sectors, particularly the consumer. On the other hand, these dialogues provided useful information concerning stakeholders that were previously overlooked, as well as useful data that led to further review of available literature.

There was no experimental work in this study but instead the techno-economic methodology focused on data collection from various sources. Analyzed plant samples would have been preferred, however, the plant irregularities described in Section 3.3.1 would deem these to be a poor representation of the CFWWTW. A component balance further verified this reasoning. Even then, this investigation is limited by the reliability and availability of WWTW data as well as "engineering" assumptions made. The results were tested and validated within a large degree of uncertainty in section 5.4. Therefore this method is suitable for providing decision makers with reasonable cost estimates for comparing potential retrofit projects.

6.2 Achievement of objectives

The research objective stated at the outset of this dissertation was divided into the following aims:

1. Describe sustainability within the waste water sector;
2. Investigate available nutrient recovery technologies;
3. Obtain the viewpoints of experts along the fertilizer produce value chain on products grown from fertilizers manufactured from waste water; and
4. Present and techno-economically analyze a case study of how a nutrient recovery process could be incorporated into a biological waste water treatment works in South Africa.

The first two aims were addressed by the comprehensive literature review presented in chapter 2, which was partly adapted from the WRC Report No: K5/2218 by Sikosana et al, (2014). A global shift to more ecological and economical alternatives to conventional waste water methods, with a need for more social considerations, was identified. Literature indicated that crystallisation is the most promising industrial scale phosphate recovery method and therefore formed the basis of the proceeding chapters. Potential markets that could use fertilizers derived from sewage were identified in Chapter 4, where the viewpoints of various stakeholders were considered. In Chapter 5, conceptual designs for three potential retrofit projects at the CFWWTW were assessed and compared using net-present costs derived from a techno-economic framework. These insights were linked and addressed aims 3 and 4 respectively.

6.3 Conclusions

Based on background information and the gap identified in literature, it was hypothesized that **"The South African market is better suited for low quality sturivte for use in secondary (non-food) markets. This will come in cheaper than both traditional chemical precipiation (phosphate elimination) methods and high-qulaity struvite production.** This section will synthesize the findings summarized in Chapter 5 and Chapter 4, to answer the two research questions and to conclude on the hypothesis. The key questions were:

1. What space is there for fertilizer production (such as struvite) from human waste in the South African markets?
2. Would the installation of a centralized nutrient recovery technology at a biological WWTW coupled with anaerobic sludge stabilization, be an economically viable side stream treatment technique in the South African context?

6.3.1 Review of social assessment findings

The main findings presented in Chapter 4 were that:

- **The South African consumer is not ready for use of fertilizer derived from sewage**: it is not a viable intervention to tackle the growing food security issues.
- **More feasible markets lie within secondary, non-food markets**: As hypothesized, there is potentially a significant market for lower grade fertilizer derived from human waste.
- **To date, there are no South African policies on organic agriculture or certification**: instead, producers aim for compliance to the EU organic standards, which prohibit the use of human waste; this may limit the development of a high value struvite market.

Thereotical and practicalIImplications

Social shaping of technology goes beyond post installation, user experiences and should involve market assessments (Munch et al., 2001; Algeo & O'Callaghan, 2012). The findings in Chapter 4 could potentially form the basis of a conceptual framework and decision-making tool, for sustainable technology development, implementation and design based on market considerations, within the South African context. This could provide a more effective approach to design that is reflective of stakeholders (Marter, 2000; Franks, et al., 2010). As such, "expensive mistakes" can be avoided, as were seen in the ill received urine diversion toilet installation project, commissioned by the eThekwini municipality (Roma et al., 2013).

Technology success cannot be transposed from one context to another: Despite positive social experiences of human waste fertilization demonstrated in the Nepal (Pahl - Wostl et al., 2001) case, the SA market is not ready due to cultural differences and lack of "consumer-ready" information. Therefore, perception can surpass need. At present, these user perceptions should therefore push research focus from decentralized to more centralized resource recovery solutions for the South African context. However, centralized nutrient recovery (at WWTWs) incurs a much higher financial investment, due to the increased difficulty that comes with treating more dilute waste streams.

In addition, this study found various subtle links between socio-techno-economic assessments and speaks towards a greater need for a "systems approach" as is indicated by Cordell (2013).

Policy implications

Organic agriculture policy: According to the struvite expert, the EU is not experiencing a phosphate shortage, but rather an excess. Yet in South Africa, which is at a greater risk of resource and food scarcity, organic producers aim to be compliant with EU organic food standards. Organic agriculture policy, when formulated, should therefore be more reflective of the South African context.

6.3.2 Review of techno-economic findings

The main empirical findings in Chapter 5 were that:

- **The net present costs for high-grade, low-grade and chemical precipitation installations at the Cape Flats Waste Water Treatment works (CFWWTW), discounted at 10% over a 20 year period were R76,2, R25,4 and R51,2 million respectively**: as hypothesized 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 CFWWTW upgrade.
- **High phosphate loading to flowrate ratio is key:** other WWTWs with a higher ratio may have yielded better economics.
- **Struvite will have to establish its own market**: the current phosphate market price is too low to offset the costs of phosphate recovery.

Thereotical and Practical Implications

These findings may help further mobilize South Africa's shift to more sustainable waste water treatment techniques: Although common and affordable, chemical precipitation incurs significant costs and diverging the phosphate from waste water to solid waste merely shifts the environmental burden. Policy that will bar sewage sludge disposal to agriculture as of 2015 (CDM Executive Board, n.d.), seen against increasingly limited landfill space, already has decision-makers exploring new options for sludge treatment and disposal..

Implementation of low-grade struvite production is more cost effective: Similar to findings by Bilyk et al. (2010), low grade struvite production comes in cheapest of the three options investigated. Despite having the most attractive economics, local municipalities may find it hard to justify the high capital investment and unprofitable operations. Other than most struvite production case studies, which have shown profitable outcomes within the 20-year period, this is not the case here. However, this option does fall within the global cost bracket for struvite production at R8,90/kgstruvite and may be justified from this angle. Municipalities will have to consider the environmental benefits over the costs.

Phosphate loading to flowrate ratio affects profitability: High CAPEX associated with high-grade struvite production makes this the most costly choice, especially as the South African market may be better suited to lower grade struvite production. However, this process only marginally increases treatment costs to R1,42/kL which is well within an acceptable range for waste water treatment. Other WWTWs with a higher phosphate loading to flowrate ratio may yield economics in favour of high-grade production. But one may need to consider the substantial electrical/carbon footprint.

There is space for innovation: The CAPEX for struvite production is substantial. Locally constructed reactors, with improved kinetics, might come in cheaper than both the OSTARA and Multiform Harvest installations and may lead to both funding and research opportunities in SA.

Policy implications

Phosphate policy to address scarcity rather than just pollution: Although progressive, the recent South African legislation limiting effluent phosphate to 1 mg/L treats phosphate as a nuisance rather than an essential resource. Policy could be modified to promote the reduction, reuse and recycling of phosphate; this would inherently tackle the pollution issue. The Nutrient Credit Trading system described by Algeo & O'Callaghan (2013) is an example of such policy.

Policies to control fertilizer imports and market prices: government does not regulate the fertilizer markets. Both struvite processes were shown to be unprofitable, partly due to the low struvite prices, which are subject to South African phosphate fertilizer prices on the local market. As such fertilizer policy and price regulations would help better understand the placement of struvite in the fertilizer market. In addition, this could increase fertilizer prices to values more comparable to the global market.

6.3.3 Hypothesis conclusion

In summary, the findings are in line with and therefore prove the hypothesis: If a WWTW is to reduce effluent phosphate loading to within legislative standards, low-grade struvite production has been shown to be 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 secondary non-food markets. Although it is a simple process, it is not cheap; the capital investment is 10 times that of South Africa's more familiar chemical precipitation route.

6.4 Recommendations for future research

- **Mapping of an economy-wide phosphate pathway**: relative to phosphate run-off on farms and other urban sinks, the low amount of nutrients extractable from waste water profile makes it technically and economically difficult to justify. Larger sinks must be identified.
- **Identify and quantify the implications of phosphate recovery on WWTW plant operations**: obtain more detail from installations globally and integrate these findings into a model for local WWTWs.
- **Identify and interview various potential consumers**: conclusions made on consumer acceptability were based on the subjective views of the experts interviewed and were therefore based on conjecture. Consumer interviews and surveys would give a more comprehensive view on the social acceptability (in various markets) of fertilizers/ raw materials derived from human waste.
- **Use or develop a systems framework for an even more holistic approach to phosphate recovery:** this study found various subtle links between socio-techno-economic assessments and speaks towards a greater need for a "systems approach". More synergies and contradictions can be found between stakeholders, related projects and policy, than what is stated in this dissertation.

7 References

Adam, C., 2009. *SUSAN: Sustainable and Safe Re-use of Municipal Sewage Sludge for Nutrient Recovery.* Activity Report.

AFRISCO, 2012. *AFRISCO Organic Standards.* [Online] Available at: HYPERLINK "http://www.afrisco.net/" http://www.afrisco.net/ [Accessed August 2013].

Alexandra, E. & Limnios, M., 2008. *Incoporating complex systems dynamics in sustainability assessment frameworks: enhanced predictions and management of socio - ecological systems performance.* PhD Thesis. University of Australia.

Algeo, T. & O'Callaghan, P., 2012. *BlueTech Insight Report Nutrient Removal and Recovery Market Overview.* Vancouver: Blue Tech.

Baiphethi, M.N. & Jacobs, P.T., 2009. The contribution of subsistence farming to food security in South Africa. *Reseach in agriculture and applied economics*, 48(4).

Balmer, P., 2003. Phosphorus recovery, an overview of potential and possibilities. In *IWA Specialist conference. Waste water Sludge as a Resource.* Trondheim, 2003. IWA S.

Barak, P. & Stafford, A., 2006. Struvite: A recovered and Recycled Phosphorus Fertilizer. In *Aglime & Pest Management Conference.*, 2006.

Barbeau, D., Kresge, B. & Bowers, K., 2009. West Boise WWTF Use of Struvite Crystallisation Technology as Part of the Phosphorus Removal Plan. In *PNCWA 2009.*, 2009. PNCWA.

Bilyk, K., Pitt, P., Taylor, R. & Wankmuller , D., 2011. *PROCESS AND ECONOMIC BENEFITS OF SIDESTREAM TREATMENT.* Hazen and Sawyer Environmental Engineers and Scientists.

Bowers, K., 2011. Phosphorus removal by struivte precipiation. In *Manure technology workshop.* Ohio, 2011.

Brent, A.C. & Musango, J.K., 2011. A conceptual framework for energy technology sustainability assessment. *Energy for Sustainable Development*, pp.84 -91.

Brent, A.C. et al., 2011. *Systems dynamics modelling to assess the sustainability of renewable energy technologies in developing countries*. Council for Scientific and Industrial Research, South Africa..

Britton, A., Prasad, R., Balzer, B. & Cubbage, L., 2009. Pilot testing and economic evaluation of struvite recovery from dewatering centrate at HRSD's Nansemond WWTP. In *Nutrient Recovery from Waste water Streams Vancouver, 2009*. Vancouver, 2009.

Burger, S., 2011. Algal wastewater treatement plant under construction. *Rhodes Latest News*, March.

Cabeza Perez, R., Steingrobe, B., Romer, W. & Claassen, N., 2009. Plant availability of P fertilzers recycled from sewage sludge and meat and bone meal in field and pot experiments. In *International Conference on Nutrient Recovery from Waste water Streams*. Vancouver, 2009. IWA publishing.

CDM Executive Board, n.d. *City of Cape Town Treatment of Organic Waste Streams CDM Projects*. UNFCCC/CCNUCC.

CEEP, 2013. *Current*. [Online] Available at: HYPERLINK "http://www.ceep-phosphates.org/Documents/shwList.asp?NID=1&HID=34" http://www.ceep-phosphates.org/Documents/shwList.asp?NID=1&HID=34 [Accessed 27 February 2013].

City of Cape Town, 2014. *Waste water and Industrail Effluent By-laws,2013*. Cape Town: Sabinet Online City of Cape Town.

City of Yakima, 2014. *Yakima Regional Waste water Treatment*. [Online] Available at: HYPERLINK "http://www.yakimawa.gov/services/waste water-treatment-plant/" http://www.yakimawa.gov/services/waste water-treatment-plant/ [Accessed 28 july 2014].

COCT, 2010. *City of Cape Town Waste water treatment Secion 78(3) assessment*. Report. Cape Town: City of Cape Town municipality.

COCT, 2012. *WASTE WATER TREATMENT IMPROVEMENTS 7 YEAR MASTER PLAN 2009/10 – 2015/16 : CAPITAL WORKS DRAFT ESTIMATES*. [Online] Available at: HYPERLINK "http://www.capetown.gov.za/en/Pages/Results.aspx?k=duplicates:%22http%3A%2F%2Fwww.capetown.gov.za%2Fen%2FWater%2FWaterservicesDevPlan%2FDocuments%2FWSDP_201

1 2012%2F5 9 GOTO Ch5 7 year Master Plan.pdf%22"
http://www.capetown.gov.za/en/Pages/Results.aspx?k=duplicates:%22http%3A%2F%2Fwww.capetown.gov.za%2Fen%2FWater%2FWaterservicesDevPlan%2FDocuments%2FWSDP 2011 2012%2F5 9 GOTO Ch5 7 year Master Plan.pdf%22.

Cordell, D., Drangert, - & White, S., 2008. The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19, pp.292 - 305.

Cordell, D., Rosemarin, A., Schroder, J.J. & Smit, A.L., 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, 84(6), pp.747 - 758.

Cornel, P. & Schaum, P., 2009. Phosphorus recovery from waste water: needs, technologies and costs. *Water Science & Technology*, 59(6).

Coulson & Richardson, J.F., 1994. *Coulson and Richardson's Chemical Engineering*. Elsevier.

Crutchik , D. & Garrido, J.M., 2011. Struvite crystallisation versus amorphous magnesium and calcium phosphate precipitation during the treatment of a saline industrial waste water. *Water Science and Technology*, 64(12).

de Rosnay, J., 1979. The systemic revolution: A new culture. In de Rosnay, J. *The Macroscope*.

de-Bashan, L.E. & Bashan, Y., 2004. Recent advances in removing phosphorus from waste water and its future use as fertilizer (1997–2003). *Water Research*, 38, pp.422 - 4246.

de-Bashan, L.E. & Bashan, Y., 2003. Fertilizer potential of phosphorus recovered from wastewter treatment. In *First International Meeting on Microbial Phosphate Solubilization*. Mexico, 2003.

deBarbadillo, C., Benisch, M., Barnard, J. & Neethling, J.B., 2012. *Sustainable Operating Practices fro Achieving Low Phosphorus Effluents*. WERF.

deBarbadillo, C., Levesque, S. & Maxwell, M., n.d. *Strategies for meeting ultra-low phosphorus limits: State of the art technologies and case studies*. Kansas City: Black & Veatch Corporation.

Deparment of Water Affairs, 2012. *Sanitation Services: Quality of Sanitation in South Africa*. Progress Report.

Department of Agriculture, Forestry and Fisheries, 2005. *National Policy on Organic Production.*
Department of agriculture, forestry and fisheries, 2013. *Economic Review of the South African Agriculture: 2012/2013.* Pretoria: National Development Agency.

Departmet of Water Affairs, 2012. *2012 Green Drop Progress Report.* Regulatory Progress Report. Department of Water Affairs South Africa.

differencebetween, 2011. *Diferrence between crystallisation and vs precipitation.* [Online] Available at: HYPERLINK ": http://www.differencebetween.com/difference-between-crystallisation-and-vs-precipitation/" \l "ixzz2PPCOPT4A" : http://www.differencebetween.com/difference-between-crystallisation-and-vs-precipitation/#ixzz2PPCOPT4A [Accessed July 2013].

Dittrich, C., Rath, W., Montag, D. & Pinnekamp, J., 2009. Phosphorus recovery from sewage sludge ash by a wet-chemical process. In *International Conference on Nutrient Recovery form waste water streams.* Vancouver, 2009. IWA.

East African Community, 2007. EAS 456:2007 ICS 67.020 *East African Standard: East Arican Organic Products Standards.* Report of Standards. Arusha: Kilimohai Organic.

EPA, 2000. *Waste water Technology Fact Sheet Chemical Precipitation.* Washington D.C: EPA United States Environmental Protection Agency.

Etter, B., 2009. *Struvite recovery from urine at community scale in Nepal.* Project intermediate report. Nepal: Eawag Eawag.

Etter, B., Tilley, E., Khadka, R. & Udert, K.M., 2011. Lost Cost Struvite production using source-separated urine in Nepal. *Water Research*, 45, pp.852-62.

FAO, 2005. *Fertilizer use by crop in South Africa.* Rome: Land and Plant Nutrition Management Service.

Feineigle , , 2011. *Urine: Closing the NPK Loop.* [Online] Available at: HYPERLINK "http://permaculturenews.org/2011/11/27/urine-closing-the-npk-loop/" http://permaculturenews.org/2011/11/27/urine-closing-the-npk-loop/ [Accessed 25 April 2013].

Foskor, 2014. *Product Prices.* [Online] Available at: HYPERLINK "http://www.foskor.co.za/cd_products.php" http://www.foskor.co.za/cd_products.php [Accessed 10 March 2014].

Franks, , D., Cohen, T., McLellan , B. & Brereton , D., 2010. *Technology Futures Discussion Paper : Technology Assessment and the CSIRO Minerals Downunder National Research Flagship.* The University of Queens land.

Fridge, 2008. Ir285 *study to develop a value chain strategy for sustainable development and growth of organic agriculture.* Assessment. Durban: fund for research into industrial development, growth and equity (fridge).

Ganrot, Z., 2005. *Urine processing for efficient nutrient recovery and reuse in agriculture.* Thesis. Goteborg: Gotebirg University Gotebirg University.

Ganrot, Z., n.d. *Fertilizer products from human urine.* Gööteborg: Melica Environmental Consulting.

Gell, K. et al., 2011. Effectiveness of Struvite from Black Water nadn Urine as a Phosphorus Fertilizer. *Journal of Agricultural Science* .

Giesen, A. et al., 2009. Experience with crystallisation as sustainabale, zero - waste technolgoy for treatment of waste water. In *Internationla Mine Water Conference.* Pretoria, 2009. Document transformation technologies.

Goldblatt, A., 2011. *Agriculture: Facts & Trends, South Africa.* WWF.

Gordon, J., n.d. *Precipitation and Crystallisation Processes.* Los Alamos National Laboratory.

Green, c., Johnson, P., Allen, V. & Crossland, S., 2004. *Treatment Technologies for Phosphorus Removal from water derived from cattle feedyards.* Texas: Texas Tech University.

Guest, J.S. et al., 2009. A New Planning and Desing Paradigm to Achieve Sustainable Resource Recovery from Waste water. *Environmental Science and Technology*, 43, pp.6126 - 6130.

Gunningham, N., Kagan, R.A. & Thorton, D., 2004. Social License and Environmental Protection: Why Bussinesses Go Beyond Compliance. *American Bar Foundation.*

Hampton Roads Sanitation District, 2010. OSTARA Increases Plant Efficiencies for Hampton Roads Sanitation District in Innovative Public/Private Partnership Launching. *Virginia Waste water Treatment Plant First In Chesapeake Bay Watershed to Recover Nutrients and Transform them into "Green" commercial fertilizer*, 27 May.

HRSD, 2009. *Nutreint recovery at HRSD, Nansemond WWTP: Nutrient Recovery system equipment agreement.* HRSD.

IFDC, 2012. *Promoting Affordable Sources of Plant Nutrients in Africa Through Innovative Composting Alternatives.* [Online] Available at: HYPERLINK "http://www.ifdc.org/Training/Recent_Training_Programs/Promoting_Affordable_Sources_of_Plant_Nutrients_in" http://www.ifdc.org/Training/Recent_Training_Programs/Promoting_Affordable_Sources_of_Plant_Nutrients_in [Accessed 24 April 2013].

Infomine, 2014. *Historical Phosphate Rock Prices and Price Chart.* [Online] Available at: HYPERLINK "http://www.infomine.com/investment/metal-prices/phosphate-rock/all/" http://www.infomine.com/investment/metal-prices/phosphate-rock/all/ [Accessed 20 March 2014].

Intergovernmental panel on climate change (IPCC), n.d. *Methodological and Technological Issues in Technology Transfer.* [Online] Available at: HYPERLINK "http://www.ipcc.ch/ipccreports/sres/tectran/index.php?idp=7" http://www.ipcc.ch/ipccreports/sres/tectran/index.php?idp=7 [Accessed 8 April 2013].

IPCC, 2000. *Summary for Policymakers: Methodological and Technolgical Issues in Technology Transfer.* summary. Intergovernmental panel on climate change.

Johnson, A.E. & Richards, I.R., 2003. Effectiveness of different precipitated phosphates as phosphorus sources for plants. *Soil Use and Management*, 19(1), pp.45-49.

Kalmykova, , Harder, R., Borgestedt, H. & Svanang, I., 2012. Pathwats and Management of Phosphorus in Urban Areas. *Journal of Industrial Ecology*, 16(6).

Kates, R.W. et al., 2001. Research and Assessment Systems for Sustainability Environment and Natural Resources Program. *Environment and development: sustainability science.*, 292, pp.641-2.

Kratz, S., Adam, C., Schnug, E. & Schick, J., 2009. *Techniques for P-recovery from waste water and sewage sludge and fertilizer quality of P-recycling products.* [Online] Julis Kuhn-Institut Available at: http://www.mmm.fi/attachments/mmm/ministerio/5n8h6xg9T/presentation_judith_schick.pdf [Accessed 24 March 2014].

Kroiss, H., Rechberger, H. & Egle, L., 2011. Phosphorus in Water Quality and Waste Management. In M.S. Kumar, ed. *Intergrated Waste Mangament.* Austria: Intech. pp.183- 218.

Le Corre , K.S., Valsami-Jones , E., Hobbs , P. & Parsons , S.A., 2009. Phosphorus Recovery from Waste water by Struvite Crystallisation: A Review. *Critical Reviews in Environmental Science and Technology.*
Lenntech, 2005. *Phosphorus removal from waste water.* [Online] Available at: HYPERLINK "http://www.lenntech.com/phosphorous-removal.htm" http://www.lenntech.com/phosphorous-removal.htm [Accessed 10 January 2014].

Liberti, L., Petruzzelli, D. & De Florio, L., 2001. REM-NUt ION Exchange Plus Struvite Precipitation Process. In *Holland Conference.*, 2001.

Liu, y., Villalba, G., Ayres, R.U. & Schroder, H., 2008. Global Phosphorus Flows and Environmental Impacts from a Consumption Perspective. *Journal of Industrial Ecol*, 12(2).

MacKeinzie, D. & Wajcman, J., 1999. The social shaping of technology. In *The social shaping of technology.* 2nd ed. Buckingham, UK: Open University Press.

Marter, J.W., 2000. *The IPCC Special Report on Technology Transfer.* IPCC.

Matthews, S., 2003. New Sludge Treatment Technology Benefits Environment and Saves Millions. *The Water Wheel*, February.

Matynia, A. et al., n.d. Influence of process parameters on struvite continuous crystillisation kinetics. *Chemical Engineering*, pp.160-76.

Metcalf & Eddy, 2004. Waste water: An overview. In G. Tchobanoglous, F.L. Burton & D.H. Stensel, eds. *Waste Water Engineering: Treatment and Re-use.* 4th ed. U.S.A: McGraw Hill.

Minnesota pollution contorl agency, 2006. *Phosphorus Treatment and removal technologies.* Brochure. Minnesota pollution control agency.

Mohammed, S. & Shansool, H., 2009. Phosphorus Removal from Water and Waste Water by Chemical Precipitation Using Alum and Calcium Chloride. *Iraqi Journal of Chemical and Petroleum Engineering*, 10(2).

Morris, M., Kelly, V.A., Kopicki, R.J. & Byerlee, D., 2007. *Fertilizer Use in African Agriculture.* Washington: The World Bank The World Bank.

Morse, G.K., Brett, S.W., Guy, J.A. & Lester , J.N., 1997. Review: Phosphorus removal and recovery technologies. *The Science of the Total Environment.*

Mostert, A., 2013. *Fertilizer Consumption in South Africa 2013.* [Online] Available at: HYPERLINK "http://www.fssa.org.za/Statistics/Fertilizer_Consumption_in_South_%20Africa_1955-2017.pdf" http://www.fssa.org.za/Statistics/Fertilizer_Consumption_in_South_%20Africa_1955-2017.pdf [Accessed 13 November 2013].

Motevallian, S.S. & Tabesh, M., 2009. *A Framework for Sustainability Assessment of Urban Water Systems Using a Participatory Approach.* Thesis. Tehran: University of Tehran.

Muga, H. & Mihelcic , J.R., 2007. Sustainability of waste water treatment technologies. *Journal of Environmental Management* , 88.

Muller, J.A. et al., 2007. *Nutrient Recycling from Sewage Sludge using the Seaborne Process.* Gifhorn: Insitute of Sanitary and Environmental Engineering.

Multiform Harvest, 2014. *The benefits of Multiform Harvest Technology.* [Online] Available at: HYPERLINK "http://www.multiformharvest.com/technology/articles13.php" http://www.multiformharvest.com/technology/articles13.php [Accessed 15 July 2014].

Munch, E.Y., Benesovsky-Scott, A., Josey, J. & Barr, K., 2001. *Making a business from struvite crystallisation for waste water treatement: Turning wast into gold.* Brisbane Water.

Musango, J.K. et al., 2012. A system dynamics approach to technology sustainability assessment: The case of biodiesel developments in South Africa. *Technovation*, 32, pp.639 -651.

Muzanenhamo, P. & Sikosana, M., 2012. *Phosphate recovery from waste water treatement effluent using ion exchange resins.* Cape Town: Unversity of Cape Town University of Cape Town.
Nawa, Y., 2001. *P-recovery in Japan – the PHOSNIX process.* [Online] Available at: HYPERLINK "http://www.jki.bund.de/fileadmin/dam uploads/ koordinierend/bs naehrstofftage/baltic21/8 poster%20UNITIKA.pdf" http://www.jki.bund.de/fileadmin/dam uploads/ koordinierend/bs naehrstofftage/baltic21/8 poster%20UNITIKA.pdf [Accessed 13 January 2014].

Neethling, J.B., 2008. *A Technical Review: Tertiay Phosphorus Removal.* Technical Review. WERF.

Neethling, J.B., 2013. Phosphorus removal challenges and opportunities. In *IWEA Nutrient Removal and Recovery Workshop.* Addison, IL, 2013. HDR Engineering.

Nguyen, T.A.H., Ngo, H.H., Guo, W. & Nguyen, T.V., 2013. Phosphorus removal from Aqueous Solutions by Agriculture By -products: A Critical Review. *Journal of Water Sustainability*, 2(3), pp.193-207.

Nieminen, J., 2010. *PHOSPHORUS RECOVERY AND RECYCLING FROM MUNICIPAL WASTE WATER SLUDGE.* M.Sc. Thesis. Aalto University.

Ohlinger, K.M., Young, T.M. & Schroeder, E.D., 2000. Kinetic effects on preferential struvite accumulation in waste water. *Environmental Engineering Journal*, (125).
OSTARA, 2013. [Online] Available at: HYPERLINK "http://www.OSTARA.com/sites/default/files/pdfs/Saskatoon OSTARA Case%20Study.pdf" http://www.OSTARA.com/sites/default/files/pdfs/Saskatoon OSTARA Case%20Study.pdf [Accessed 10 February 2014].

Padel, K., 2007. *Organic-food Sector Sees 'unprecedented growth'.* [Online] [Accessed January 2015].
Pahl - Wostl, C. et al., 2001. *Investigating consumer attitudes towards the new technology of urine separation.* Osnabruck: Armadilo Webworks Insitute of Environemental Systems Research, University of Osnabruck.

Paul, R.H., 1987. Improving the New Product Development Proces: Making Technology Push Work. *Journal of Business and Industrial Marketing*, 7(3), pp.59 - 61.

Petzet, S. & Cornel, P., 2013. Phosphate Recovery from Waste water. In Hester, R.E. & Harrison, R.M. *Waste as a Resource*. Cambridge, UK: RSCPublishing.

Putnam, D., 1971. *Composition and concentrative properties of human urine*. Washington: NASA National Aeronautics and Space Administration.

Quintana, M. et al., 2008. Removal of phosphorus through struvite precipitation using a by-prodcut of magnesium oxide production (BMP): effects of the mode of BMP preparation. *Chemical Engineering Journal*, pp.204-09.

Rahman, M.D. et al., 2013. Production of slow release crystal fertilizer from waste waters through struvite crystallisation – A review. *Arabian Journal of Chemistry*, 7, pp.139-55.

Reisman, A., 1989. Technology Transfer: A Taxonomic View. *Journal of Technology Transfer*, pp.31 - 36.

Richert, A. et al., 2010. *Practical Guidance on the Use of Urine in Crop Production*. Stockhlom: Sustainable Sanitation Alliance Stockhlom Environment Instiute.

Riskworld, 1997. *Framework for Environmental Health and Risk Management*. [Online] Washington D.C Available at: HYPERLINK "https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCcQFjAA&url=http%3A%2F%2Foaspub.epa.gov%2Feims%2Feimscomm.getfile%3Fp_download_id%3D36372&ei=_RcVZKQOMmuU9i0gcgP&usg=AFQjCNFzlZtwRuioZwWSh2x5yULx9ZXE-A&bvm=bv.93756505,d.d24" [Accessed 20 May 2015]

Rocks for Crops, 2001. South Africa. In *Rocks for Crops*. pp.257-68.

Rogers, E.M., 1995. Diffusion of innovation. New york: Simon & Shuster.

Roma, E. et al., 2013. *User perceptions of urine diversion dehydration toilets: Experiences from a cross-sectional study in eThekwini Municipality*. Durban: Water Research commision University of KwaZulu-Nata.

Rundgren, G. & Lustig, P., 2005. *Feasibility study for the establishment of certification bodies for organic agriculture in Eastern and Southern Africa)*. [Online] Available at: HYPERLINK "http://www.grolink.se/Resources/studies/719%20Afrocert%20Rapport%20Final.PDF" http://www.grolink.se/Resources/studies/719%20Afrocert%20Rapport%20Final.PDF [Accessed 13 February 2014].

Rybicki, S.M., 1997. *New Technologies of phosphorus removal from waste water.* Royal Institute of Technology.

Sartorius, C., von Horn, J. & Tettenborn, F., 2011. *Phosphorus Recovery from Waste water - State-of-the-art and Futre Potential.* Karlsruhe : Water Environment Federation Fraunhofer Institute for Systems and Innovation Research.

Scheidig, K., Schaaf, M. & Mallon, J., 2009. Profitable recovery of phosphorus from sewage sludge and meat & bone meal by the Mephrec process-a new means of thermal sludge and ash treatment. In *Internationa Conference on Nutrient Recovery from Waste water Streams.* London, 2009. IWA.

Schick, J., Kratz, S., Adam, C. & Schnug, E., 2009. Techniques for P-recovery from waste water and sewage sludge and fertilizer quality of P-recycling products. In *P-recycling conference.* Berlin, 2009.

Schipper, W.J. & Korving, L., 2009. Full-scale plant test using sewage sludge ash as raw material for phopsphorus production. In *Internation Conference on Nutrient Recovery from Waste water Streams.* Vancouver, 2009. IWA.

Schipper, W.J. et al., 2001. Phosphate recycling in the phosphorus industry. *Environmental Technology.*

Schouw, N.L., Danteravanich, S., Mosbaek, H. & Tjell, J.C., 2009. Composition of human excreta: A case study from Southern Thailand. *Science Total Environ*, pp.155-66.

Schröder, , J.J., Cordell, D., Smit , A.L. & Rosemari, A., 2009. *Sustainable Use of Phosphorus.* Report 357. Plant Research International.

Seaborne, n.d. *Sewage Slduge to Fertilizer.* [Online] Seaborne Available at: HYPERLINK "http://www.seaborne-epm.de/englisch/3_Downloads/daten/info_project_gf_e.pdf" http://www.seaborne-epm.de/englisch/3_Downloads/daten/info_project_gf_e.pdf .

Sikosana, M.K., von Blottnitz, H., Randall, D. & Petrie, D., 2014. *Nutrient and Energy Recovery from sewage: Technology review and exploration of possibilities in South Africa.* K5/2218. Cape Town: Water Research Commission South Africa Water Research Commission South Africa.

Smith, J.A. & Osborn, M., 2007. Interpretative Phenomenological Analysis. In Smith, J. *Qualitative Psychogy.* pp.53 -80.

SNB, 2013. *Phosphate recovery.* [Online] Available at: HYPERLINK "http://www.phosphaterecovery.com/the-phosphate-issue/how-much-phosphate-is-left/77" http://www.phosphaterecovery.com/the-phosphate-issue/how-much-phosphate-is-left/77 [Accessed 27 February 2013].

Southern Africa knowledge node on sustainable sanitation (SAKNSS), 2012. *Southern Africa network for sustainable sanitation.* [Online] Available at: HYPERLINK "www.win-sa.org.za" www.win-sa.org.za [Accessed 28 April 2013].

Spuhler, D. & Gensch, R., 2011. *Sanitation Systems.* [Online] Sustainable sanitaiton and water management Available at: HYPERLINK "http://www.sswm.info/print/1728?tid=707" http://www.sswm.info/print/1728?tid=707 [Accessed 28 May 2013].

Statistics South Africa, 2014. *Gross domestic product: Third quarter 2013.* Pretoria: Statistics South Africa.

StatsSA, 2009. *Census of Commercial Agriculture 2007.* Census. Pretoria: Statistics South Africa.

StatsSA, 2013. *Agriculture Households.* Census 2011. Pretoria.

Stratful, I., Scrimshaw, M.D. & Lester, J.N., 2004. Removal of struvite to prevent problems associated with its accumulation in waste water treatment works.. *Water Environment Research*, 76, pp.437-43.

Strom, P.F., 2006. *Technologies to remove phosphorous from waste water.* Rutgers University.

Szabo, T. et al., 2008. Significance of design and operational variables in chemical phosphorus removal. *Water Environ Res.*

Tetra Tech, 2013. *Cost Estimate of phopshate removal at waste water treatment plants.* Technical Support Document. Environmental Protection Agency.

The first full-scale Multiform Harvest system became operational at the Yakima WWTP in May 2012. 2012. [Film] Directed by D Smith. US: Multiform Harvest.

The Money Converter, 2014. *The Money Converter.* [Online] Available at: HYPERLINK "http://themoneyconverter.com/ZAR/EUR.aspx" http://themoneyconverter.com/ZAR/EUR.aspx [Accessed 13 March 2014].

Trenkel, M.E., 1997. *Controlled-Release and Stabilized Fertilizers in Agriculture.* Paris: International Fertilzier Industry Association International Fertilzier Industry Association.

Turovskiy, I.S. & Mathai, P.K., 2006. *WASTE WATER SLUDGE PROCESSING.* New Jersey, USA: John Wiley & sons Inc.

Turton , R. et al., 1998. Technical analysis of a Chemical Process. In P. Hall, ed. *Analysis, Synthesis & Design of Chemical Processes.* Safari Books online.

UNEP, 2001. *ENVIRONMENTALLY SOUND TECHNOLOGIES in waste water treatment for the implementation of the UNEP GLOBAL PROGRAMME OF ACTION (GPA) "GUIDANCE ON MUNICIPAL WASTE WATER"* . UNEP.

UNEP, 2007. *Organic Agriculture in Africa.* [Online] Available at: HYPERLINK "http://www.unep.org/training/programmes/Instructor%20Version/Part_2/Activities/Human_Societies/Agriculture/Supplemental/Organic_Agriculture_in_Africa.pdf" http://www.unep.org/training/programmes/Instructor%20Version/Part_2/Activities/Human_Societies/Agriculture/Supplemental/Organic_Agriculture_in_Africa.pdf [Accessed 3 March 2014].

UNFCCC, 2012. *COMPONENT PROJECT ACTIVITIES DESIGN DOCUMENT (CPA-DD).* COMPONENT PROJECT ACTIVITIES DESIGN DOCUMENT. Cape Town: UNFCCC UNFCCC.

UNMDG, 2010. *UNMDG, (2010).* [Online] Available at: HYPERLINK "http://www.un.org/millenniumgoals/bkgd.shtml , " http://www.un.org/millenniumgoals/bkgd.shtml , [Accessed 2013].

USEPA, 1989. *Design Manual: Phosphorus Manual.* Environmenatl Research Information.

USEPA, 1997. Cost of Treatment Technologies. In USEPA *Development Document for the CWT Point Source Category*.

USGS, 2013. *Mineral Commodity Summaries 2013*. USGS.

Van Rensburg, P., Musvoto, E.V., Wentzel , M.C. & Ekama, G.A., n.d. MINERAL PRECIPITATION FROM ANAEROBIC DIGESTOR LIQUOR AT THE CAPE FLATS SEWAGE TREATMENT PLANT. In *Water Institute of Southern Africa (WISA)*. WISA.

Vinneras, B., 2001. *Faecel separation and urine diversion for nutrient management of household biodegradable waste water*. Thesis. Swedish University of Africultural Sciences.

Von Hippel, E., 1986. Lead Users: A Source of Novel Product Concepts. *Management Science*, 32(7), pp.791 - 805.

VUNA, 2013. Urine Fertilizers: Greenhouse trials with struvite and nitrified urine. *Promoting sanitation and nutrient recovery through urine separation*, [Brochure] December.

Water Research commission, 1997. *Permissible Utilisation and Disposal of Sewage Sludge*. Handbook. Pretoria: Water Research commission.

WEF, 2005. Chemical Phosphorus Removal. In W.E. Federation, ed. *Biological Nutrient Removal (BNR) Operation in Waste water Treatment Plants*. USA: McGraw-Hill Professional.

Wefnet, 2009. *Chemical Phosporus removal*. [Online] Available at: HYPERLINK "http://www.wefnet.org/biological/NutrientRemoval/Chapter%2007%20Final%20Draft.pdf" http://www.wefnet.org/biological/NutrientRemoval/Chapter%2007%20Final%20Draft.pdf [Accessed 10 January 2014].

Werner, C., 2006. *Closing the loop through ecological sanitation*. Report. GTZ.

Wilkinson, M.J., Crafford, J.G., Jonsson, H. & Duncker, L., 2009. *Cost Benefit Analysis of the Use of Humanure from Urine Diversion Toilets to Improve Subsistence Crops in the Rural Areas of South Africa*. Pretoria: Sustento Development Services CSIR - Built Environment and Swedish Univesity of Agricultureal Sciences.

Wilsenach, J.A., 2003. *An overview of initiatives in Europe to recover phosphate from source separated urine*. Overview. Delft University of Technology.

8. Appendices

Appendix A: phosphate removal, recovery and reuse processes.

Table A.1: Summary of Phosphorus removal and recovery technologies - process summaries, updated and adapted from (Morse et al., 1997)

Type	Technology	Objective	Process Summary	Treated Stream	Auxiliary inputs	Main Output	P form/ content
Physical	Tertiary filtration	Effluent polishing	Filtration	Secondary Effluent	Media	Tertiary sludge	Insoluble phosphate
	Magnetic	Phosphorus removal	Precipitation, magnetic attachment, separation and recovery	Waste water (secondary effluent)	Lime, magnetite	Primarily calcium phosphate	Calcium phosphate (CAP)
	Membrane Reverse osmosis	Phosphorus removal	Remove suspended and dilute solids	Waste water (primary influent)	N/A	Phosphates in suspended solids	Phosphates in suspended solids
	Ion exchange	Fertilizer struvite production	Removes ammonium and phosphate precipitation.	Waste water (secondary effluent)	Ion exchange material and regenerating agents	Struvite or Fertilizer mix	Phosphate slurry or phosphate solution
Physio - Chemical	Chemical Precipitation	Phosphorus removal	Addition of trivalent metal salts to precipitate phosphate removed in sludge	Primary, secondary or tertiary effluent Side stream separated urine	Fe, Al, Ca May require anionic polymer	Chemical sludge	Mainly chemically bound as metal phosphate. Non - biodegradable

Wolstenholme, E.F., 2003. The use of system dynamics as a tool for intermediate level technology evaluation: three case studies. *Science Direct*, 20, pp.194 - 204.

Zhigang, L. & Qingliang, Z., 2008. . nhanci- ng phosphorus recovery by a new internal recycle seeding MAP reactor.. *Bioresource Technology*, 99, pp.6488-93.

Zhou, A. & Tang, J., 2008. *Progress in the Study of Magnesium Ammonium Phosphate Crystallisation Reactor*. University of Science and Technology Beijing.

8 Appendices

Table A.2: Continuation Summary of Phosphorus removal and recovery technologies - process summaries, updated and adapted from (Morse et al., 1997)

Type	Technology	Objective	Process Summary	Treated Stream	Auxillary inputs	Main Output	P form/ content
Physio - Chemical	Advanced chemical precipitation	Phosphorus and nitrogen removal	Crystallisation/ hydrolysis	Waste water primary influent	Polyaluminimum chloride (PAC)	Chemical sludge	Chemical sludge
	Crystallisation	Phosphorus removal and recovery	Crystallisation of CAP using sand as a seeding material or stuvite/Magnesium ammonium-phosphate (MAP)	Waste water secondary effluent or side stream	Caustic soda/milk of lime, sand; may need sulphuric acid. For struvite Mg and NaOH for pH.	Calcium phosphate, sand. Struvite crystals.	Calcium phosphate (40% -50% P) Struvite
	Phosphorus adsorbents	Phosphorus recovery	Adsorption and separation	Waste water effluent Sludge liquor	Fe–oxides, allophone or poly-mineralic soils /clays		
	Phosphorus bio-sorbents	Phosphorus recovery	Adsorption of iron in solution to chemically bind to phosphates	Waste water effluent Sludge Liquor	Chemically modified agriculture by-products (ABPs). Pine Sawdust or reeds or cotton stalks	Phosphate loaded ABPs for fertilizers	Phosphate loaded ABPs
	Electro -chemical	Phosphate recovery	Electrochemical dissolving for struvite	Source separated urine /liquor	Magnesium Steel Plate	Phosphate rich slurry	Struvite

Table A:3: Continuation Summary of Phosphorus removal and recovery technologies - process summaries, updated and adapted from (Morse et al., 1997)

Type	Technology	Objective	Process Summary	Treated Stream	Auxillary inputs	Main Output	P form/ content
Biological	Biological phosphorus removal	Phosphorus removal	Luxury uptake of P by bacteria in aerobic stage, followed by the anaerobic stage	Waste water primary effluent	May need an external carbon source (e.g methanol)	Biological sludge	Phosphorus biologically bound
	Sludge treatment	Sludge disposal	Sludge drying Sludge dewatering Composting	Sludge	Process dependent	Soil conditioner	Dry granule low in P
	Recovery from sludge ash	Phosphorus recovery	Extraction from sludge ash (thermo-chemical)	Sludge ash from biological removal	Heat	Fertilizer	Sludge ash
Other	Sludge digestion	Sludge disposal Phosphate recovery	The separation of supernatant of anaerobic digestion. Sludge liquor treated	AD sludge supernatant	Process dependent	Sludge (fertilizer) Sludge liquor: Struvite CAP Biogas	Sludge (fertilizer) Struvite CAP

Appendix B: crystallization technologies

TableB:1: Crystallisation technologies adapted and updated from (Le Corre et al., 2009)

Process / Technology	Scale	Source	Recovery Efficiency	Form of P recovered	Reference
Selective ion exchange RIM-NUT Process	Full Scale	Chlorinated secondary effluents	> 90%	Struvite	Liberti et al. (1986)
Aerated, Stirred tank reactor and crystallisation	Bench and Pilot	Supernatant from anaerobic digester	60-70%	Struvite	Fujimoto et al. (1991)
CSIR Fluidized bed crystallisation column using quartz sand as seed	Bench	Supernatant from anaerobic digester, Pond effluents, Abattoir	90%	Struvite/HAP	Brett et al. (1997)
Kurita fixed bed seeded with phosphate rock grains	Full Scale	Secondary effluent	Up to 90%	HAP	Brett et al. (1997)
PHOSNIX Air –agitated FBR	Full Scale (Industrial)	Sludge liquor, Industrial process water side streams	80-90%	Struvite	Strafel et al (1999)
DHV Crystalactor	Full scale (Industrial)	Supernatant from anaerobic digester	-	CAP	Giesen (1999)

Table B.1:: Continuation Industrial scale crystallisation technologies adapted and updated from (Le Corre et al., 2009)

Process / Technology	Scale	Source	Recovery Efficiency	Form of P recovered	Reference
FBR, seeded with sand	Bench	Supernatant from anaerobic digester	62-81%	Struvite or mixed HAP	Battistoni et al. (2000)
Aerated reactor	Bench	Centrifuge liquors	Up to 97%	Struvite	Jaffer (2000)
FBR seeded with struvite	Pilot Scale	Sludge lagoon supernatant	> 80%	Struvite	Ohlinger et al. (2000)
FBR	Full Scale	Dewatered liquors anaerobic sludge	> 90%	Struvite	Ueno and Fuji (2001)
Air – agitated column reactor	Pilot Scale	Centrate from anaerobically sludge	94%	Struvite	Von Munch and Barr (2001)
Aeration column	Pilot Scale	Swine waste water	65%	Struvite /HAP	Suzuki et al. (2002)
2L beakers seeded with sand /struvite	Bench	Centrate from sludge from centrifuge	65-70%	Struvite	Wu and Bishop (2003)
FBR	Pilot Scale	Synthetic liquors	90%	Struvite	Adnamet al. (2003a, 2003b)
Two – tank FBR	Pilot Scale	Synthetic liquors	84-92%	Struvite	Shimamura K et. al
WWTP Trevisio FBR seeded with silica	Full Scale	Anaerobic supernatant	62%	Struvite /HAP	Cecchi et al. (2003)
Nishihara Reactor Cation exchange, FBR	Pilot Scale	Anaerobic supernatant	-	Struvite	Kroiss et al. (2011)

Table B.1:: Continuation Industrial scale crystallisation technologies adapted and updated from (Le Corre et al., 2009)

Process / Technology	Scale	Source	Recovery Efficiency	Form of P recovered	Reference
FBR draft –tube reactors	Pilot Scale	Synthetic solution	92%	Struvite	Yoshimo et al. (2003)
Air –agitated reactor	Full Scale	Centrifuge liquors	60-80%	Struvite	Jaffer and Pearce (2004)
FBR seeded with struvite	Full Scale	Centrate from dewatering system	>90%	Struvite	Ishikawa et al. (2004)
Stirred reactor	Pilot	Supernatant from anaerobic digester	90%	Struvite /CAP	Seco et al. (2004)
Stirred reactor	Pilot	Synthetic liquors	>60%	Struvite	Mangin and Klein (2004)
Stirred reactor	Pilot	Pre-treated swine waste	Up to 98%	Struvite	Laridi et al. (2005)
FBR	Full scale	Supernatant	64-69%	Struvite /HAP	Battistoni et al. (2005b)
AirPrex, air-stripped CO2 then precipitation	Full scale	Centrifuge liquors	98%	Struvite	Berliner Wasserbetriebe (2010)
MESC Single –chamber microbial electrolysis	Bench	Synthetic solution to mimic Supernatant from anaerobic digester	40%	Struvite	Roland et. Al (2011)
Manual Sedimentation reactor and Filtration rea	Pilot Scale Pilot Scale	Source separated urine	50% 90%	Struvite	Etter et. Al (2011)
Ion exchange FBR	Pilot Scale	Waste water effluent	94%	Ammonium P and Sodium nitrate mix	Muzanenhamo & Sikosana (2012)

Appendix C: techno-economic assessmet

Table C.1: Market assessment derived from expert interviews (Munch et al., 2001)

Survey result		Significance for the business
1	65% of the participants were unaware of MAP process	Company X would have been the first on the market and would have promoted the technology
2	2/3 of the participants thought that it would be beneficial to have separate sidestream treatment for biological nutrient removal WWTPs. 25% did not know – some of these may not have been familiar with the term "sidestream".	There was a general consensus in the industry that sidestream treatment will become an emerging trend
3 3	35% of the respondents knew of other processes with useful by-products. 70% of respondents knew that struvite was a valuable fertiliser and 60% thought there would be a market for it.	The fact that struvite's fertiliser qualities are generally known means less promotional work will be required in that area. The other "useful" by-products listed were of much lower commercial value than MAP.
3 4	85% of the respondents were convinced that the Environmental Protection Agency (EPA) limits would become stricter.	This confirms the emerging trend in EPA licensing to become more stringent
5 5	All but one respondent thought that animal production industries had effluent problems with respect to nitrogen and phosphorus.	This confirms that the animal production industry is a major client for Company X.
6 6	Piggeries were quoted by 70% of the respondents as having the most effluent problems compared to other animal production industries,	This confirms that amongst the animal processing industry, piggery operators are the most likely target market.
7 7	None of the respondents ruled out that piggery operators might be interested in the SC Process technology (55% yes, and 45% undecided).	As above

Table C.1: Market assessment derived from expert interviews (Munch et al., 2001), continued

	Survey result	Significance for the business
8	45% of the respondents thought that piggery operators would pay a separate company for effluent treatment if such a service was offered (45% were undecided).	This shows that there would be a market for the service of waste water treatment for piggery operators.
9	60% of the respondents knew of unintentional struvite crystallisation, and piggeries and anaerobic digesters were cited as examples.	Anywhere where there is unintentional struvite formation there is also potential for the SC Process.

Appendix D: social assessment interviews and analysis

TableD.1:: Academic experts on struvite production

	Phosphate Recovery Expert A	Agronomical Expert A	Phosphate Recovery Expert B
Area	EAWAG VUNA project	VUNA project: Crop Science Department at UKZN	VUNA project business model research
Fertilizer quality and quantity		If the NPK concentration is sufficient then: How does the fertilizer affect the soil and interact with salts? How do we deal with pathogens? Handling practices are essential	-
Organic Practices		Organic fertilizers are bulky: 50kg for 1 acre will not be attractive to farmers	-
Organic Certification		--	-
Phosphate fertilizer from Human waste	Phosphate recovery from waste water is a small amount Larger sinks are in industrial flows and solid waste Best option is the incineration of sewage sludge.	Struvite is comparable to inorganic fertilizers such as TSP (6% P) compared to 10.5%	-

TableD.1: Contiuation of Academic experts on struvite production

	Phosphate Recovery Expert A	**Agronomical Expert A**	**Phosphate Recovery Expert B**
Market Channel and Value chain	Potential markets are smaller home gardens Specialized fertilizers in flower production	How does one advertise the product? Need a source to market business model	Market for specialized fertilizers is the most feasible Marketing and branding is essential Must aim to be a specialized supplier and blender of crop, flower and agroforestry specific fertilizer Community based gardens are an option A centralized community WWTP for easy collection and treatment Not possible to sell phosphorus as a stand alone fertilizer constituent as the quantities are too small for the commercial market **Potential Supply chain:** • Fertilizer "designer" • Farmer who wants a specialized fertilizer • Mix specific fertilizer blends
Health and Safety	Urine will only be used if properly treated	Micro-contamination and pathogen content is low Pharmaceutical and heavy contamination is possible	
Prediction of societal views	Make urine valuable to society Pilot trials would be convincing Consumer acceptance is based on culture	Effective marketing and business model is essential May work best in a community setting	
Additional Comments		Resource recovery is a sustainable practice	Resource recovery is a sustainable practice

TableD.2: Summary of interviews with industry agriculture industry experts: in organic agriculture and fertilizer

	Agronomical Expert B	Fertilizer Production A
Area	Organic Expert Member of IFOAM and AFRISCO Lecturer	Member of Fertilizer association of South Africa (FSSA)
Fertilizer quality and quantity	The most common fertilizer is Potash (NPK) Phosphate needs to be 10:1 (P:K)	There are 3 categories of fertilizers (fssa.org) 1) > 10% NPK content is 2) 2) < 10% NPK – organic fertilizer
Organic Practices	**Practices in SA** • Organic agriculture in South Africa is slow • Government intervention needed • Government policy has been in the pipeline for 9 years • Biological farmers are 80% organic **Issues with Organic Agriculture** • Pesticides are an issue • Organic standards are too strict • High risk farming • Not enough organic matter to make compost • Nitrogen is in abundance, phosphate is the issue • Direct use of rock phosphate was acceptable but is no longer available	-
Organic Certification	AFRISCO Organic standards are registered as private standards through SABS Current Organic Certification is too stringent	-
Phosphate fertilizer from Human waste	His upcoming research involves mixing urine with grass cuttings to make compost	

TableD.3: Continuation Summary of interviews with industry agriculture industry experts: in organic agriculture and fertilizer

	Agronomical Expert B	**Fertilizer Production A**
Market Channel and value chain	Participatory Guarantee System (PGS) is our best choice. • Farmer gate sales to neighbours • Farmers come together to create a box scheme • Farmers form a corporation (PGS) for in house accreditation • Supply supermarket (HAZOP and Hygiene tests required) Biodynamic certification may be an alternative to organic certification Green road in Stellenbosch is a possible avenue Organic certification is a barrier to small holder farmers	Small quantities to small scale markets is costly Look to sell product to larger manufacturing companies for blending into inorganic fertilizers
Health and Safety	Risk assessment needed: HAZOP and Hygiene tests	
Prediction of societal views	Must gain consumer trust	There will be no acceptability issues – just have to prove that the product is safe The source will not be important to the manufacturing companies
Additional Comments	There is no need for 100% organic certification It could be better to allocate sustainability indicators for farmers to work towards and improve their performance Risk assessment and Quality management is key Organic certification is a barrier to small holder farmers	There is no fertilizer or phosphate shortage

TableD.4: Summary of interviews with organic certification boards: AFRISCO and BioSA

	Organic Certification Board Member A	**Organic Certification Board Member B**
Area	Representative from AFRISCO – organic certification board	Representative from Biodynamic farmers association
Fertilizer quality and quantity	**Acceptable fertilizers in Organic certification** • Natural silicates can be certified • If it is an artificial fertilizer and it is soluble it is accepted • They must understand the fertilizer production process	
Organic Practices	The main export of organic produce is fruit (citrus and avocados) Farmers would opt for organic farming due to bad experiences with agri-chemicals Organic agriculture is a niche market and is hard to control	Biodynamic farmers support the holistic replacement of ALL macro and micro nutrients.
Organic Certification	**Organic Certification procedure** • See Fertilizer quality above **Standards** • Do not allow human excrement at this point due to the pathogens that come with faeces • South African organic standards are compliant with the EU and equivalent to the IFOAM standards • Standards focus on the active ingredients • The EU standards do not allow human waste • IFOAM standards used in African countries do allow the use of Human waste	Biodynamic farming does not permit inputs from human sewage at all. Similar to AFRISCO standards

TableD.4: Continuation of Summary of interviews with organic certification boards: AFRISCO and BioSA

	Organic Certification Board Member A	**Organic Certification Board Member B**
Phosphate fertilizer from Human waste	They would consider struvite precipitation, but must know the source of Magnesium? There is a potential market for phosphate from human waste as phosphorus is often locked in the soil It would be difficult to organically certify these products	Struvite production is an agro-chemical rather than organic farming input
Market Channel and Value chain	PGS is not an option as there is complete transparency in PGS Organic certification boards are mores trusted One can not export organic produce through a PGS Leading retailers such as Woolworths and Checkers have their own standards A large agriculture sector are biological farmers Biological farmers accept soft artificial fertilizers	
Health and Safety	Must be safe	-
Prediction of societal views	People are not ready for fertilizer from human waste It is important to inform the customer base	
Additional Comments	Phosphate recovery from waste water is a step towards sustainability South African consumers are not ready for fertilizers from human waste. We must start using phosphorus from waste streams to avoid accumulation. Industry will be forced to take this route in the future	

Table D.5: Summary of interviews with an organic farmer and a retail store that sells organic produce

	Organic Farmer	**Retail Store Representative A**
Area	Organic Farmer on a community Farm BSc Soil Science	Head of Sustainability program of a Leading Retail store
Fertilizer quality and quantity	-	Phosphate overloading is common in agriculture
Organic Practices	Compost nutrients are sufficient for plant requirements as plants adapt to the nutrients available to them Must micro-manage the soils by natural means	They believe in making commercial farming sustainable and not making organic main stream Large scale organic agriculture can not be sustainable and is more suited to small holder farmers
Organic Certification	The farm is organically certified Soil samples are taken and tested by organic certification boards If organic- soils must not show signs of additional nutrient loading	The retails store has external accreditation boards They are compliant with EU standards There are no South African organic standards Get the approval of EFSA, FDA and then the fertilizer can be used
Phosphate fertilizer from Human waste	Urine is too concentrated and burns vegetables The source of magnesium (struvite production) should be preferably organic. His farming practices must be fully organic **Composting toilets** • Use of this compost is only permissible on ornamental plants Need handling standards to avoid burning of plants and transferring pathogens Would try it at pilot scale first	Technologies take 5 to 10 years to kick off Needs to know the product is safe Testing standards must be compiled
Market Channel and Value chain		There is no need to disclose the source of fertilizers to consumers A public statement is needed This retail chain will consider cooperation of small holder farmers

Table D.5: Continuation of summary of interviews with an organic farmer and a retail store that sells organic produce

	Organic Farmer	**Retail Store Representative A**
Health and Safety	-	This retail chain have in house standards Health and safety comes first: all foods are tested before they are accepted in store Need to ensure that struvite is safe for use and consumption
Prediction of societal views	Societal views depend on how the product is marketed Society will accept the use of such fertilizers if they understand the advantages	Publicity of the human waste fertilizers would be the most important factor The methods used are sustainable but it would be difficult to convey it to society Will have to plan in advance to deal with a public uproar Need to consider both the user and consumer acceptance People don't like change if there is no advantages
Additional Comments	There is no waste and all loops should be closed Must promote subsistence farming	Interested by phosphate recovery from human waste, especially struvite If it is safe, this retail outlet may take it on

Appendix E: summary of the Cape Flats WWTW (CFWWTW)

E.1: Process flow diragram for the CFWWTW

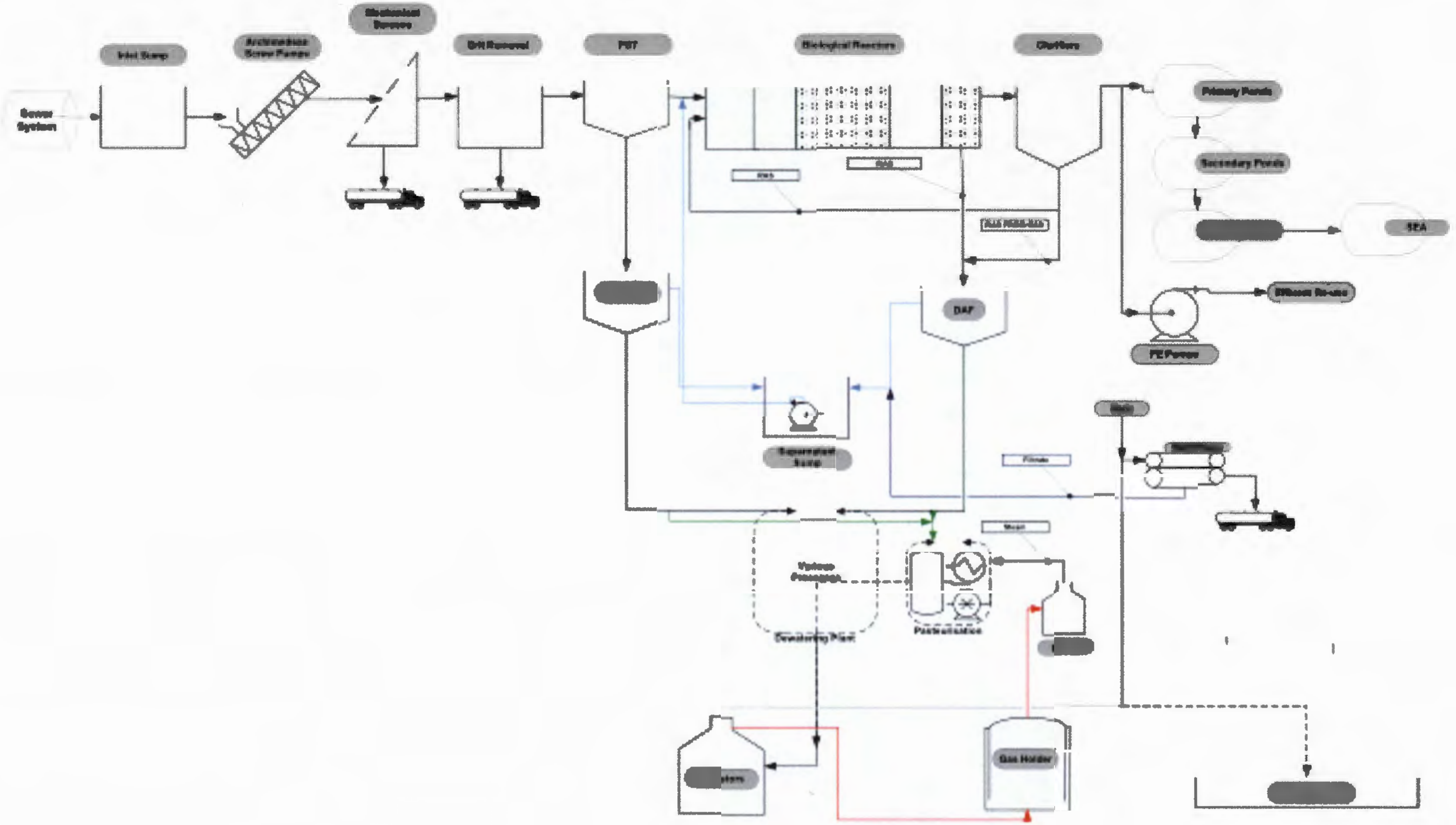


Figure E.1: Cape Flats WWTW PFD

E.2: Sludge handling factility

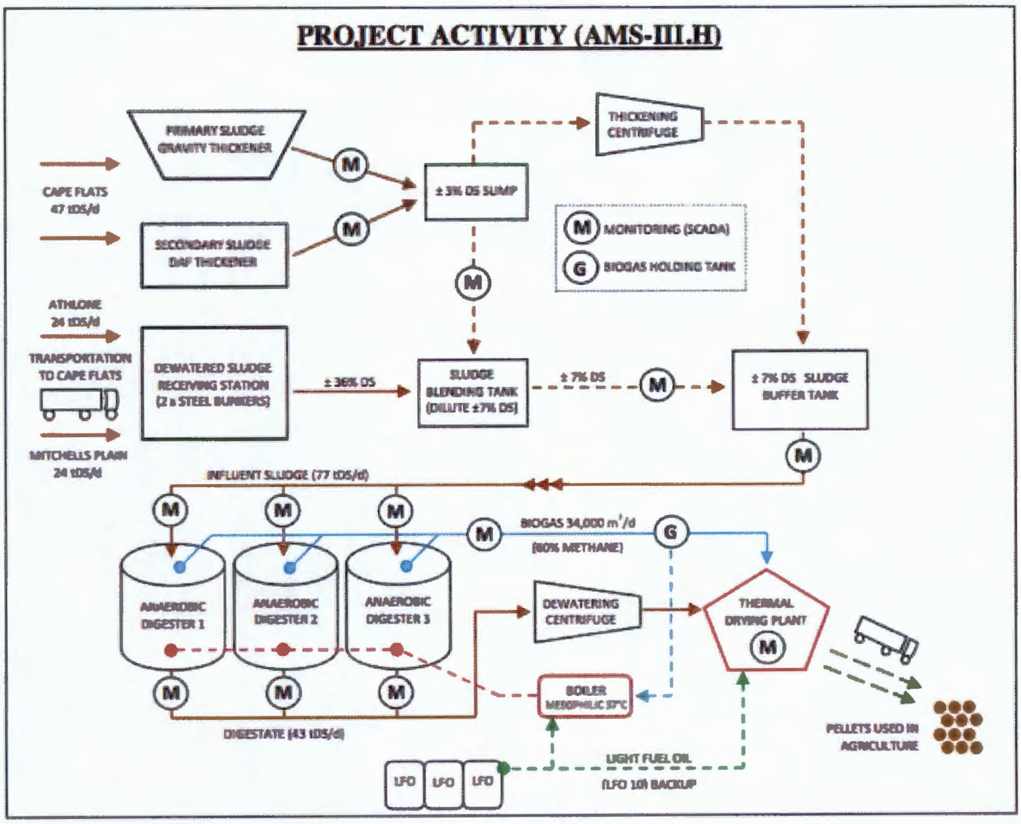


Figure E.2: Overview of slduge handling facility

E.3: Phosphate cycle in the Cape Flats WWTW

The 5-stage PhoRedox (Bardenpho) comprises of an anaerobic tank, followed by anoxic and aerobic stage with an internal recycle that serves as a pre-dentrification stage. Additional anoxic and aeration steps follow; reducing the nitrate into the anaerobic zone in the returned activated sludge.

Biological excess phosphate removal: Bardenpho process

In the anaerobic stage, short fatty acid are stored as poly-hydroxyl-alkanoate in phosphate accumulating organisms (PAOs). Energy for this mechanism is provided by the breakdown of polyphosphates into orthophosphates, hence increasing the soluble P concentrations.

In the aerobic zone, polyphosphate production increases the concentration of P in the solid phase. There is typically an excess uptake of P than the release to liquid phase experienced in the anaerobic zone. P-removal is disposed of in the excess waste activated sludge. Typical concentrations of P in the sludge

The main factors affecting phosphorus removal are:

- Anaerobic and aerobic stages must be in sequence
- VFAs must be present in the influent
- Minimize oxygen and nitrate in the recycle stre

TableE.1: Plant Effluent data

Compositions		average	wet season	dry season
Total Suspended Solids	mg/l	31,7	13,3	49,0
Volatile Suspended Solids	mg/l	481	480	485
COD	mg/l	95,6	56,0	113
COD filtered	mg/L	55,2	53,2	52,6
Ammonia	mg N/l	11,1	6,71	14,3
Nitrate/Nitrite	mg N/l	1,93	2,92	0,59
Ortho-Phosphate	mg P/l	5,11	4,7	5,78
pH		7,51	7,43	7,81
Conductivity	mS/m	78,2	77,5	87,7
Chloride	mg/l	99,7	97,5	103
Alkalinity	mg CaCO3/l	197	170	229
E.coli	per 100ml	2110	2800	1890

Appendix F: Technical assessment calculations

F.1: Technical assessment calculations for Option 1 and 2

Table F.1: Summary of process model calculations for Option 1 and 2

Flowrates	Units	
1 % desgn flow	L/day	1258000
Belt press	L/day	552000
only two digesters	L/day	435000
out of centrifuge	L/day	106000
Chosen design flow	L/day	106000
Percentage of inlet		0,800%
Mass OrthoPhosphate in	kgP/d	202
Mol OrthoPhosphate in	molP/d	2120
Design selection	molP/d	2120
Stochiometric feed rate [X: P]		1,30
Moles Magnesium reacting	gmolMg/d	2760
Mass Magnesium reacting	kgMg/d	67,1
Mass Magnesium in solution	kgMg/d	25,8
Moles Magnesium in solution	molMg/d	1060
Moles to be added	molMg/d	1700
Mass Magnesium to be added	kgMg/d	41,3
Mass Magnsium Chloride in	kgMgCl2/d	162
Mass Magnesium Oxide in	kgMgO/d	68,5

Table F.2: Summary of Reaction Kinteics for Option 1and 2, processe models

STOCHIOMETRY: Limiting reagent phosphate		
Conversion	mol %	0,9
Species		IN
PO4	mol/d	2124
Mg+	mol/d	2762
NH4+	mol/d	2762
Struvite (NH4MgPO4.H2O)	mol/d	0
Mass of recovered PO4	kg/day	182
Mass of P recovered P	kg/day	59
mols reacted	mol/d	-1912

Table F.2: Summary of Reaction Kinteics for Option 1and 2, processe models

Kinetics		
Residence time	min	30,0
Volume	m3	50,3
DOWNSTREAM TREATMENT (high grade)		
Mass flowrate dry struvite (hexahydrate)	kg/d	469
Mass flowrate dry struvite (hexahydrate)	kg/year	171000
Moisture content wet	wt%	1,50
Wet struvite from reactor (40% DS)	kg/d	1170
After drying solids %		0,900
Struvite mass after drying	kg/d	510
Water	kg/day	40,8
High grade	DS	92,0%
	dry basis	469
	processed	510
Low grade	DS	80%
	Dry basis	0,920
		1,15

Table F.3: Mass Balance over Option 1 and 2's process model

MASS BALANCE TABLE		INPUTS	OUTPUTS
Influent			
Influent stream	kg/d	1060000	
Salts	kg/d	269	
Chemical dosing			
Magnesium Oxide	kg/d	68,5	
Products			
Dried struvite	kg/d		469
Effluent	kg/d		1060000
Salts	kg/d		
Water vapour	kg/d		663
TOTAL	kg/d	1060000	1060000

TableF.4: PH adjustment calculations for Option 1 and 2

pH adjustment	
% NaOh in Caustic	47,0%
pH	4,90
pH	H+ions
4,9	1,26E-05
8,7	2,00E-09
Diff H+ions/dm3	1,26E-05
H+ions/day	1,01E-07
OH ions need	1,01E-07
moles of NaOH	1,01E-07
Mass of NaOH g	4,03E-06
Mass of caustic kg/day	8,57E-09
Solution available g/kg water	5,00E+02
Water kg/water	1,71E-08
Density kg/m3	1,53E+03
volume m3/day	9,27E-12

F.2: Technical assessment calculations for Option 3

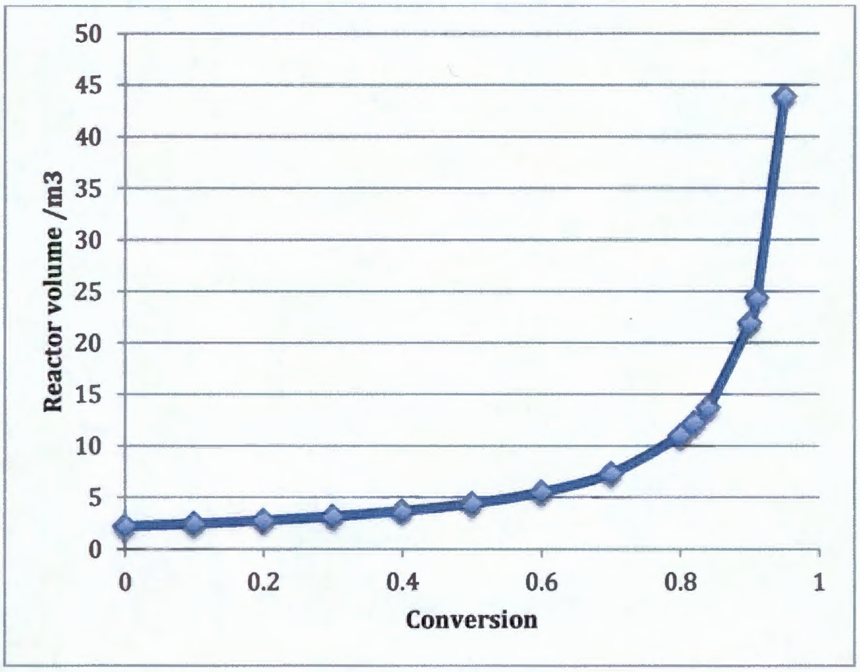
Table F.5: Slduge calculations for chemical ppt.

Sludge production after clarifier		unit	value
	Flowrate	L/day	1062000
		m3/day	1062
	Mass of stream	kg/day	1062000
Dry basis	aluminimu phosphate + hydroxide	kg/day	243
	Other solids	kg/day	1530
	TSS solids removal increase		0,25
	Solids %		0,00
	TSS concentration	mg/L	228
	Effluent back to head	kg/day	104200
	Solids recovery		0,96
wet basis	Sludge	kg/day	20000
	Solids %		0,03

Table F.5: Continuatio of slduge calculations for chemical ppt.

Dewatering belt press	unit	value
Sludge	kg/day	20000
Other solids	kg/day	1540
Solids	kg/day	243
Water	kg/day	64800
Dewatered slduge	%	0,3
Sludge	kg/day	2400
Recovery	%	1,01
Water in sludge		1800
Water back to effleunt	kg/day	646000
dry		601

F.3: Reactor sizing calculations for Option 1 and 2



FigureF.1: Ractor size vs. Conversion for the OSTARA design

TableF.6: OSTARA process parameters

Based on case study		
Max capacity	416	kL/day
Max capacity	416	m3/day
Max loading	186	kg/day
Effluent	30	kg/day
Conversion	84,0%	
Residence time	30,0	min
Volume	8,67	m3
Struvite produced	1610	kg/day

F.4: Reactor sizing calculations for Option 3

Table F.7: Reactor for Option 3 sizing information using heurestics

Option 3 reactor		
T	min	5
vo	L/min	737
V	L/day	1060000
	L/min	739
	L	3 690
	m3	3,69

F.5: Equipment sizing for Option 1,2 and 3

Table F.8: Feed tank example calculation using heurestics

Feed Tank			
Orientation	Horizontal		Heureustics
Hold up time - half full	0,20	days	Heureustics
Flowarate in	1060	m3/day	
Flowrate in	0,737	m3/min	
Volume 1/2- 3/4 full	212	m3	
Vessel size	283	m3	
Diameter	6,50	m	Heureustics
L/D	1,31		
Height/ Length	8,53	m	

F.6: Pump Sizing Calculations for Option 1, 2 and 3

The calculations for the pump power, efficiency, head and NPSH were performed using engineering design heuristics and class notes as guidelines

$$PSUCT = PSOURCE + PSTATIC - PLINE\ LOSS$$

It was assumed that the line loss pressure from the source was negligible. Prior to NPSH calculations all vessel elevations were considered to be zero.

P_{DISC}	Discharge pressure
P_{SUCT}	Suction pressure

ϱ	Density of substance
g	Acceleration due to gravity (9.8 m/s^2)
Z_1	Is the vessel elevation + the liquid height in the vessel
P_{SOURCE}	Gauge pressure at the origin vessel
P_{VESSEL}	Operating Pressure of the vessel

TableF.9: Sample pump calculations

Equipment	Units	Influent	Recycle pump
Quantitiy		3	1
Capacity	m3/hr	48,7	4,90
Head	m	7,63	74,4
Efficiency	%	62,4	30,1
Power	kW	1,62	3,28
(NPSH) avaliable	m	12,7	15,4

F.7: OSTARA Technical brochure Pearl 2000 for use in Option 1

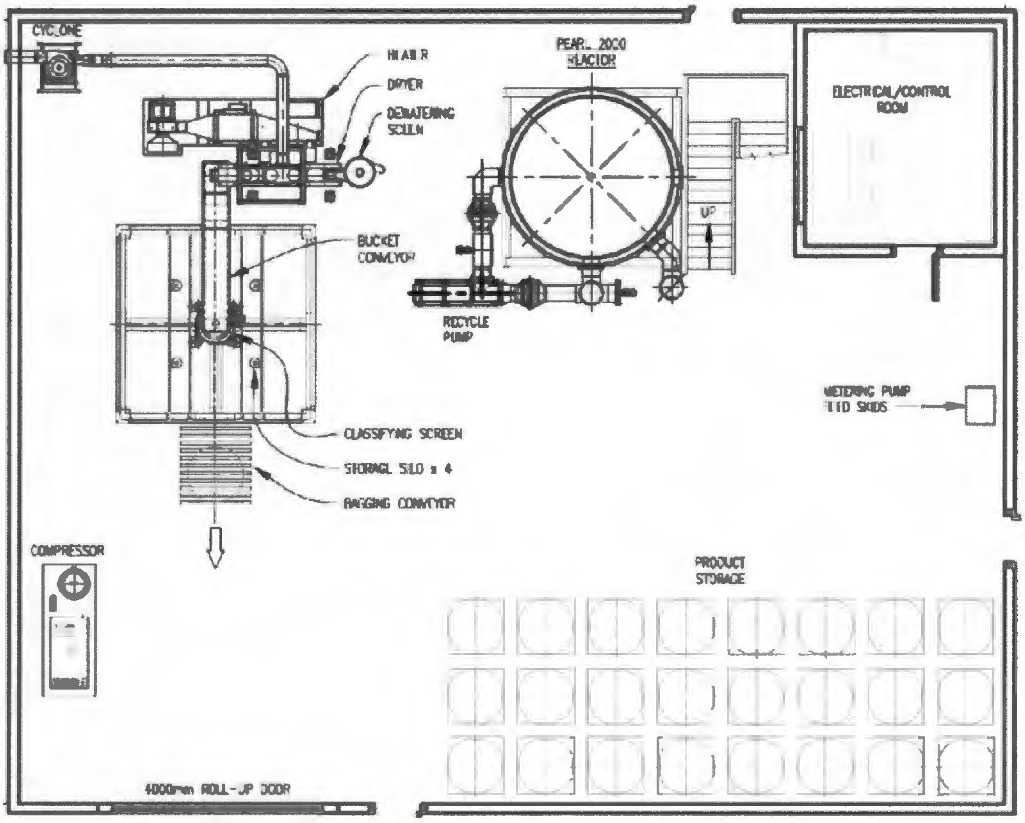


Figure F.2: OSTARA technical brochure for Pearl 2000 setup

Appendix G: economic assessment of Option 1, 2 and 3

G.1: Costing for Option 1 and 2

Table G.1: Option 1 based on using location factor and CEPI

Based on case study		
Max capacity	416	kL/day
Max capacity	416	m3
Max loading	186	kg/day
Effluent	30,0	kg/day
Conversion	84,0%	
Residence time	0,791	min
Volume	13,7	m3
Struvite produced	1610	kg/day
Full installation price 2010	□2□ 00□□□	ZAR
CEPI 2010	551	
CEPI 2013	568	

Full installation price 2013	33 300 000	ZAR

Table G.2 Location factors

Location change	Factor
UK to SA	1.25
USA to SA	1.15

Table G.3: Costing using plant flowarte capacities for 6th tenths rule

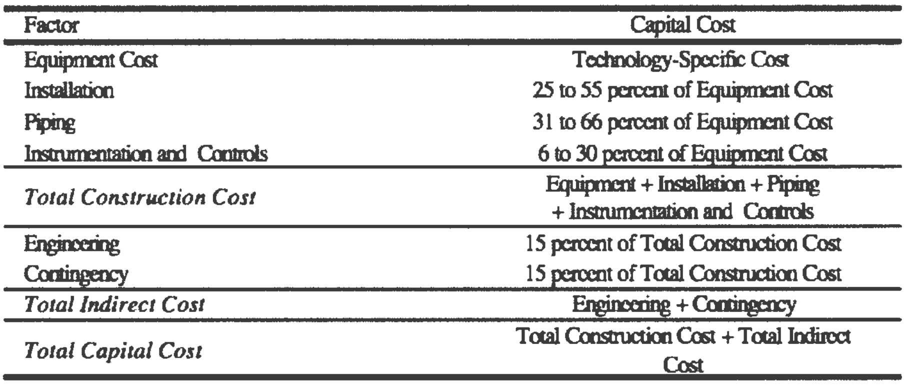
CAPEX			OSTARA	Multifrom
X	V	T	price	
0,7	18,7	0,42	40100000	1060000
0,71	19,3	0,44	40900000	10800000
0,8	28,0	0,63	51100000	13600000
0,84	35,0	0,79	58400000	15600000
0,9	56,0	1,27	77400000	20600000
0,91	62,2	1,41	82500000	21900000
0,92	70,0	1,58	88500 000	23500000
0,95	112,0	2,53	117000000	31100000

G.2: Option 3 costing

Used the costing for sixth tenths rule scale up from tertiary chemical precipitation $/Ml estimates in Tetra Tech.

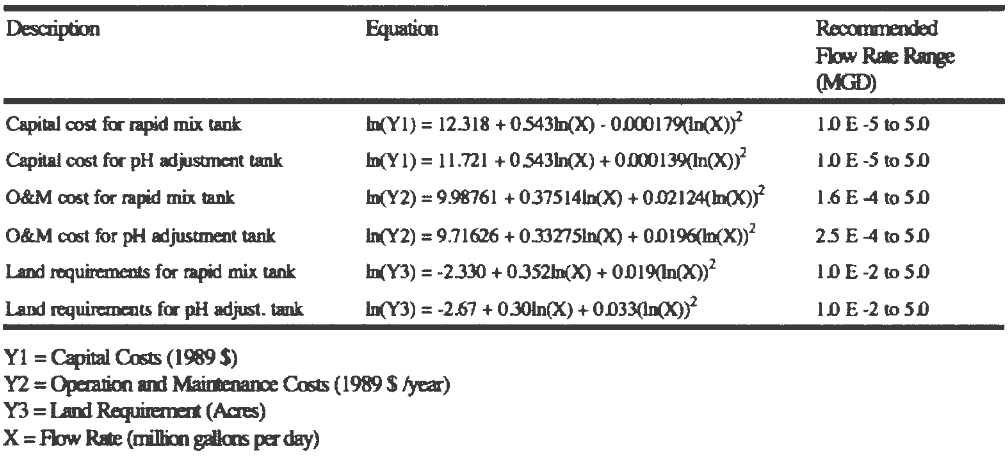
Table G.4: Capital costing for optin 3 using Tetra Tech (2013)

	unit		unit
1,00	mgd		
3,78	mld	954000	l/day
0,89	gdp		
0,235	l/day	225000	$/ml
225 000	$/ML	2410000	zar
2 410 000	ZAR mill		



Factor	Capital Cost
Equipment Cost	Technology-Specific Cost
Installation	25 to 55 percent of Equipment Cost
Piping	31 to 66 percent of Equipment Cost
Instrumentation and Controls	6 to 30 percent of Equipment Cost
Total Construction Cost	Equipment + Installation + Piping + Instrumentation and Controls
Engineering	15 percent of Total Construction Cost
Contingency	15 percent of Total Construction Cost
Total Indirect Cost	Engineering + Contingency
Total Capital Cost	Total Construction Cost + Total Indirect Cost

Figure G.1: Capital Cost Algorith for both costing systems (USEPA, 1997)



Description	Equation	Recommended Flow Rate Range (MGD)
Capital cost for rapid mix tank	$\ln(Y1) = 12.318 + 0.543\ln(X) - 0.000179(\ln(X))^2$	1.0 E -5 to 5.0
Capital cost for pH adjustment tank	$\ln(Y1) = 11.721 + 0.543\ln(X) + 0.000139(\ln(X))^2$	1.0 E -5 to 5.0
O&M cost for rapid mix tank	$\ln(Y2) = 9.98761 + 0.37514\ln(X) + 0.02124(\ln(X))^2$	1.6 E -4 to 5.0
O&M cost for pH adjustment tank	$\ln(Y2) = 9.71626 + 0.33275\ln(X) + 0.0196(\ln(X))^2$	2.5 E -4 to 5.0
Land requirements for rapid mix tank	$\ln(Y3) = -2.330 + 0.352\ln(X) + 0.019(\ln(X))^2$	1.0 E -2 to 5.0
Land requirements for pH adjust. tank	$\ln(Y3) = -2.67 + 0.30\ln(X) + 0.033(\ln(X))^2$	1.0 E -2 to 5.0

Y1 = Capital Costs (1989 $)
Y2 = Operation and Maintenance Costs (1989 $ /year)
Y3 = Land Requirement (Acres)
X = Flow Rate (million gallons per day)

FigureG.2: Capital cost algorithms for tertaiy chemical precipitation (USEPA, 1989)

Table G.5: Cost estimates using (USEPA, 1989)

	CAPEX if all new	OPEX
US$1989	632000	417000
US$2013	923000	4110000
ZAR	9930000	44200000
	If already have filter	
US$1989	226000	28000
US$2013	330000	279000
ZAR	3540000	3000000
	If already have a clarifier	
US$1989	571000	25300
US$2013	834000	250000
ZAR	8970000	2683000
	Have both clarifier and filter	
US$1989	164100	24400
US$2013	240000	240000
ZAR	2580000	2580000
Chemical costs	CAPEX	OPEX
If all new equipment	9930000	44200000
If you have filter	3543000	3000000
If you have clarifier	8970000	2680000
If you have all	2580000	2580000

G.3: Fertilizer market and struvite costing

TableG.6: Summary of phopshate based fertilizer prices as of March 2014

Fertilizer	ZAR
Di –ammonium Phosphate (DAP) Bulk	5600
Di –ammonium Phosphate (DAP) 1 Ton	5800
Di –ammonium Phosphate (DAP) 50 kg	6000
Mono –ammonium phosphate (MAP) Bulk	4800
Mono –ammonium phosphate (MAP) 1 Ton	5100
Mono –ammonium phosphate (MAP) 50kg	5200
Mono –ammonium phosphate with zinc (MAPZ) Bulk	5000
Mono –ammonium phosphate with zinc (MAPZ) 1 Ton	5200
Mono –ammonium phosphate with zinc (MAPZ) 50kg	5300
Palfos B	1300
Palfos R	1200

In 2013, imports and costs increased by 21.1% and 27% (R2900 million) respectively between 2012 and 2013. The estimated price per tonne imported is about R4000, a 4.8% increase within a year (Mostert, 2013). Alternative fertilizer use such as cattle and chicken manure, amounted to 30 000 tons in 2013; a 3-4% equivalence to inorganic fertilizer.

G.4: Struvite costing

Table G.7: Weighted values and regression to determine struvite prices

		MR	N	P04	K	Mg	NH4
DAP	$(NH_4)_2HPO_4$	132	11,0%	72%			14%
MAP	$NH_4H_2PO_4$	115	12,1%	83%			16%
MAPZ	$NH_4H_2PO_4$	180	7,98%	53%			10%
Palfos	Ca_5PO_4F	313	3,95%	30%			6%
TSSP	$Ca(H_2PO_4)_2.H_20$	252	6,10%	38%			7%
Struvite ($NH_4MgPO_4.6H_2O$)		245	6,21%	39%		10%	7%
$MgCl_2$		95,205				26%	

		per kg				
	price/R	N	PO4	Mg	K	NH4
DAP	5,7	0,605	4,10	0	0	0,778
MAP	5	0,609	4,1			0,783
MAPZ	5,2	0,404	2,74			0,519
Palfos	1,3	0,0582	0,394			0,0748
TSSP	0,00	0,00	0,00			0
Struvite ($NH_4MgPO_4.6H_2O$)		0,419	2,84			0,539
$MgCl_2$	8,3			2,12		

Appendix H: net present values calculations

H.1: profitability analysis

Profitability indicators were calculated using the following formulae:

H.2: payback period

$$\text{Payback period} = \frac{\text{Fixed capital investment}}{\text{Average annual cash flow}}$$ **Equation H.1**

H.3: net present value (NPV)

$$\text{NPV} = \sum_j^N \text{DCF}$$ **Equation H.2**

Table H.1: Costing parameters

Information	
Depreciation (years)	0,1
Tax Rate %	0,28
Discount Rate %	10
2014/2015	
Fixed capital	25600000
Exchange rate	10,8
Working capital	15,0%
Infrastructure	3084000
civil	1030000
Utilities	
Electricity kWh/day	204
Electricity inflation	4,00%
Fixed	
Depreciation	1030000
Maintenance	
	822000
Labour	117000
Utilities	
Electricity	74300
Chemicals	
Magnesium	4,90E+05
Caustic soda	970
Water	1700
Total	1510000
Revenue	63400

Table II.2: NPV calculations overview for Option 2

Year	Revenue	Electricity	Operatin cost	Gross Profit	Depreciation	Gross -dep	tax	net profit	net cash flow	discounted	NPV
	6,34E+04	7,43E+04	2,20E+07	-2,20E+07	1,03E+06	-2,30E+07	-6,45E+06	-1,66E+07	-1,56E+07	-13524724,72	
2014	0,00E+00	7,43E+04	0,00E+00	0,00E+00	1,03E+06	0,00E+00	0,00E+00		-4,25E+07	1,00E+00	-1,35E+07
2015	6,34E+04	7,73E+04	1,51E+06	-1,52E+06	1,03E+06	-2,55E+06	-1,81E+06	-7,43E+05	2,85E+05	2,59E+05	-1,33E+07
2016	6,34E+04	8,04E+04	1,51E+06	-1,52E+06	1,03E+06	-2,55E+06	-5,06E+05	-2,05E+06	-1,02E+06	-8,41E+05	-1,41E+07
2017	6,34E+04	8,36E+04	1,51E+06	-1,53E+06	1,03E+06	-2,55E+06	-1,42E+05	-2,41E+06	-1,39E+06	-1,04E+06	-1,51E+07
2018	6,34E+04	8,69E+04	1,51E+06	-1,53E+06	1,03E+06	-2,56E+06	-3,96E+04	-2,52E+06	-1,49E+06	-1,02E+06	-1,62E+07
2019	6,34E+04	9,04E+04	1,51E+06	-1,53E+06	1,03E+06	-2,56E+06	-1,11E+04	-2,55E+06	-1,52E+06	-9,45E+05	-1,71E+07
2020	6,34E+04	9,40E+04	1,51E+06	-1,54E+06	1,03E+06	-2,56E+06	-3,11E+03	-2,56E+06	-1,53E+06	-8,66E+05	-1,80E+07
2021	6,34E+04	9,78E+04	1,51E+06	-1,54E+06	1,03E+06	-2,57E+06	-8,70E+02	-2,57E+06	-1,54E+06	-7,90E+05	-1,88E+07
2022	6,34E+04	1,02E+05	1,51E+06	-1,54E+06	1,03E+06	-2,57E+06	-2,44E+02	-2,57E+06	-1,54E+06	-7,21E+05	-1,95E+07
2023	6,34E+04	1,06E+05	1,51E+06	-1,55E+06	1,03E+06	-2,58E+06	-6,82E+01	-2,58E+06	-1,55E+06	-6,57E+05	-2,01E+07
2024	6,34E+04	1,10E+05	1,51E+06	-1,55E+06	1,03E+06	-2,58E+06	-1,91E+01	-2,58E+06	-1,55E+06	-5,99E+05	-2,07E+07
2025	6,34E+04	1,14E+05	1,51E+06	-1,56E+06	1,03E+06	-2,59E+06	-5,35E+00	-2,59E+06	-1,56E+06	-5,46E+05	-2,13E+07
2026	6,34E+04	1,19E+05	1,51E+06	-1,56E+06	1,03E+06	-2,59E+06	-1,50E+00	-2,59E+06	-1,56E+06	-4,98E+05	-2,18E+07
2027	6,34E+04	1,24E+05	1,51E+06	-1,57E+06	1,03E+06	-2,59E+06	-4,19E-01	-2,59E+06	-1,57E+06	-4,54E+05	-2,22E+07
2028	6,34E+04	1,29E+05	1,51E+06	-1,57E+06	1,03E+06	-2,60E+06	-1,17E-01	-2,60E+06	-1,57E+06	-4,14E+05	-2,27E+07
2029	6,34E+04	1,34E+05	1,51E+06	-1,58E+06	1,03E+06	-2,60E+06	-3,29E-02	-2,60E+06	-1,58E+06	-3,77E+05	-2,30E+07
2030	6,34E+04	1,39E+05	1,51E+06	-1,58E+06	1,03E+06	-2,61E+06	-9,20E-03	-2,61E+06	-1,58E+06	-3,44E+05	-2,34E+07
2031	6,34E+04	1,45E+05	1,51E+06	-1,59E+06	1,03E+06	-2,62E+06	-2,58E-03	-2,62E+06	-1,59E+06	-3,14E+05	-2,37E+07
2032	6,34E+04	1,51E+05	1,51E+06	-1,59E+06	1,03E+06	-2,62E+06	-7,22E-04	-2,62E+06	-1,59E+06	-2,87E+05	-2,40E+07
2033	6,34E+04	1,57E+05	1,51E+06	-1,60E+06	1,03E+06	-2,63E+06	-2,02E-04	-2,63E+06	-1,60E+06	-2,62E+05	-2,42E+07
2034	6,34E+04	1,63E+05	1,51E+06	-1,61E+06	1,03E+06	-2,63E+06	-5,66E-05	-2,63E+06	-1,61E+06	-2,39E+05	-2,45E+07