UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CHEMICAL ENGINEERING

INTRODUCING LOOP-CLOSURE FOR PHOSPHATES INTO A PROVINCIAL DEVELOPMENT STRATEGY: AN ANALYSIS OF OVERLAPS OF PRIMARY AND SECONDARY PHOSPHATE PROCESSING TECHNOLOGIES

Prepared By: Sizwe Vidima

SUPERVISOR: PROF HARRO VON BLOTTNITZ, UNIVERSITY OF CAPE TOWN

CO-SUPERVISOR: PROF JOCHEN PETERSEN, UNIVERSITY OF CAPE TOWN

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ABSTRACT

Almost 90% of the global phosphoric acid demand can primarily be linked to fertiliser production for application onto agricultural lands (PotashCorp, 2014). To fulfil the phosphate fertiliser demand in South Africa's arable soils, the country largely relies on the mining and processing of the extensive igneous phosphate ore deposits found in Phalaborwa, Limpopo (DMR, 2008); but this extractive approach to procuring phosphates is not sustainable. Moreover, due to rising phosphate demands and declining ore grades, worldwide phosphate ore reserves are expected to last only approximately 100 - 400 years (Smil, 2000). The intensification of phosphate resource consumption has also resulted in increased phosphate loads in wastewater treatment plant (WWTP) influents thereby exerting pressure on existing treatment systems and potentially, on water ecosystems in which these phosphates end up. Therefore, it is because of the myriad difficulties associated with linear phosphate resource flows that there has been ongoing research on the recovery of phosphate nutrients from wastewater (Durrant, et al., 1999; Levlin and Hultman, 2004; Sikosana, 2015) and source-separated urine (Ganrot, 2005; Pronk and Kone, 2009).

Consequently, the purpose of this dissertation is to investigate a novel approach to loop-closure through the recovery of urine-bound phosphates. Uniquely, this research considers the subsequent integration of the recovered phosphate into existing primary phosphate processing facilities – stimulated by a process to develop a sub-national minerals beneficiation strategy for the kwaZulu-Natal (KZN) province in South Africa. Not only does the investigation seek to understand the technical potential of reintroducing waste-bound phosphates into the phosphate value chain but it also seeks to understand the potential for the respective contribution into the socio-economic sphere of sustainable development through employment creation.

Three research approaches were used in obtaining results in this dissertation. Firstly, flowsheet simulations of Dihydrate phosphogypsum (DH) and Hemihydrate phosphogypsum (HH) producing processes were done. The materials balance simulations included a base case where a secondary phosphate source was not introduced in the process and the case where it was introduced into the processes in the form of struvite recovered from sanitation infrastructure. Secondly, a socio-economic assessment was carried out. This involved a cost analysis of implementing a reverse logistics network that collects urine from non-sewer-served areas, processes it into struvite and transports the struvite into a phosphoric acid complex, such as the one owned by Foskor in Richards Bay. In addition to this, the quantity of jobs was determined. Lastly, interviews and desktop research were used to learn about past experiences in recycling thereby providing insight regarding key considerations when implementing extended producer responsibility schemes.

With the assumptions that are detailed in Chapter 3, the results of Chapter 4 reveal that it should be possible, from a technical standpoint, to integrate struvite into existing phosphoric acid generation processes. However, the use of struvite in such a process raises concern in the form

of loss of phosphoric acid production if the feed tonnage is kept constant. Furthermore, there is a presence of magnesium in the product acid which has been known to adversely affect the formation of gypsum crystals. Additionally, when using the struvite cost obtained from Sikosana (2015) it can be argued that there is little to no process-related financial benefit in integrating struvite in a phosphoric acid generation complex such as the investigated DH and / or HH processes.

The socio-economic analysis showed that implementing a reverse logistics network for the recycling of phosphates would cost 147,000 ZAR per ton of struvite generated whilst creating approximately 9,000 to 18,000 jobs (depending on the approach) in the respective collection, processing and transportation phases in recycling, if urine collection were to be extended to all households in KZN not served by network sewer systems. Furthermore, the study revealed that the funding model in the extended producer responsibility scheme would have to contribute an average of 152,000 ZAR per year, through some form of subsidy, for every job that exists in the network.

Critical insight was drawn from the literature study and interviewing process. It was found that the key considerations that need attention when setting up an extended producer responsibility (EPR) scheme include a well-governed and aligned producer responsibility organisation (PRO) to assist the producer in achieving their respective production targets. Secondly, there is evidence that mandatory approaches to EPR funding have been less successful as funding approaches for EPR schemes in South Africa; in fact, the more successful EPR schemes have been voluntary / industry driven approaches.

As a basis, the work in this dissertation can be used in influencing future work in the phosphate loop-closure context. It can then be concluded that the return of urine-derived struvite, as a secondary phosphate raw material, into industrial phosphoric acid processing should be technically possible. In doing so, a more circular phosphate value chain could be achieved. The reintroduction of a secondary phosphate source in the HH and DH processes would therefore bring about new work opportunities, and thus the upliftment of the socio-economic status of the individuals involved in the reverse logistics that facilitate struvite supply.

It is recommended that technical questions, for example the specifics of how struvite interacts with sulphuric acid, be further investigated from a thermodynamic and reaction kinetics perspective. Also, there is enough evidence to start an expert discussion about the suitability of existing mechanisms that have been accepted and used by industrial producers to give effect to their extended environmental responsibilities, for application in phosphate loop-closure.

DECLARATION

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own. This thesis/dissertation has been submitted to the Turnitin module (or equivalent similarity and originality checking software) and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

Student Name: Sizwe Bonga Innocent Vidima

Student Number: VDMSIZ001

Date of original submission: 17 July 2018

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Signature: Signed by candidate

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The time is exactly 04:07:30 AM (of course I had to Google this to make sure I was right!) on the 14/06/2018 as I sit on my chair astonished by how much the MPhil has opened my eyes to a much-needed progressive way of problem-solving.

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‘A luta continua, vitória é certa’

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GLOSSARY

Eutrophication	A widespread problem which occurs in water bodies because of excess nutrient content. It refers to the excess growth of algae and toxins which deplete the oxygen content of water thus being harmful to humans and aquatic lifeforms.
Marine Phosphate Mining	The deep-sea mining of phosphate minerals. This method of mining dredges the seabed and exposes the benthic zone to nutrients while also upsetting the gravel sand layer structure.
Comminution	The average size reduction of solid minerals by crushing, grinding or other processes. This process is effective for increasing the total surface area of particles to prepare for reaction with chemical reagents.
Flotation	The separation process associated with separating crushed minerals from one another using chemical reagents to selectively float mineral present in the ore.
Phosphoric Acid	The main intermediate product formed by reacting phosphate rock with sulphuric acid during the mineral processing stage of phosphate beneficiation. Liquid phosphoric acid can be dried until a white crystalline solid anhydride – phosphorus pentoxide – is formed.
Biomimicry	An innovative design approach which mimics nature's time-tested patterns and strategies in the design of modern technology design.
Sustainable Development Goals	A list of universal goals aimed at developing and developed countries to improve the social, economic and environmental conditions.
Circular Economy	An economy whose growth has been decoupled from waste generation and environmental pollution.
Extended Producer Responsibility (EPR)	EPR is a "policy concept aimed at extending the producers responsibility for their products to the post-consumer stage of their products lifcycle" (Nahman, 2010)

CHAPTER 1. INTRODUCTION

The finite nature of natural mineral resources, coupled with the rise in ore extraction rates from reserves as well as the linearity of the conventional industrial economy, introduce the challenge of premature resource depletion (Anderson, 2006; Harthwick & Olewiler, 1986). To delay this depletion, industrial economies must and are becoming increasingly circular. Circular economies allow for the reduction in the use of natural/virgin resources, avoid waste burdens on ecosystems and often also reduce energy consumption in extractive and processing industries. The concept of a circular economy is important in industrial ecology, but not to be confused with industrial symbiosis, which '*envisions a form of material symbiosis between otherwise very different companies and production processes*' (Anderson, 2006).

There is a growing literature and industrial practise of phosphate loop-closure, to which the research pursued in this dissertation aims to make a specific contribution, in the context of sub-national economic development planning, specifically of the KwaZulu-Natal (KZN) province of South Africa. The potential opportunity of phosphate recycling in the context of the KZN province is informed on the one hand by the presence of a reputable phosphate processing plant in Richards Bay, KZN and on the other and by the sanitation backlog in the developing parts of South Africa.

1.1 BACKGROUND TO RESEARCH

Phosphorus (P), nitrogen (N) and potassium (K) are three of the sixteen elements that are essential for the development of flora. Each element is embedded into various complex chemical compounds that have unique roles in the growth of living species (Baligar, et al., 2001; Uchida, 2000).

Three notable terrestrial phosphate exploration, development or mining projects exist in South Africa. The first is owned by Foskor Limited. With ore being the dominant source of phosphate rock in South Africa, Foskor Limited has mined this ore near Phalaborwa, Limpopo since the mid-1900s. The mined rock is then railed to Richards Bay, KZN for processing into various phosphate products and a certain portion is exported to international markets (DMR, 2008; Foskor, 2014). The second largest phosphate reserves are the sedimentary deposits that lie on the West Coast of South Africa. At the time of writing this document, Elandsfontein Exploration and Mining (Pty) Ltd had been developing this area into one that can be mined industrially (Elandsfontein, 2016). Lastly, Montero Mining and Exploration is currently exploring phosphate deposits in the Western Cape and Northwest provinces of South Africa. There are currently four exploration sites being explored by Montero Mining and Exploration, three of which are situated in the Western Cape and one in the Northwest Province (Montero Mining , 2015).

Extensive research on phosphates has revealed that global terrestrial phosphate-bearing rock reserves are expected to be depleted in the next 100-400 years (Brunner, 2010; Smil, 2000; Van Kauwenbergh, 2010). As an alternative to the conventional mining of land reserves, the eccentric unearthing of phosphate reserves through marine mining has also been gaining traction. Similar to the mining of terrestrial phosphate reserves, marine phosphate mining would secure phosphate supplies for a certain time but would be blind to the environmental burdens that would result from phosphate flow intensification (Centre for Environmental Rights, 2015). Thus, the desirability of marine phosphate mining is in question.

1.1.1 PHOSPHORUS BIOLOGICAL IMPORTANCE TO LIVING SPECIES

The phosphorus element, specifically, is typically found and absorbed into fauna and flora as orthophosphate (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$) compounds. Vegetation absorb phosphate nutrients from the soil through roots whereas animals do so through the consumption of vegetation and other animals. Phosphorus has multiple roles in both plants and animals, some of which include, but are not limited to: the storage and transfer of energy during photosynthesis and respiration (plants), formation of DNA and RNA structures (plants and animals as shown in Figure 1 for DNA molecules) and in aiding root development as well as seed and fruit development in plants (Uchida, 2000; EFMA, 2000a). The application of fertiliser onto arable soil therefore supplements nutrient content and thus maintains the right balance of key nutrients, including phosphates, in the soil, if applied correctly (Baligar, et al., 2001; EFMA, 2000a). Approximately 80% of the phosphorus in animals and humans is found in the bone structure, the balance is distributed throughout the body as part of proteins, inorganic salts and fats (IPNI, 1999). Moreover, the uptake of phosphorus in both fauna and flora varies according to species type. Furthermore, the recommended daily intake (RDI) of phosphorus in humans varies from 0.5-1 grams phosphorus, depending on age, metabolism and other factors (EFMA, 2000a).

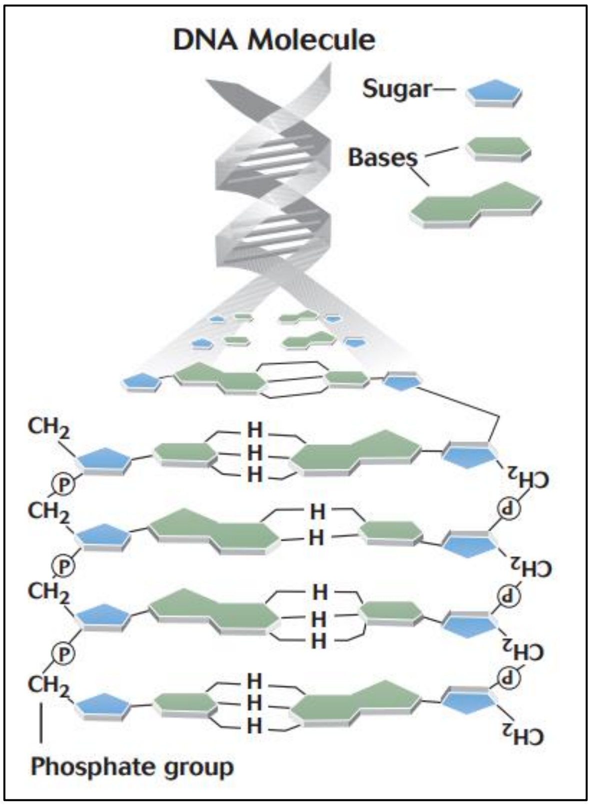

Figure 1: Phosphates as DNA Building Blocks (Anglo American, n.d.)

1.1.2 PHOSPHATE NUTRIENTS AND AGRICULTURE IN SOUTH AFRICA

In agriculture, the phosphate, nitrogen and potassium-based macronutrients have a notable commercial value. Owing to industrialisation and population growth, phosphate fertilisers are procured through the mining of finite phosphate-bearing ores (such as apatite rock) and the subsequent processing of these mineral ores. The processing of ores into commercial grade fertiliser thus heavily relies on fossil energy and the mined mineral resources. After processing, liquid or solid fertiliser is applied onto soil with the purpose of maintaining the right nutrient balance in the soil for plant uptake. What remains a challenge to the agricultural sector is, however, the **efficient** application of fertiliser onto soils. In the case where excessive application of fertiliser to soils is followed by heavy rains, phosphate surface runoff can occur. Nutrient runoff into waters often then leads to eutrophication of these water bodies thus disrupting aquatic ecosystems (EFMA, 2000a). In other instances, such as that in highly porous soils the water-dissolved nutrients may leach into the soil (EFMA, 2000a), and can eventually contaminate ground water systems and affecting users thereof. Inadequate application of fertiliser on the other hand has adverse effects in that it limits healthy plant growth (Ganrot, 2005; Uchida, 2000) thereby restricting crop yield if an incorrect balance of macronutrients is obtained.

The contribution of agriculture to South Africa's GDP has continued to decline (Department of Agriculture, Forestry and Fisheries, 2013). Whilst agriculture contributes only a small portion to overall economic activity, it is a foundational activity. South Africa is one of the few countries globally that is a net exporter of food. Much agricultural activity happens in KZN and the Western Cape, the two provinces contributing 26.4% and 22.6%, respectively (Statistics South Africa, 2014).

1.1.3 SANITATION IN SOUTH AFRICA

Contrary to the agricultural sectors experience, the common perception in sanitation is that nutrients carried in waste water is a problematic material as opposed to a resource. This perception then fuels the current status quo of the detachment of commercial value from nutrient-rich animal manures and *water-carried* nutrient sources such as sewage and more recently source-separated urine. The sanitation industry often disposes of ‘wastewater’, albeit a nutrient rich resource, into water bodies after treatment which mainly involves the removal of phosphates from water effluents as is detailed in chapters to follow. Upsets in any of the upstream processes that treat waste often has the potential to cause further downstream upsets to natural ecosystems through eutrophication (Ganrot, 2005).

South Africa’s Department of Water and Sanitation (DWS) is the custodian of the country’s water resources. The primary responsibility of the DWS is to provide clean water access and dignified sanitation while promoting effective water resources management to ensure sustainable economic and social development (Department of Water & Sanitation, 2016). The total budget allocated to the DWS for the 2016/2017 financial year amounted to R15.2 billion, R3.1 billion of which has been set aside for the Water Services Infrastructure Grant (WSIG) (DWA, 2016). The WSIG primarily aims to tackle water and sanitation backlogs around the country. All in all, South Africa has invested heavily in combating unhygienic sanitation and according to the report by the Department of Water Affairs (DWA), the sanitation backlog has been reduced from 52% in 1994 to 20% in 2017 (SERI, 2011; Statistics South Africa, 2010; DWS, 2018).

The Valorisation of Urine Nutrients (VUNA) project has already explored nutrient recovery from urine in rural parts of the KZN Province. Three main recovery methods, nitrification and distillation, electrolysis and struvite precipitation have been tested for their respective abilities to recover value in the form of fertiliser from source-separated urine. Of interest in this study is the struvite precipitation process. The VUNA project has however pointed out knowledge gaps such as the downstream consequence of using pathogen-bearing fertiliser directly onto crops.

1.1.4 KZN’S PROVINCIAL MINERAL BENEFICIATION STRATEGY

The minerals beneficiation strategy of the province of kwaZulu-Natal (KZN) is meant to interpret the national minerals beneficiation strategy in the context of the province’s economic reality and strategy. The provincial strategy is aimed at ‘*further driving the minerals sector in KZN towards a more profitable, socially accountable and environmentally sustainable future’* – former KZN Premier Senzo Mchunu stated. In economic terms, the beneficiation strategy aims to identify ways of translating the country’s comparative advantage, mainly inherited from the abundance of mineral resources, to a national competitive advantage (Department of Mineral Resources, 2011).

Five minerals of importance to this strategy are: aluminium, mineral sands and titanium, coal, iron and steel and phosphates. The success of manufacturing and agricultural industries, in and outside of the province, rely on the abovementioned minerals.

Of interest in this study is the phosphate mineral value chain. Foskor's Acid Division in Richards Bay has a good reputation regarding product quality and is well-positioned to continue driving economic growth in the province. However, the industry does have a few weaknesses, including the dependence on international imports of ammonia and sulphur and previously also electricity supply shortages (Foskor, 2014). It is such weaknesses that the minerals beneficiation strategy aims to address with the purpose of identifying new opportunities for further driving inclusive economic growth provincially and nationally.

1.2 PROBLEM STATEMENT

Phosphorus flows in South Africa, and the rest of the world, begin at mining and processing, then application onto arable soils, followed by consumption as food by humans and animals, excretion, waste water treatment and disposal or release into waterbodies.

Population growth has led to the intensification of the above-mentioned phosphate flows but has neglected effective and efficient resource management. In the phosphate context, this means the sanitation branch of government will continuously have to invest in sanitation facilities that can handle increasing wastewater volumes. Additionally, mining industries are having to persistently mine increasing quantities of phosphate ore so as to address demand that primarily comes from agriculture in the form of food and non-food (e.g. biofuels) industries. The Department of Water and Sanitation currently faces the challenges of meeting sanitary needs of all South Africans through provision of adequate sanitation facilities (toilets and clean water) to households. The mining industry ultimately has to consider primary phosphate ore depletion as well as the more pressing issues of declining ore grades and social and environmental impacts. Lastly, agriculture not only faces the challenge of addressing food security but also the challenge of inefficient fertiliser application and hence nutrient runoff into waterbodies; again a cause for social and environmetal concern.

Given the abundance of phosphates in human wastes coupled with the need for achieving universal sanitation services in the peri-urban and rural areas of KZN, the presence of a reliable phosphate processing plant in Richards Bay and the KZN Minerals Beneficiation Strategy, it is noteworthy that industrial symbiosis possibilities between mineral beneficiation, sanitation and agriculture for closing the phosphate loop exist but have not yet been studied.

1.3 OBJECTIVE OF STUDY

Broadly, the key intent of this study is to produce knowledge. This study investigates the possibility of phosphate loop-closure through the fulfilment of the aims listed below:

i. A thorough investigation into the potential use of a secondary phosphate source, struvite derived from source-separated human urine, as a feed material into existing industrial phosphate processing complexes.
ii. An investigation into the potential socio-economic impacts of the collection, treatment and transportation of urine.
iii. A brief investigation into institutional mechanisms for recovering a valuable compound from waste for return into industrial production.

The study thus also aims to make recommendations of possible strategies that could guide a more sustainable procurement of phosphate-based fertiliser.

1.4 SCOPE AND LIMITATIONS OF STUDY

Most literature focuses on phosphate recovery from sewage systems at wastewater treatment plants (WWTP) however this study focuses on phosphate procurement from decentralised source-separated urine collection, followed by treatment into struvite and then further processing in an existing phosphate complex. The study will however use knowledge gained from literature on WWTPs to gain an overall understanding of existing work and guide thinking into phosphate recovery from source-separated human urine. Secondly, although urine is rich in many other nutrients, the focus in this work will be restricted to the recovery of phosphate nutrients only. Furthermore, the study will not at all focus issues on social acceptability of recycling phosphate through struvite recovery and processing. Since struvite is processed into phosphoric acid using sulphuric acid, it was taken that social issues emanating from the direct use of struvite would be insignificant for the public to concern about.

The work also aims to contribute to the development of a regional economic materials management strategy, viz. the minerals beneficiation strategy for the South African province of KwaZulu-Natal (KZN). Of relevance in this province are the presence of an industrial phosphate processing complex at Foskor Limited in Richards Bay, diverse and intensive agriculture, and significant sanitation needs and innovations in South Africa.

The study is undertaken for a Master of Philosophy degree and is as such not undertaken to develop core technical or scientific knowledge, though it is informed by the author’s training in Chemical Engineering.

1.5 PLAN OF DEVELOPMENT

Having presented the background, problem statement, objectives and scope in Chapter 1 of this work, the dissertation proceeds into a Chapter 2: Literature review. The literature review sets the tone for the research in that it critiques the status quo in phosphate market dynamics, current methods used in beneficiating phosphate rock into phosphoric acid and lastly, assesses the need for loop-closure and how this can contribute to sustainable development. The research key questions and approach taken are then presented in Chapter 3 and are followed by the findings of the dissertation. The findings seek to answer the questions posed in Chapter 3. The work assesses whether struvite can be integrated into an existing phosphoric acid generation process in Chapter 4. Furthermore, the financial cost associated with setting up a reverse logistics network is obtained in Chapter 5. Lastly, Chapter 6 seeks to understand the lessons that can be learned from past experiences in recycling. The conclusions and recommendations are then presented in Chapter 7.

CHAPTER 2. LITERATURE REVIEW

Chapter 2 begins by presenting an overview of the current phosphate market, looking at information such as global phosphate reserves together with import and export details in Section 2.1. Section 2.2 then proceeds to explain the common methods used to process phosphate-bearing ores into fertiliser and thereafter questions the sustainability of these methods in Section 2.3. Additionally, Section 2.3 also links conventional phosphate procurement with sustainable development. Section 2.4 then discusses the opportunity for phosphate procurement from waste and reviews related research on phosphate recovery approaches from wastewater and source-separated urine. Lastly, Section 2.5 briefly touches on the two cases of the Recycling and Economic Development Initiative of South Africa and that of the Recycling Oil Save the Environment Foundation in recycling in South Africa.

2.1 PHOSPHATE MARKET DYNAMICS AND GEOPOLITICS

2.1.1 PHOSPHATE RESERVES AND ORE GRADES

The world's largest phosphate rock reserves are in Morocco, making up approximately 60 to 75% of the world total (USGS, 2015). China, South Africa and the United States also hold considerable phosphate rock reserves. Figure 2 is a geographical breakdown of the world's phosphate reserves. The combination of these global reserves amounts to approximately 67 billion tonnes of phosphate rock (Cooper, et al., 2011; USGS, 2015).

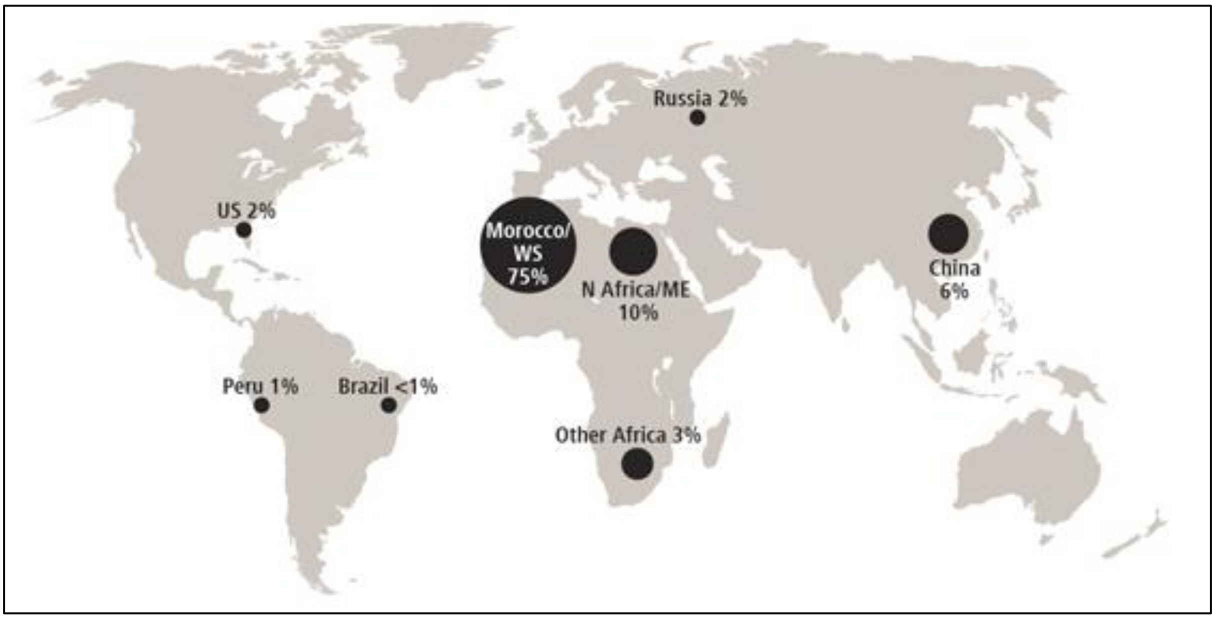

FIGURE 2: GEOGRAPHICAL DISTRIBUTION OF WORLD'S PHOSPHATE RESERVES (ADAPTED FROM POTASHCORP, 2014)

The largest phosphate-bearing rock reserves in South Africa are in Phalaborwa, Limpopo. Foskor Limited, South Africa's only vertically integrated phosphate processing company, comprises two mines in Phalaborwa with a combined maximum annual capacity of 2.6 million tonnes (Foskor, 2014). Foskor Limited processes the phosphate rock into phosphoric acid and exports a significant portion of the rock for processing to India and other countries via the Richards Bay port. Much of the phosphoric acid produced gets processed further into second level beneficiated products externally and internally within Foskor Limited and the balance gets exported. The processing of the phosphate rock into fertiliser products requires sulphuric acid and ammonia. Sulphur used as the raw material in making sulphuric acid together with ammonia are imported thus making phosphate processing vulnerable to disruptions in sulphur and ammonia value chains.

2.1.2 GEOPOLITICS AROUND PHOSPHATES

Evidently from Figure 2, only about five countries control more than 90% of the global phosphate reserves. This concentration of phosphate rock reserves leaves resource deficient countries, particularly in Europe, vulnerable to sudden disruptions in phosphate supplies. Thus, in addition to the obvious technical hindrances of water resources, electricity and increasing impurities; disruptions may also be political (HCSS, 2012). Major European importers of phosphates are France, Spain, Germany and the United Kingdom. These countries depend on imports from Russia, Asia and Africa and because of this, sound political relations play a key role in phosphate supply in Europe (HCSS, 2012; Udo de Haes, et al., 2009). On the other hand, Sweden has taken a different approach to procuring phosphates by setting a national goal aimed at recovering 75% of the phosphates in wastewater by 2010 (Levlin & Hultman, 2004). Ultimately, this approach would reduce Sweden's (and other nations that follow this movement) dependence on the volatile commodity prices. However, even though there has not been any quantifiable evidence suggesting that this was achieved by Sweden in relation to the 75% goal, there has been a definite improvement in phosphate recovery from WWTPs in recent years (Trela & Plaza, 2018; SEPA, 2016). Furthermore, phosphorus removal efficiencies between 95-96%% have been documented by the Swedish Environmental Protection Agency together with a sewage sludge return to farmlands rate of 34%. In addition to this, Swedish are gearing up to meet new wastewater discharge specifications of less than 0.2 mg P/L for total phosphorus (Trela & Plaza, 2018).

The scenario in Asia is slightly different due to the large populations as well as the phosphate reserve abundance or lack thereof, depending on the country. The study by Cooper, et al. (2011) is relevant here as it attempts to investigate how the distribution of phosphate rock reserves may change within the 21st century given a country's phosphate reserves as well as its phosphate production capacity. The study uses the indicator of phosphate reserve-to-production i.e. the quantity of phosphate reserves divided by production rate (R/P), for each country. The results of this study perhaps explain some of the decisions taken by the Chinese government to regulate phosphate rock exports. China has been the largest miner of phosphate rock in the world since 2006 after surpassing the United States (Cooper, et al., 2011; USGS, 2015). In 2010, a production rate of 65 million tonnes of phosphate rock was recorded (Cooper, et al., 2011), this value steeply rose to 108 million tonnes in 2013 (USGS, 2015). Cooper, et al. (2011) found that the R/P ratio for China was 57 years, much lower than those of countries which are key players in phosphate production. Upon realising this, China implemented high tax tariffs to exporters – effectively halting exports from China just two years after surpassing the United States in production rates (HCSS, 2012). The Chinese government reasoned their implementation of these high export tariffs on attempting to secure the domestic supply of fertiliser in China’s growing population and fertiliser demand. Other Asian countries with extensive phosphate resources are Syria, Saudi Arabia and Jordan. Ongoing conflict has recently led to Syria almost completely stopping exports to Europe (HCSS, 2012).

According to the U.S Geological Survey, another key player in phosphate market, the United States, produced 31 million tonnes of marketable phosphate product. In addition to the domestically produced products, a further 3 million tonnes were imported per year from 2010 to 2013. About 74% of these imports came from Morocco and the balance from Peru (USGS, 2015). Importantly, the R/P ratio for the United States is similar to that of China, at 54 years which could be cause for concern since the ratio does not account for population growth as well as declining ore grades which will require more resources for phosphate extraction.

2.2 PHOSPHATE VALUE-ADDITION

The phosphate beneficiation process into fertiliser products follows three main stages of value addition. Much work has been done by Patel, et al. (2015) in documenting the flows across all three stages in South Africa, with a specific focus on the KZN province. The first stage combines the processes of mining, comminution and concentration of apatite ore (Foskor, 2014) which is done at the mining site. Thereafter, an intermediate product of phosphoric acid is produced using hydrometallurgy (the wet process) or pyrometallurgy (the thermal process). The wet process accounts for approximately 96% of global phosphoric acid production whereas the thermal process is used to a lesser extent, mainly for producing high grade chemicals (Pacific Environmental Services , n.d.). The discussion that follows thus focuses on the wet process and not so much on the thermal process. During the wet process, concentrated phosphate rock undergoes leaching where it is reacted with sulphuric acid and water to produce phosphoric acid as well as a gypsum by-product (EFMA, 2000a; Schrodter, et al., 2012; Wing, 2008). The last stage of the value addition process is the conversion of the phosphoric acid into final products for use in agriculture, detergent production, food and beverage and feedstock production (Patel, et al., 2015). **Error! Reference source not found.**Figure 3 is a flow sheet of the various phosphate processing stages and shows the additional chemicals needed for this processing.

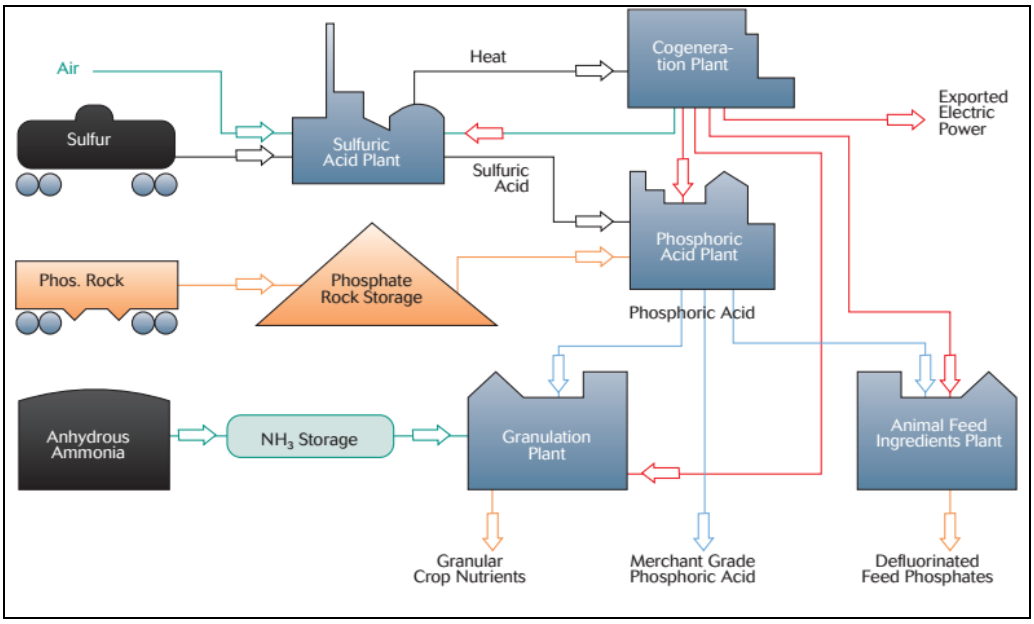

FIGURE 3: GENERAL PHOSPHATE PROCESSING PLANT FLOW SHEET (ANGLO AMERICAN, N.D.)

2.2.1 MINING, COMMINUTION AND CONCENTRATION

Apatite ore, most commonly found as flourapatite [$Ca_5(PO_4)_3F$] (Cairncross, 2004; DMR, 2008; Schrodter, et al., 2012), typically contains between 6% and 7% phosphorus pentoxide [P_2O_5] when mined (Foskor, 2014). Making up the rest of the apatite ore are heavy metal impurities such as calcium oxide, ferric oxide, magnesium oxide and others – refer to Table 1 for typical compositions.

Market grade phosphate rock on the other hand requires that P_2O_5 concentrations should at least be between 28% and 39% (Gharabaghi, et al., 2010; HCSS, 2012; Ortiz, et al., 1999) which also corresponds to the typical P_2O_5 concentration needed to begin phosphoric acid production. Additionally, Sis and Chander (2003) stress the following guidelines for the production of fertiliser:

i. the iron (iii) oxide [Fe_2O_3] and aluminium (iii) oxide [Al_2O_3] contents should both be less than 2.5%,
ii. phosphate rock should have a calcium oxide [CaO] content smaller than 1.6 times the P_2O_5 present in the rock, and
iii. the magnesium oxide [MgO] composition in the rock should be less than 1%.

These guidelines thus make it mandatory to concentrate the ore to obtain market grade phosphate rock for further processing or sale to international markets.

Generally, the first step of this stage is to progressively crush the ore from large rocks into smaller sized rocks of about 13mm. Thereafter, the rocks are further crushed and ideally the smallest size should be bigger than 20µm (Teague & Lollback, 2012). The crushed ore is then mixed with water to form a slurry that gets transported to flotation circuits (Foskor, 2014). The aim of the flotation process is to recover P_2O_5 in the form of flourapatite from other minerals. This is done through the addition of flotation reagents. Although the norm has been to ensure that the crushed ore is bigger than 20µm (for the best results in flotation), research from Teague and Lollback (2012) has investigated the recovery potential of these ultrafine particles which have often been discarded at tailings dams in the past. The type of chemical reagent used in the flotation process depends on the type of ore deposit to be concentrated – most importantly the chemical composition of impurities within the ore deposit. Broadly, phosphate flotation reagents may be subdivided into collectors, depressants and other auxiliary reagents (Sis & Chander, 2003). Thickener and filtration processes follow and are responsible for removing excess water from the slurry. The filter cake is then dried, typically in a kiln, and the resulting market grade phosphate rock transported further downstream for processing (Foskor, 2014).

After concentrating the ore to the required 28% to 39% P_2O_5 concentration, the phosphate rock is ready for immediate export as well as further processing (Patel, et al., 2015). Notably, the comminution and concentration processes are resource intensive – using substantial amounts of water, electricity, coal and chemical reagents throughout. Table 1 shows the relative compositions of the compounds making up the concentrated phosphate rock. The information was obtained from studies by Roux, et al. (1989) and Roy (1976), and shows the typical phosphate rock composition from ore bodies in South Africa and the United States, respectively.

TABLE 1: COMPOSITION OF PHOSPHATE ROCK CONCENTRATE AT PHALABORWA, SOUTH AFRICA (ROUX, ET AL., 1989) AND FLORIDA, UNITED STATES (ROY, 1976)

Compound	Typical % in concentrated phosphate rock as per study by Roux, et al. (1989)	Typical % in concentrated phosphate rock as per study by Roy (1976)
P_2O_5	36.5%	34%
CaO	52%	50%
MgO	1.5%	0.3%
Fe_2O_3	0.48%	1.3%
F	2.5%	3.8%
SiO_2	1.2%	NA
Al_2O_3	0.12%	1.3%
Other	5.7%	9.3%

Following the concentration of the phosphate rock is the phosphoric acid production step that converts the concentrated phosphate rock into phosphoric acid. This is done either through the more common **wet process** or the less used **thermal process**. The former is more common for producing phosphoric acid that subsequently gets used in the fertiliser production industry whereas the thermal process is less common due to its energy intensiveness (CIEC, 2013; EFMA, 2000a).

2.2.2 THERMAL PHOSPHORIC ACID PRODUCTION

Thermal processes require elemental sulphur, air and water as feed materials. Three production processes are common using this method, namely: Tennessee Valley Authority (TVA), Hoechst and IG processes. The TVA and IG processes differ in the method of P_2O_5 absorption and hydration. The Hoechst process on the other hand is distinguished from the two in that the phosphorus heat of combustion is used to generate steam (Pacific Environmental Services , n.d.; Schrodter, et al., 2012). Due to the irrelevance of thermal process produced phosphoric acid in the South African context, no further discussion on the process will proceed.

2.2.3 WET PROCESS PHOSPHORIC ACID PRODUCTION

Wet process derived phosphoric acid is produced through the exothermic reaction of phosphate rock with concentrated sulphuric acid and water according to the complex chemical reaction represented in Reaction 1 (Schrodter, et al., 2012; Wing, 2008).

$$Ca_5(PO_4)_3F + 5H_2SO_4 + 5xH_2O \rightarrow 5CaSO_4.xH_2O + 3H_3PO_4 + HF \qquad \text{Reaction 1}$$

Where $x \in [0, {}^{1}/_{2}, 2]$.

As mentioned in Section 112.2.1 and tabulated in Table 1, concentrated phosphate rock has other metal oxides present. This leads to concurrent reactions of these heavy metals, most of which are recovered in the phosphogypsum precipitate stream and some in the phosphoric acid stream (Tayibi, et al., 2009; Villalba, et al., 2008). After Reaction 1 occurs, Reactions 2 and 3 may also take place. The hydrogen fluoride released in Reaction 1 reacts with the silica and produced silicon tetrafluoride [SiF_4] and thereafter, the fluosilicic acid [H_2SiF_6] form via Reaction 3 (EFMA, 2000a). Reaction 2 and 3 typically occur at conditions of high temperature and/or reduced pressure (i.e. reactors and evaporators). In instances where the temperature is high enough, the fluosilicic acid may decompose to form silicon tetrafluoride and hydrogen fluoride.

$$4HF + SiO_2 \rightarrow SiF_4 + 2H_2O \qquad \text{Reaction 2}$$

$$SiF_4 + 2H_2O \rightarrow 2H_2SiF_6 + SiO_2 \qquad \text{Reaction 3}$$

Furthermore, it is estimated that 1 ton of phosphoric acid produced results in the production of 4 to 5.5 tons of phosphogypsum (Schrodter, et al., 2012; Villalba, et al., 2008). This is a major concern due to the quantity of radioactive materials recovered in the phosphogypsum waste stream. Waste challenges associated with phosphoric acid production are discussed in further detail in Section 2.2.4.

In Reaction 1 the theoretical value of 'x' is permitted to be zero, however industrial processes do not produce anhydrous gypsum crystals due to the energy demands and accelerated equipment corrosion impacts associated with operating at regions that allow for this crystal structure to be formed (Schrodter, et al., 2012). In fact, Figure 4 shows the three main regions under which gypsum crystals are stable. Two of these regions, namely hemihydrate (HH - $CaSO_4.0.5H_2O$) and dihydrate (DH - $CaSO_4.2H_2O$) gypsum are the basis on which phosphoric acid plants are designed and named (Wing, 2008). Should the need for much more detailed reactor design Schrodter, et al. (2012) go on to explain and differentiate between the different materials of construction for the units present in different phosphoric acid production processes.

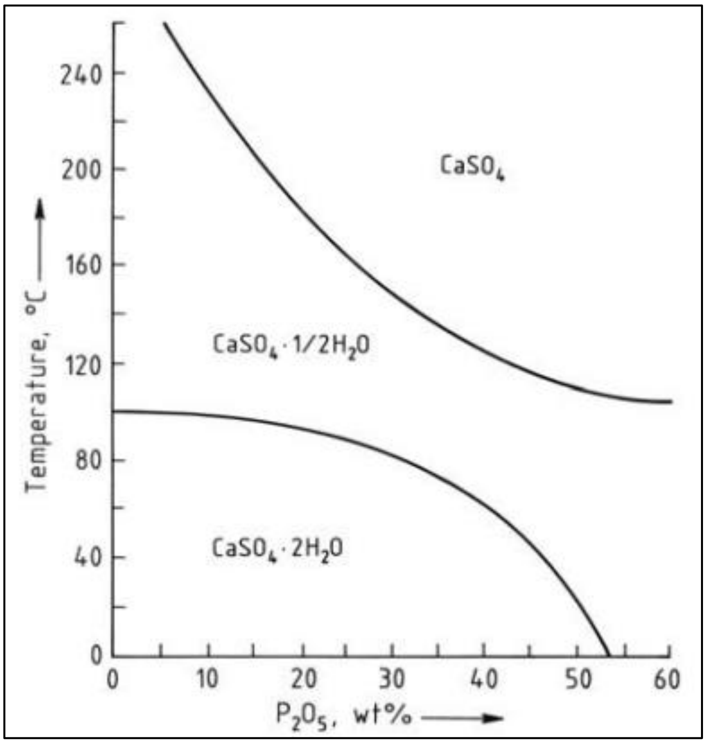

FIGURE 4: CALCIUM SULPHATE CRYSTALLISATION DEPENDENCE ON TEMPERATURE AND P_2O_5 (SCHRODTER, ET AL., 2012)

The generic wet process phosphoric acid production process comprises phosphate rock leaching, producing phosphoric acid and gypsum. Thereafter the slurry is desaturated by addition of fresh sulphuric acid in a digestion tank to ensure maximum mass transfer and reaction (Prayon, 2012). Filtration then follows to separate the valuable product, phosphoric acid, from the gypsum crystals. Steps can then be taken to further improve the quality of the produced phosphoric acid if necessary by evaporation and thereafter purification by removing metal elements from the product (Prayon, 2012; Schrodter, et al., 2012). Five flowsheet options are discussed in this section, however a discussion of the design and operation of the two most important individual processing units (reactors and slurry filters) is more imminent and thus follows.

Prayon Technologies are a dominant figure in the development of phosphoric acid production plants. With over 60 years' experience in the design and development of phosphoric acid plants, Prayon technology is responsible for over 50% of the world tonnage of phosphoric acid in over 30 countries (Gilmour, 2010; Prayon, 2012). Their expertise in this field has been relied on comprehensively in discussing available technologies in the subsections that follow.

2.2.3.1 REACTOR DESIGN

The design of leach reactors varies from several stirred tanks arranged in series to compartmentalised single tanks. The latter brings about an improvement in circulation flows so as to maintain operational temperature and concentration conditions (Gruber, 2007; Schrodter, et al., 2012). Because the reaction is exothermic, the reactors have a cooling requirement of about 2 GJ/t (for the DH process), depending on the configuration being used.

Air or vacuum water evaporation can be used to achieve cooling of the slurry. The operating temperatures of the reactors are decided on using Figure 4.

Prayon process reactors are designed according to the regions shown in Figure 5. The optional sulphate region is where phosphate rock is fed and therefore contains the lowest sulphate concentration out of the four regions shown. The sulphate concentration in region 2 is higher than that in region 3, where the slurry is drawn off and pumped into a flash cooler, due to the reaction. The digestion region, region 4, desaturates the slurry by addition of sulphuric acid, consequently further promoting the formation of large gypsum crystals (Prayon, 2012).

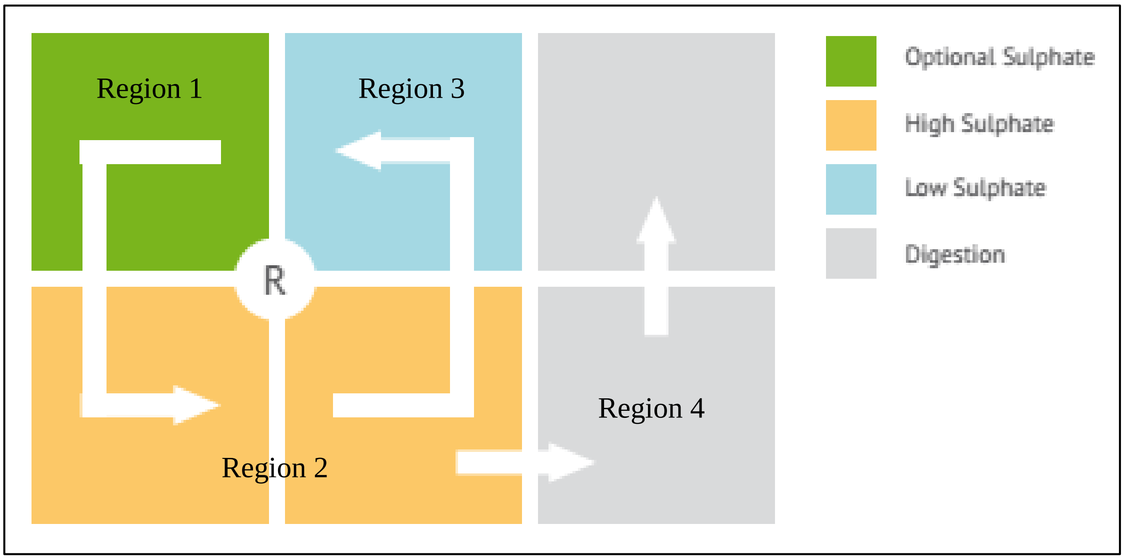

FIGURE 5: REACTION REGIONS IN PRAYON PROCESS

Alternative designs to the Prayon reactor design concept represented in Figure 5 exist and include the Rhone-Poulene, Rhone-Poulene Diplo, Dorr-Jacobs, Siaper and Badger-Raytheon process (Gilmour, 2010). For example, the Rhone-Poulene Diplo reactor – a modification of the single reactor Rhone-Poulene by the addition of another reactor – is known to achieve high recirculation rates compared to the other processes mentioned (Gilmour, 2010). High slurry recirculation avoids dead reactor zones, promotes good mixing and thus the formation of richer and larger gypsum crystals. The small surface area associated with large gypsum crystals results in enhanced filtration. On the other hand, the Badger-Raytheon process is isothermal; achieving cooling and digestion simultaneously. Thus, there is no need for the low-level vacuum chamber present in the Prayon process however, the reactor size is bigger (for the same production) so as to achieve cooling and reaction simultaneously (Felice, et al., 1998; Gruber, 2007). Each design has a claimed benefit over the other, however, Gilmour (2010) argue that for decision-making, each option must be evaluated in its own merits.

2.2.3.2 FILTRATION DESIGN

Three filter types stand out the most in wet process plants, namely: the tilting pan filter and continuous belt filter (Gilmour, 2010). As per Andritz, tilting pan filters consist of trapezoidal filter pans arranged circularly. The pans rotated, through the cycle, each trapezoidal filter is fed with cake which is washed, dried and discharged from the filter whose cloth is then washed and the cycle repeats. On the other hand, belt filters are composed of screens that move by means of rollers. Wet cake is generally fed through the headbox onto the screen, with filtration occurring by means of gravity in the early sections of the belt. Further downstream the belt, filtration is generally achieved by trapping the cake between two screen clothes and pressing them between two rollers thereby freeing excess water.

2.2.3.3 DIHYDRATE (DH) PROCESS

The dihydrate (DH) process, represented in Figure 6, was the conventional phosphoric acid method of production for most of the 20th century (Wing, 2008). The process requires finely ground phosphate rock as feed into the reactor vessel, also called attack tank. According to Schrodter, et al. (2012), at least 75% of the ground phosphate rock must be less than 150µm in average diameter. Furthermore, concentrated sulphuric acid should be fed further down the attack tanks, as illustrated in Figure 6, so that the reaction on the surface of the phosphate rock is not hindered by the formation of a gypsum layer because of the weak acid that would come into contact with a mostly reacted phosphate rock (Prayon, 2012; Schrodter, et al., 2012). Thus, fresh sulphuric acid is contacted with partially reacted particles of phosphate rock whereas the new phosphate feed reacts with a spent sulphuric acid recycle stream.

As per Figure 4, the formation of dihydrate gypsum requires that the reaction vessel temperature be kept in the region 70 – 80 ºC. The phosphoric acid coming out of this process has a mass concentration between 28%(w/w) to 30%(w/w) P_2O_5 and therefore requires further concentration before reaching market grade (Prayon, 2012; Schrodter, et al., 2012).

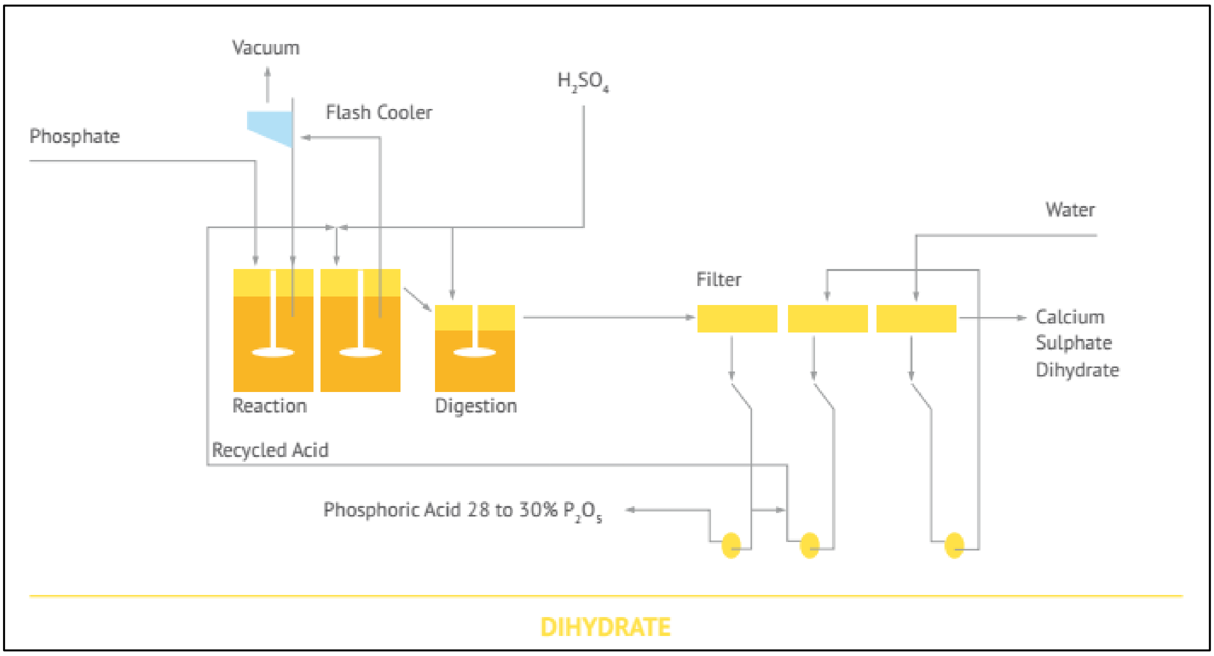

FIGURE 6: FLOWSHEET OF DH METHOD OF PHOSPHORIC ACID PRODUCTION (PRAYON, 2012)

2.2.3.4 *HEMIHYDRATE PROCESS (HH)*

The hemihydrate (HH) process is represented in Figure 7 and is an alternative to the DH process which has been explained in subsection 2.2.3.3. The individual units used within this process are similar to those used in the DH process; the difference between the two processes however is in the operation of the units and therefore the concentration of the phosphoric acid and gypsum streams. As can be seen in Figure 4, the region which results in the formation of HH gypsum crystals typically requires operation at higher temperatures than those of the DH process. The result, however, is that the phosphoric acid produced using the HH method can range from 39% to 52% % P_2O_5 (EFMA, 2000a; Prayon, 2012) compared to that of the DH process (28% to 30% P_2O_5). Furthermore, the acid produced has less free sulphate than that produced in the DH process and, the HH process does not require further concentration units such as the evaporator to increase the concentration of the product phosphoric acid.

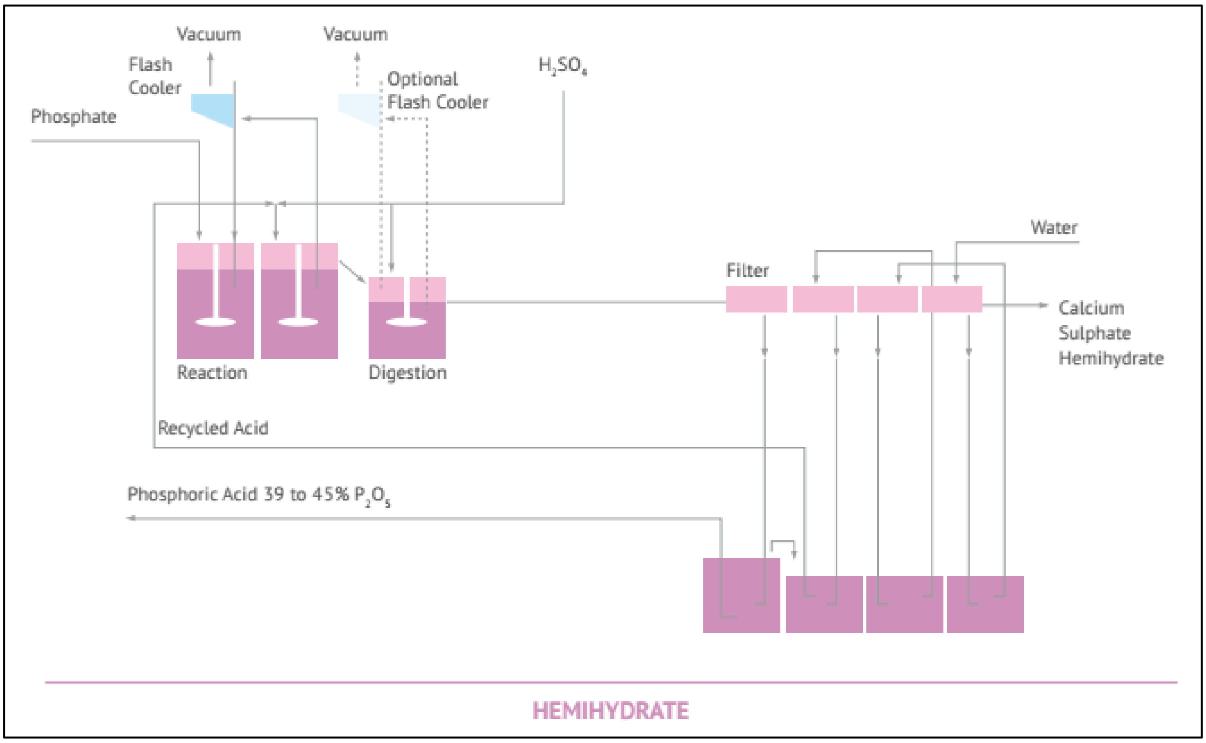

Figure 7: Flowsheet of HH Method of Phosphoric Acid Production

2.2.3.5 *DIHYDRATE-HEMIHYDRATE (DH-HH) PROCESS*

A variation of the DH process is obtained when high purity HH gypsum is required. This is typically the case for plants that are designed with the intention of selling the HH gypsum to other industries, in addition to the phosphoric acid product. In this option, the (dense) slurry exiting the digestion tank in the DH section of the combined process is further reacted with steam and sulphuric acid as shown in Figure 8. The reaction occurring in the tank labelled 'hemihydrate conversion' in Figure 8 removes water from DH crystals forming HH gypsum crystals by heating. The HH gypsum crystals formed are then washed using water and recovered for sale (Prayon, 2012). One disadvantage of this configuration over the HH process shown in Figure 7, however, is the acid concentration in the range of 32% to 36%.

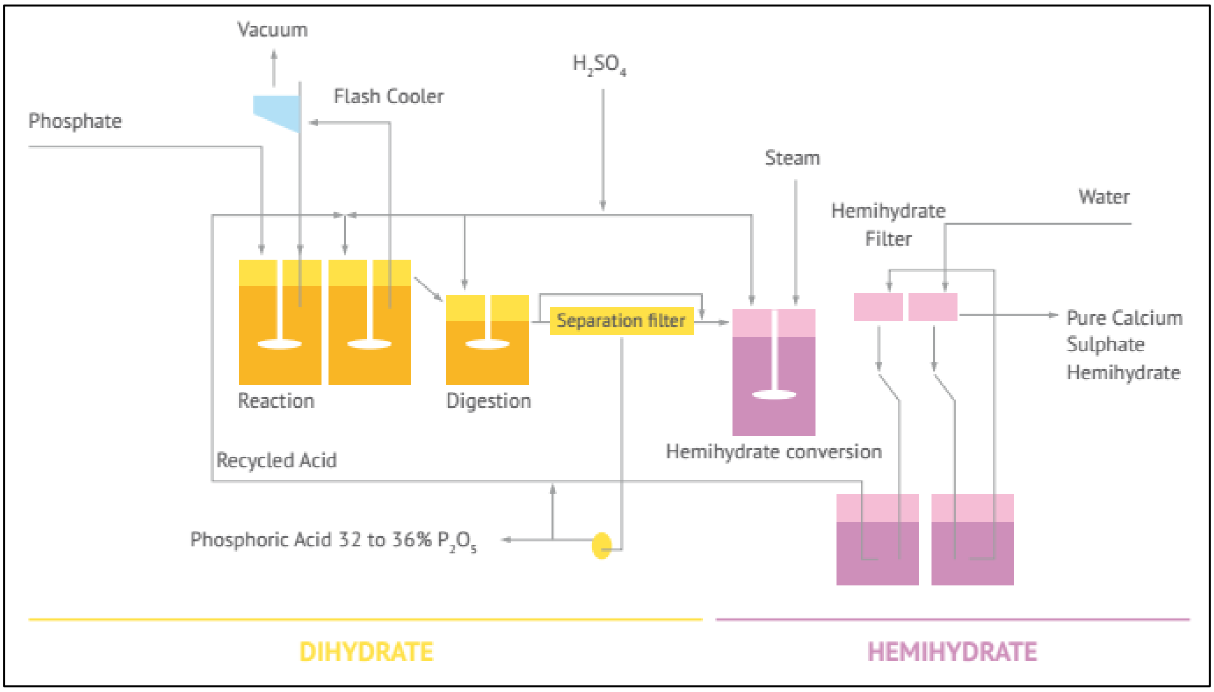

FIGURE 8: FLOWSHEET OF DH-HH METHOD OF PHOSPHORIC ACID PRODUCTION

2.2.3.6 HEMIHYDRATE-DIHYDRATE (HH-DH) PROCESS

The HH-DH process is represented in Figure 9 and is the combination of individual HH and DH processes in Figure 6 and Figure 7. For this reactor configuration, the first process is that which produces HH gypsum and thereafter DH gypsum under the conditions suitable for DH gypsum production, refer to Figure 4. Using this process, the recovery of P_2O_5 into the acid stream is greater than 98.5% and the phosphoric acid product formed is in the ranger of 40-46% (w/w) (Prayon, 2012).

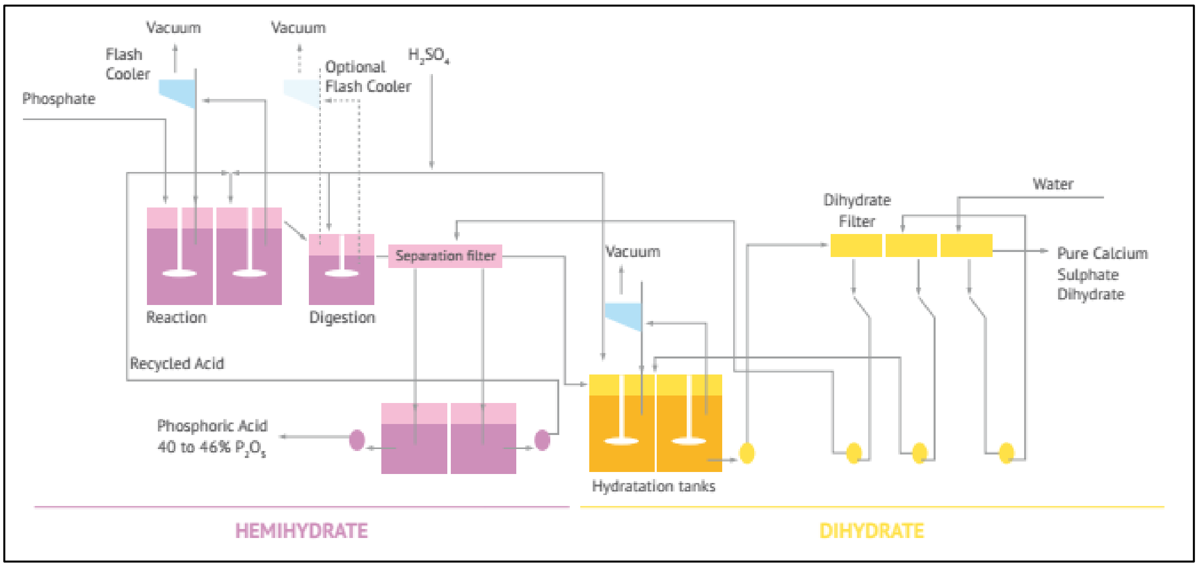

FIGURE 9: FLOWSHEET OF HH-DH METHOD OF PHOSPHORIC ACID PRODUCTION

2.2.3.7 HEMIHYDRATE-DIHYDRATE-HEMIDRATE (HDH) PROCESS

The HDH process combines the HH, DH and HH processes in that order. It is represented in Figure 10. First, HH gypsum is formed, together with acid containing 40% to 46% P_2O_5, and conveyed to the hydratation tanks where operating conditions conducive to the formation of DH gypsum are used. This converts the HH gypsum to DH gypsum whilst also converting unreacted phosphate rock into phosphoric acid; the formed DH gypsum is then dehydrated in '*dehydration tanks*' using steam and sulphuric acid (Prayon, 2012). This process configuration achieves both a high phosphoric acid product concentration and a saleable gypsum content.

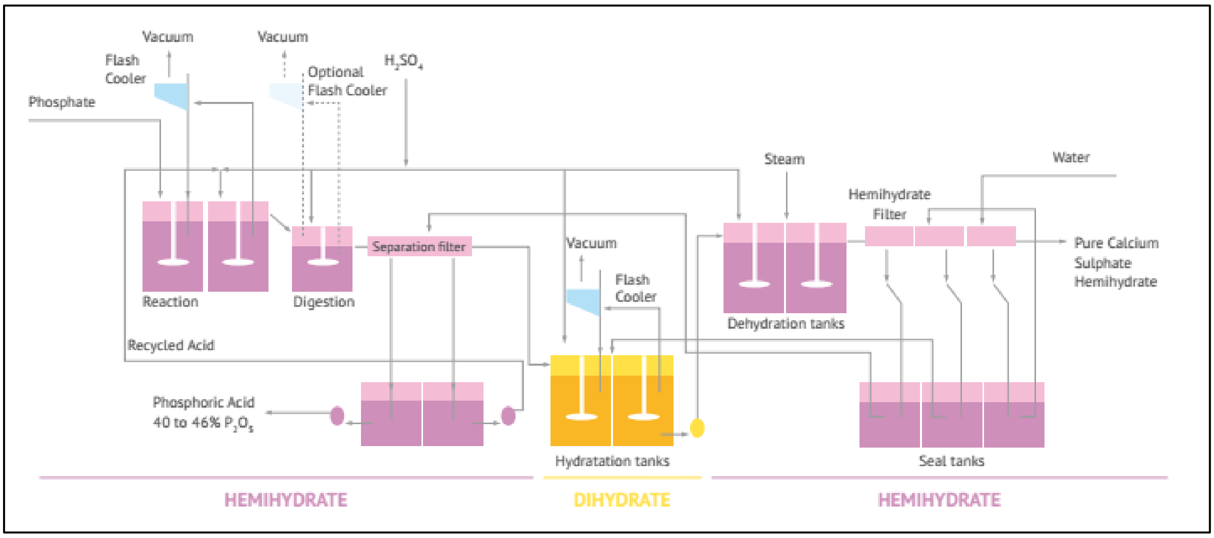

Figure 10: Flowsheet of HDH Method of Phosphoric Acid Production

Table 2: Summary of Pros and Cons of Processing Configurations[1]

Processing Configuration Technology	Advantage	Disadvantage
Dihydrate	Operating temperatures are lower than in HH process – thus fewer corrosion problems. Applicable to most grades of phosphate rock and types of ore (sedimentary and igneous). Start-up and shut-down are easy as this process requires low investment and is well-established as it has been used for most of the 20th century. Wet rock can be used in the process.	A relatively weak acid that needs further concentration is produced. High energy consumption in the acid concentration stage. About 4 – 6% of the P2O5 rock is cocrystallised with the gypsum. The need to grind the phosphate rock so that 75% is less than 150 microns. High return on investment.
Hemihydrate	Process has lower grinding requirements than DH process since larger sizes of phosphate rock can be used. Energy savings are possible through the reduction or elimination of concentration step. High concentration of phosphoric acid (39 – 52%). Easy to operate and maintain. Light on capital cost.	HH process crystals are smaller in size than those produced in the DH process, thus filtration requirements are larger. The scaling of HH crystals since HH form of gypsum is not the most stable form – as per Figure 4. Higher temperatures of operation and acid concentrations make the plant more vulnerable to equipment corrosion.
Dihydrate-Hemihydrate	Can process both sedimentary and igneous phosphate ores. Gypsum product has potential for sale – can be used for plasterboard or cement retarder.	Complex start-up and shut-down procedure. Capital cost intensive compared to single DH and HH processes.
Hemihydrate- Dihydrate	High P_2O_5 recovery into the acid stream (about 98-99%). Produces two saleable products, phosphoric acid and gypsum which is suitable as feed for other processes, such as cement making. High concentration of phosphoric acid (39 – 52%).	Complex start-up and shut-down procedure. Capital cost intensive compared to single DH and HH processes.
Hemihydrate-Dihydrate-Hemihydrate	Produces two saleable products, phosphoric acid and gypsum which is suitable as feed for other processes, such as cement making. High concentration of phosphoric acid (39 – 52%).	Complex start-up and shut-down procedure. Capital cost intensive compared to single DH and HH processes.

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[1] Information gathered from various sources including: (Wing, 2008) (Prayon, 2012) (Schrodter, et al., 2012) (EFMA, 2000a) (Tunks, 2012)

2.2.4 WASTE GENERATION

The processing of minerals produces wanted and unwanted products; the former is saleable whereas the unwanted products are often discarded as wastes. Such an unwanted by-product, dihydrate or hemihydrate phosphogypsum (CaSO4.2H2O or CaSO4.1⁄2H2O), is formed during the production of phosphoric acid using the wet-process. It is estimated that a maximum of up to 5.5 tons of unwanted phosphogypsum (PG) by-product are produced per 1 ton of phosphoric acid produced (EFMA, 2000b; Villalba, et al., 2008). Furthermore, it is also estimated that 100-280 Mt/year of PG are produced worldwide (Tayibi, et al., 2009), most of which is either stockpiled or released into the oceans where it causes environmental damage (Bituh, et al., 2009; Szlauer, et al., 1990). The biggest concern with this by-product is the presence of radioactive elements in the form of Uranium (238U), Radium (226Ra or 228Ra), Thorium (232Th) and Potassium (40K) (Al Attar, et al., 2011; Bituh, et al., 2009). According to Tayibi, et al. (2009), the PG stream recovers about 80% of the radioactive 226Ra from the phosphate rock ore and the phosphoric acid stream, on the other hand, recovers 86% of the 238U from the phosphate ore. Human and animal exposure to the radionuclides therefore commonly occurs through air particulates, water, soils near phosphoric acid production plants and in fertilisers. The World Health Organisation (WHO) documents guidelines to the ‘acceptable’ radioactivity exposure rates above which the safety and safety of the exposed may be compromised.

2.2.5 FERTILISER PRODUCTION – TERTIARY PROCESSING

Evidently from Figure 11, phosphoric acid plays the crucial intermediate product role as it feeds into the production of various other phosphate-based products in the South African phosphate mineral value chain. The process described in this section, regarding Figure 12, is that responsible for producing di-ammonium phosphate (DAP) – an inorganic fertiliser that is one of the many potential products that may be produced from phosphoric acid.

The process in Figure 12 reacts ammonia with wet-process phosphoric acid, causing the precipitation of complex iron, ammonia and aluminium orthophosphates (Houston, et al., 1955). The precipitate is filtered off, transported to a mixer, dried and sent for screening. The mother liquor can then be processed further in a crystalliser, where it is reacted with ammonia, and thereafter mixed with the precipitate formed after the first stage (Houston, et al., 1955). Importantly, the mixing is only done after a solid-liquid separation where the fluid leaving the crystalliser is centrifuged to remove excess liquid.

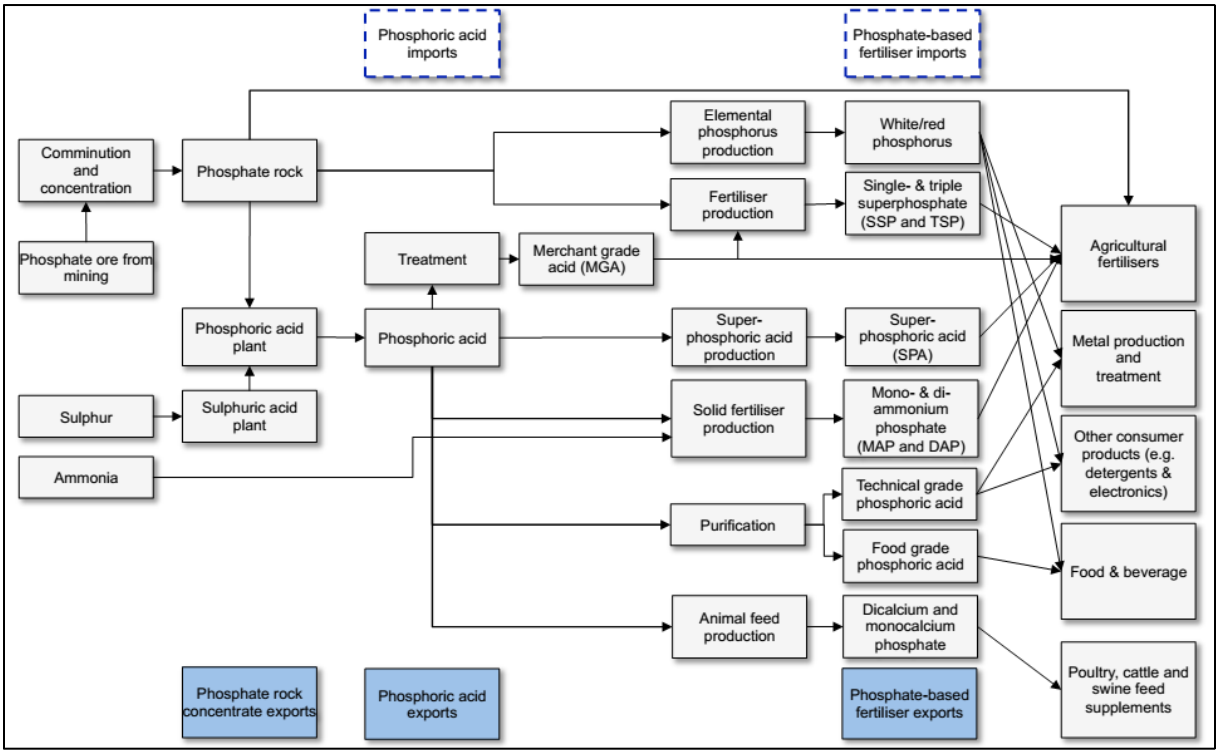


Figure 11: South African Phosphate Mineral Value Chain

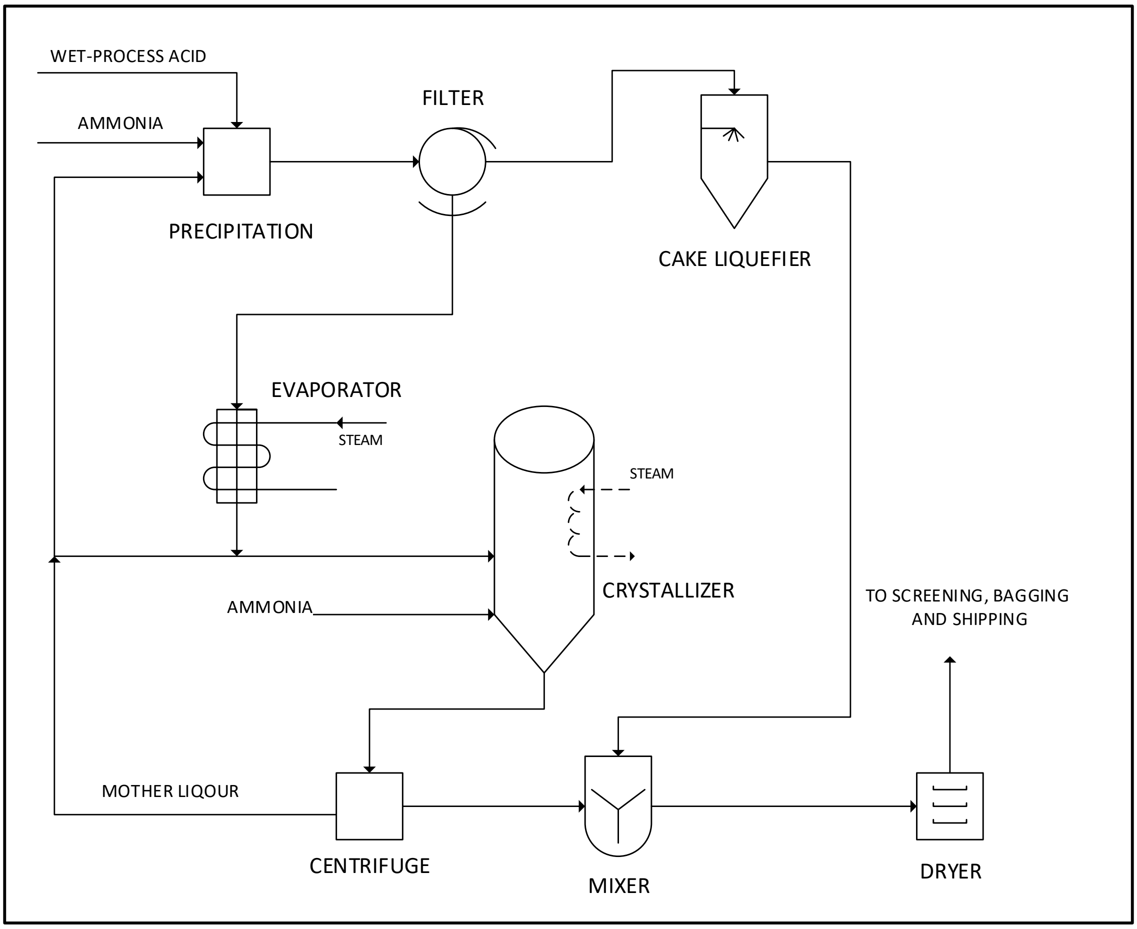


Figure 12: Typical Flow Diagram of Di-Ammonium Phosphate Fertiliser Production Process (Houston, et al., 1955)

2.3 THE LINK TO SUSTAINABLE DEVELOPMENT

The steadily growing global population has strong-armed humanity into a state where both the demand for (phosphate) mineral resources and the rate of generation of wastes are unprecedented. In the phosphate procurement context, this has led to increases in the market price of phosphates, as shown in Figure 13. The trend shown in Figure 13 displays two main price spikes, one in the mid-1970s to 70 US$/ton and another during the 2008/2009 economic crisis to more than 200 US$/ton (Mew, 2016). As at June 2016, Foskor Limited priced phosphate rock at 2114.54 R/ton (equivalent to 139 US$/ton) (Foskor, 2016). Ultimately because of the price hikes, food prices also rose due to their dependence on phosphate rock prices (Mew, 2016).

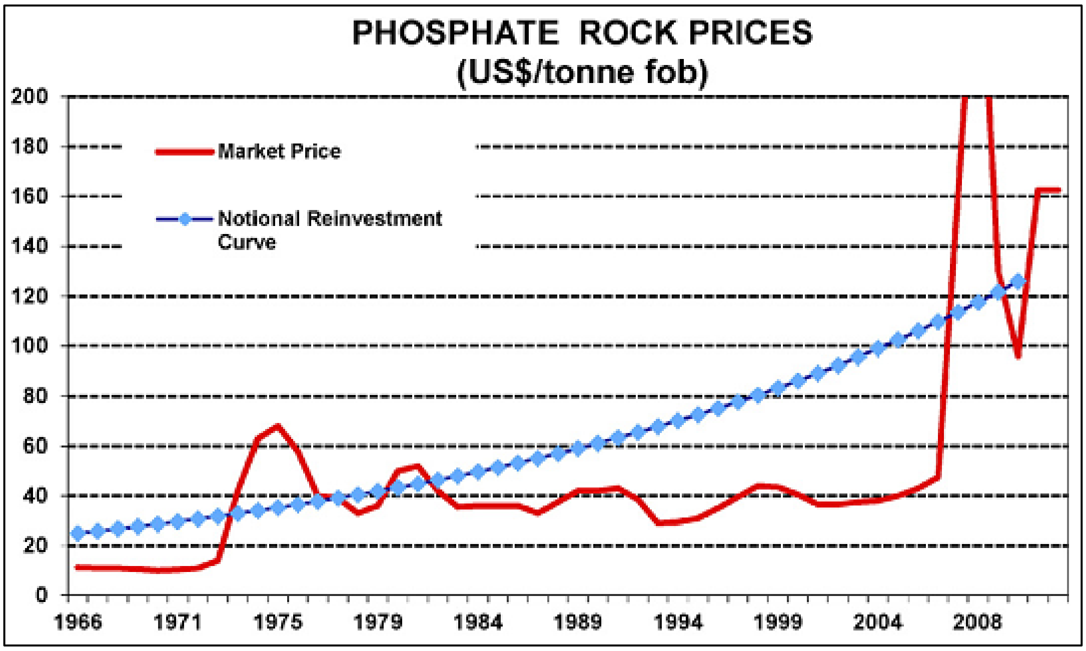


FIGURE 13: PHOSPHATE ROCK MARKET PRICE OVER THE YEARS (ADAPTED FROM MEW (2016))

The sensitivity of fertiliser prices to socio-political and socio-economic crises then begs the question: **how can an integrated approach to phosphate procurement help in sustainably securing fertiliser for food security?** This is a question of sustainable development, and the Sustainable Development Goals (SDGs) of 2015 can be referred to when dealing with food security issues. The report by the Stakeholder Forum assessed the performance of developed countries against SDGs. Most relevant to this study are Goal 1 and Goal 2. Goal 1 aims to 'end poverty in all its forms everywhere'; while Goal 2 aims to 'end hunger, achieve food security and improved nutrition, and promote sustainable agriculture' (Stakeholder Forum, 2015). Under the current mineral resource-dependant and waste-generating economy, developed countries scored 1.8 and 2.3 out of a total of 10 for SDG 1 and SDG 2, respectively (Stakeholder Forum, 2015). This suggests the need for a different approach, not just in developing countries but also in developed countries.

The phosphate cycle shown in Figure 14 is key to gaining a holistic understanding of phosphate sinks and sources. Although Figure 14 provides a thorough overview of the phosphate cycle, it lacks two important features. These are: numerical flow balances and time scales of the processes. The papers by Cordell, et al. (2009) and Smil (2000) shed light on these two important variables in the phosphate cycle.

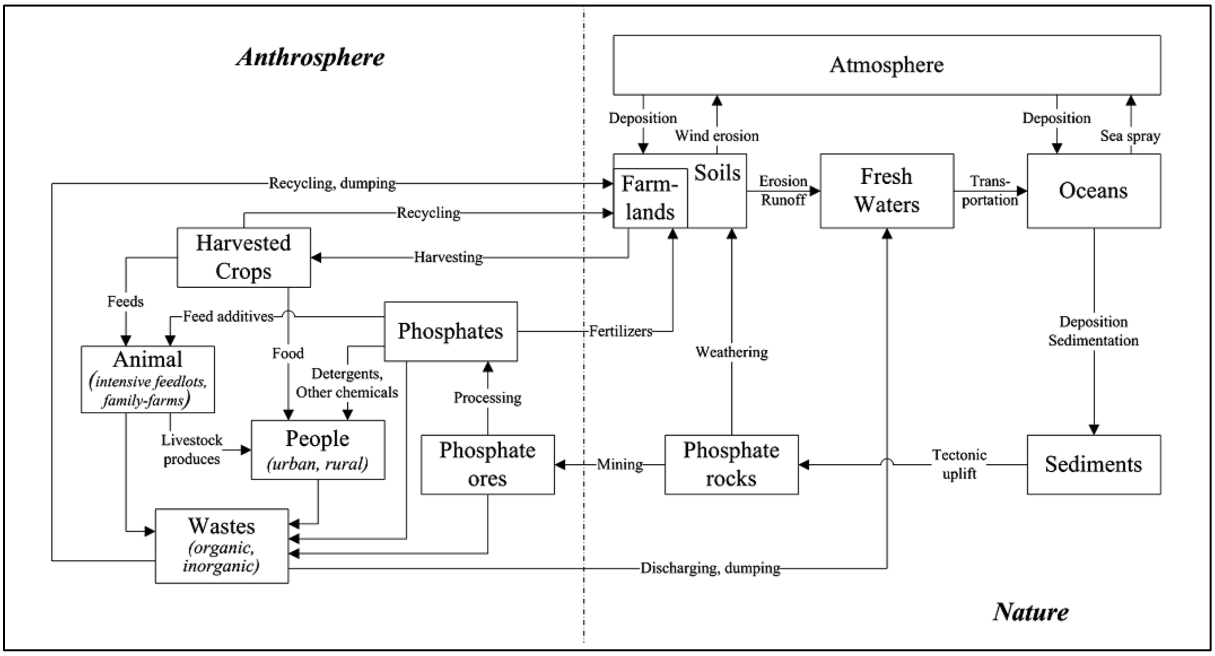


FIGURE 14: GLOBAL PHOSPHATE CYCLE (LIU, ET AL., 2008)

According to Cordell, et al. (2009), about 17% of the land-mined phosphate ends up getting excreted as human waste. Of this 17%, about half of it is lost in coastal or inland waters – contributing to eutrophication. Furthermore, only 10% of the phosphates excreted by humans gets reused in arable soils; the balance is lost mainly as landfill sludge. Animals on the other hand release approximately 85% of the mined phosphates into the environment as manure – half of which is released into arable land and the balance lost in non-arable soils and water bodies (Cordell, et al., 2009). Also important is that the rate at which humans and animals lose phosphates into the environment (water bodies and non-arable soils) far exceeds the rate at which phosphates are formed as phosphate rock reserves. Industrial phosphate flows occur at daily and yearly rates whereas natural biochemical phosphate flows occur at rates of millions of years (Cordell, et al., 2009; Smil, 2000). Therefore the opportunity for a circular/green economy exists, where water-carried phophates are recovered and reused directly as fertiliser or possibily indirectly as feed into phosphate fertiliser production processes instead of being released into the environments as wastes.

2.4 THE OPPORTUNITY IN WASTE

Even though Africa has the largest quantity of phosphate reserves, African agricultural soils are considered the least fertile in the world (Cordell, et al., 2009). There is, however, opportunity to close the phosphate cycle by reusing phosphates present in wastewaters by applying them as fertiliser directly to land but the impact is not one that is understood well especially in Africa where health issues are prime (Ganrot, 2005). Alternatively, phosphate-bearing wastes can be re-introduced to the value chain via existing phosphate processing processes (Ganrot, 2005). The closed-loop model has great potential to ultimately provide the agriculture industry with a sustainable source of fertiliser. The model also gives humanity the option to slacken its dependence on mineral resources and potentially to move away from chemical intensive processing. Furthermore, Ganrot (2005) and Yuan, et al. (2012) agree that between 15% to 45% of commercial fertiliser demand can be substituted with nutrient recovery from wastewaters. Figure 15 is a diagram showing the potential for reuse and recovery of nutrients as well as utilisation examples.

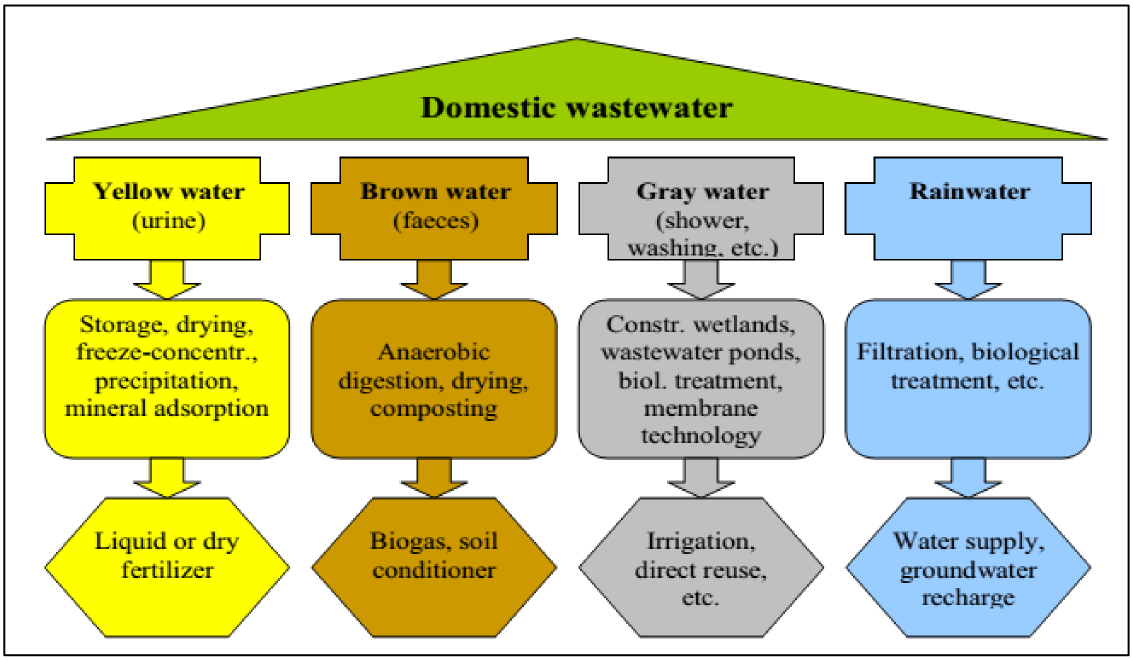


FIGURE 15: ECOSAN MODEL SHOWING NUTRIENT SOURCE, POSSIBLE TREATMENT TECHNOLOGY AND UTILISATION EXAMPLE (GANROT, 2005)

Importantly, Figure 15 also shows the much-needed mind-set shift from the conventional system that require potable water for all domestic needs to one that matches end-use to a certain ‘minimum quality needed’. As an example, nutrient-bearing greywater which has been ecologically treated is as effective (if not better) as potable water for irrigating plants.

Phosphate is found in both types of human excreta, viz. urine and faeces. Subsections 2.4.1 and 2.4.2 are included herein to provide further insight on urine and faecal properties with the intention of building on existing knowledge and exploring treatment solutions.

2.4.1 EXISTING WASTEWATER TREATMENT WORKS

The centralised wastewater treatment approach possesses several flaws that impact on its suitability for the developing world. Ganrot (2005) stresses that one of the main flaws of this approach is its pollution of large quantities of water with small amounts of human excreta. Not only is this not ideal for water scarce countries, but it also dilutes the nutrient content of faecal matter and urine thus making it harder to recover nutrients present in these wastes. Nonetheless, various technologies have been developed with the intention of maximising phosphate recovery from wastewaters. The technologies can broadly be divided into physical, chemical, biological and physical-chemical; extensive technology reviews have been documented by de-Bashan and Bashan (2004), Sikosana (2015) and Strom (2006). Enhanced biological phosphorus removal, a biological method, is the method discussed briefly herein due to its effectiveness in concentrating the phosphate content in wastewater.

Phosphates in wastewater are generally present in three main forms, namely orthophosphates, polyphosphates and organic phosphates. Orthophosphates (PO_4^{3-}, HPO_4^{2-} and $H_2PO_4^{-}$) are freely available for uptake in plants. Polyphosphates such as $P_3O_{10}^{5-}$ commonly came from detergents in the past – they can be converted into orthophosphates (Sotirakou, et al., 1999). And lastly organic phosphates which are formed through biological processes and can also be converted into polyphosphates during activated sludge treatment. Making up about 70% of the total phosphate content in wastewater are the latter two of the three, polyphosphates and organic phosphates (Sotirakou, et al., 1999).

Following domestic dilution, wastewater treatment works receive influent typically with a 5-20 mg/L total phosphorus content. For an economically viable recovery of valuable phosphate product, specifically struvite through precipitation, dilute influent streams containing phosphorus levels below 10 mg/L require concentration as a first step (Sikosana, 2015; Yuan, et al., 2012). To date, enhanced biological phosphorus removal (EBPR) is the most effective technique that can achieve the required concentration. This method makes use of polyphosphate accumulating organisms (PAOs) in anaerobic and aerobic conditions to concentrate the dilute phosphate stream and finally, sedimentation is used to separate the phosphate-rich final product from the phosphate-depleted water. The EBPR process diagram is detailed in Figure 16.

During EPBR conditions are changed from anaerobic, to aerobic and finally sedimentation allows the separation of the phosphate rich phase from the phosphate depleted water in a duration of 3-24 hours (de-Bashan & Bashan, 2004).

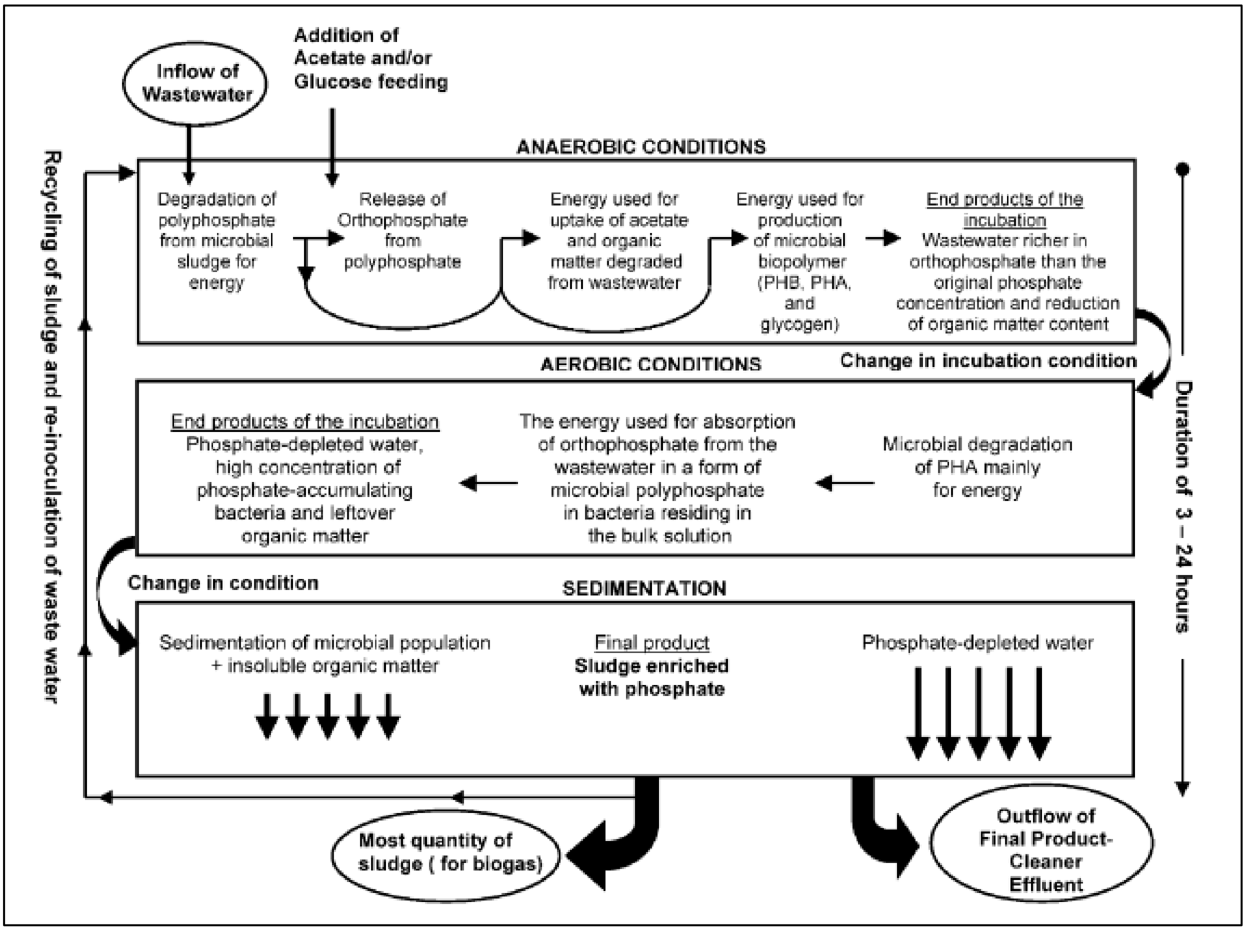


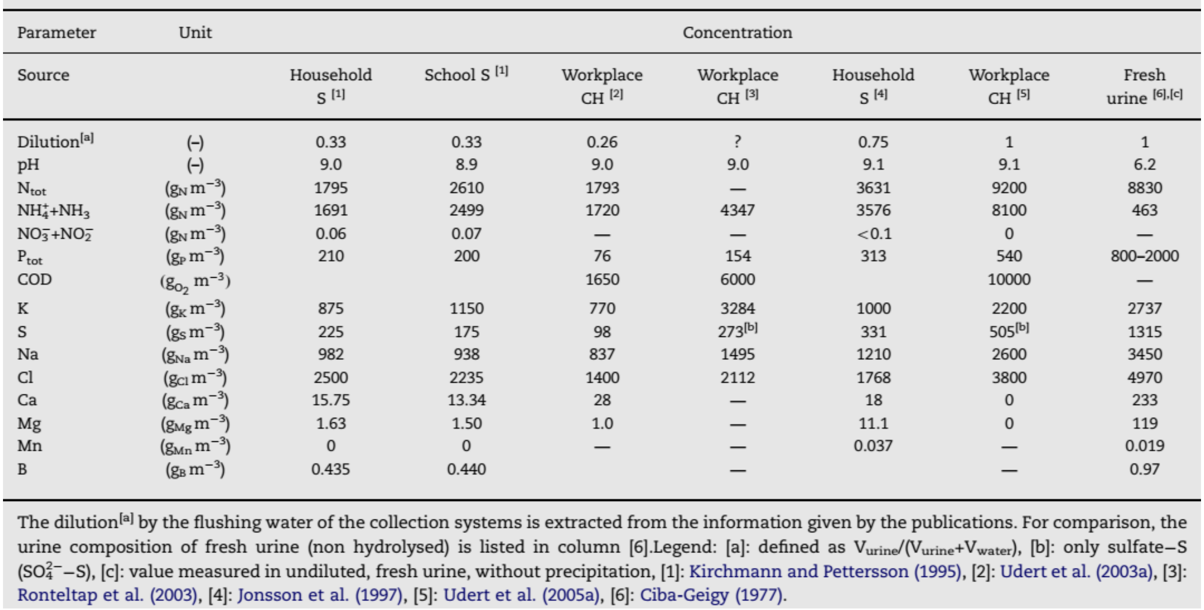
FIGURE 16: EBPR PROCESS MODEL (DE-BASHAN & BASHAN, 2004)

2.4.2 SOURCE-SEPARATED URINE

Source-separated urine is another potential source for phosphates. In fact, wastewater comprises only 1% (pure) urine content and yet approximately 55% of the phosphate present in wastewater comes from pure urine (Ganrot, 2005; Pronk & Kone, 2009). The composition of urine varies with diets and age groups. Fresh urine is reported to contain a total phosphorous content in the range 800-2000 g/m^3 (Maurer, et al., 2006). The concentrations of phosphates (and other nutrients) also vary with pH and water dilution.

Notably in Table 3 is that urine is not only rich in phosphates but also in other nutrients, particularly nitrogen, potassium, that are useful for plant growth. Sulphur and chlorine are also present in potentially recoverable concentrations that are above 1000 mg/L; potentially offering a solution to close other cycles, or in the case of sulphur, potentially offering South Africa a localised source of sulphur for sulphuric acid production. Additionally, urine does not contain heavy metal impurities which require additional processing for removal.

TABLE 3: COMPOSITIONS OF URINE FROM DIFFERENT SOURCES (MAURER, ET AL., 2006)



Parameter	Unit	Concentration						
Source		Household S [1]	School S [1]	Workplace CH [2]	Workplace CH [3]	Household S [4]	Workplace CH [5]	Fresh urine [6],[c]
Dilution[a]	(–)	0.33	0.33	0.26	?	0.75	1	1
pH	(–)	9.0	8.9	9.0	9.0	9.1	9.1	6.2
N_{tot}	($g_N\,m^{-3}$)	1795	2610	1793	—	3631	9200	8830
NH_4^++NH_3	($g_N\,m^{-3}$)	1691	2499	1720	4347	3576	8100	463
NO_3^-+NO_2^-	($g_N\,m^{-3}$)	0.06	0.07	—	—	<0.1	0	—
P_{tot}	($g_P\,m^{-3}$)	210	200	76	154	313	540	800–2000
COD	($g_{O_2}\,m^{-3}$)			1650	6000		10000	—
K	($g_K\,m^{-3}$)	875	1150	770	3284	1000	2200	2737
S	($g_S\,m^{-3}$)	225	175	98	273[b]	331	505[b]	1315
Na	($g_{Na}\,m^{-3}$)	982	938	837	1495	1210	2600	3450
Cl	($g_{Cl}\,m^{-3}$)	2500	2235	1400	2112	1768	3800	4970
Ca	($g_{Ca}\,m^{-3}$)	15.75	13.34	28	—	18	0	233
Mg	($g_{Mg}\,m^{-3}$)	1.63	1.50	1.0	—	11.1	0	119
Mn	($g_{Mn}\,m^{-3}$)	0	0	—	—	0.037	—	0.019
B	($g_B\,m^{-3}$)	0.435	0.440		—		—	0.97

The dilution[a] by the flushing water of the collection systems is extracted from the information given by the publications. For comparison, the urine composition of fresh urine (non hydrolysed) is listed in column [6].Legend: [a]: defined as $V_{urine}/(V_{urine}+V_{water})$, [b]: only sulfate−S ($SO_4^{2-}$−S), [c]: value measured in undiluted, fresh urine, without precipitation, [1]: Kirchmann and Pettersson (1995), [2]: Udert et al. (2003a), [3]: Ronteltap et al. (2003), [4]: Jonsson et al. (1997), [5]: Udert et al. (2005a), [6]: Ciba-Geigy (1977).

According to various literature sources, bacteria-free urine also has the potential for direct application as fertiliser. However, urine is not always sterile since it carries micro-pollutants in the form of pathogens and bodily hormones (Pronk & Kone, 2009). In fact, the common application of urine as liquid fertiliser faces various other challenges, many of which have mitigation measures. Table 4 summarises some of these common challenges and makes suggestions for dealing with these challenges.

TABLE 4: CHALLENGES AND MITIGATION MEASURES ASSOCIATED WITH DIRECT APPLICATION OF LIQUID URINE AS FERTILISER

Challenge	Solution	Technology
Presence of pathogenic micro-organisms and bodily hormones	Urine storage is able to reduce the content of micro-organisms. Maurer, et al. (2006) suggest that urine be stored for 6 months at 20 ⁰C to be considered safe to use.	*Storage containers.*
Unpleasant smells due to fresh urine storage	Water-flush sanitation? Urine Stabilisation via Acidification to prevent vaporisation of ammonia from urine (Etter, et al., 2015; Maurer, et al., 2006; Randall, et al., 2016).	*Urine acidification, nitrification or treatment with slaked lime.*
Transportation of large quantities of urine	Application of decentralised volume reduction technologies. Evaporation, freeze-thaw, inline ion exchange and reverse osmosis technologies are available for this (Maurer, et al., 2006; Randall & Naidoo, 2018).	*Evaporation, reverse osmosis, ion exchange and freeze-thaw.*
Lower concentration of nutrients compared to commercial fertiliser	Concentration of urine by forming struvite through precipitation. Commercial grade product can be formed using struvite precipitation (Pronk & Kone, 2009).	*Struvite precipitation.*
Volatilisation of urine after direct application	Stoppage of hydrolysis of urine through the addition of acid to the urine (Ganrot, 2005).	*Stabilisation.*
Social and ethical issues arising from urine usage as fertiliser	Educating users on the product.	*Not applicable.*
Pharmaceuticals present in urine	Addition of powdered activation carbon to during nitrification (Etter, et al., 2015).	*Addition of powdered activation carbon adsorption*

Broadly, phosphate rich urine derivatives (such as struvite) have the potent to offer opportunity for use as a raw feed into an existing phosphate fertiliser processing plant, or a distributed approach where people would collect urine and transport it into close depots where it could be: **(a)** reduced in volume and transported to a centralised place where it could be used as a feed **OR (b)** processed via one of the decentralised technologies into the final product, such as struvite, which can be sold locally.

2.4.3 STRUVITE CHEMISTRY

Struvite is white inorganic crystalline mineral which can easily be precipitated out of source separated urine or wastewaters, usually by addition of magnesium (Stratful, et al., 2001). The crystalline mineral precipitates out under conditions where the wastewater concentrations of magnesium, ammonium and phosphate ions are above the solubility limit. Often, struvite scale forms spontaneously in wastewater treatment works when the pH of the wastewater increases following the loss of carbon dioxide (Doyle & Parsons, 2002). According to Andrade and Schuiling (2001), precipitation and solubility equilibria of struvite from urine or wastewaters can be expressed as shown in Reaction 4.

$$NH_4{}^{+} + Mg^{2+} + \ HPO_4{}^{2-} + \ 6H_2O \leftrightarrow \ MgNH_4PO_4.6H_2O + \ H^{+} \qquad \text{Reaction 4}$$

Reaction 4 implies that the pH of the solution (urine or wastewater) decreases during the formation of struvite. This suggests the release of H^{+}ions into solution and therefore the participation of $HPO_4{}^{2-}$ in the precipitation of struvite over the more commonly reported $PO_4{}^{3-}$ (Andrade & Schuiling, 2001). Additionally, the availability of each of the ions mentioned is dependent on the solution pH of the solution as shown on Figure 17 (Ohlinger, et al., 1998; Stratful, et al., 2001). As shown in Figure 17, acidic environments favour the dominance of ammonium ions as well as phosphoric acid formation. Figure 17 however, does not detail how struvite behaves in stronger acidic solutions with pH values less than 0.

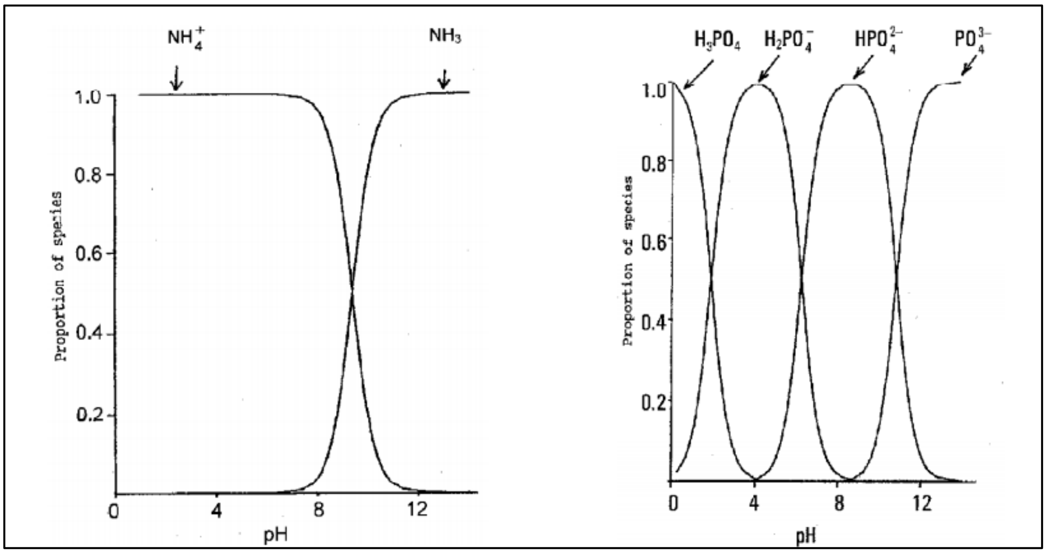


FIGURE 17: PRESENCE OF VARIOUS SPECIES WITH SOLUTION PH (ANDRADE & SCHUILING, 2001)

Although the crystallisation of struvite from wastewaters is well documented in literature, the same cannot be said for struvite reactivity with acids. The extensive research carried out by Ariyanto, et al. (2011) has however somewhat engaged with questions around how struvite responds to acidic environments. The aim of the work by Ariyanto, et al. (2011) was to investigate the solubility of struvite crytsals in solutions that are kept at certain temperatures, atmospheric pressures and have known initial pH. The results of the study have been shown in Figure 18.

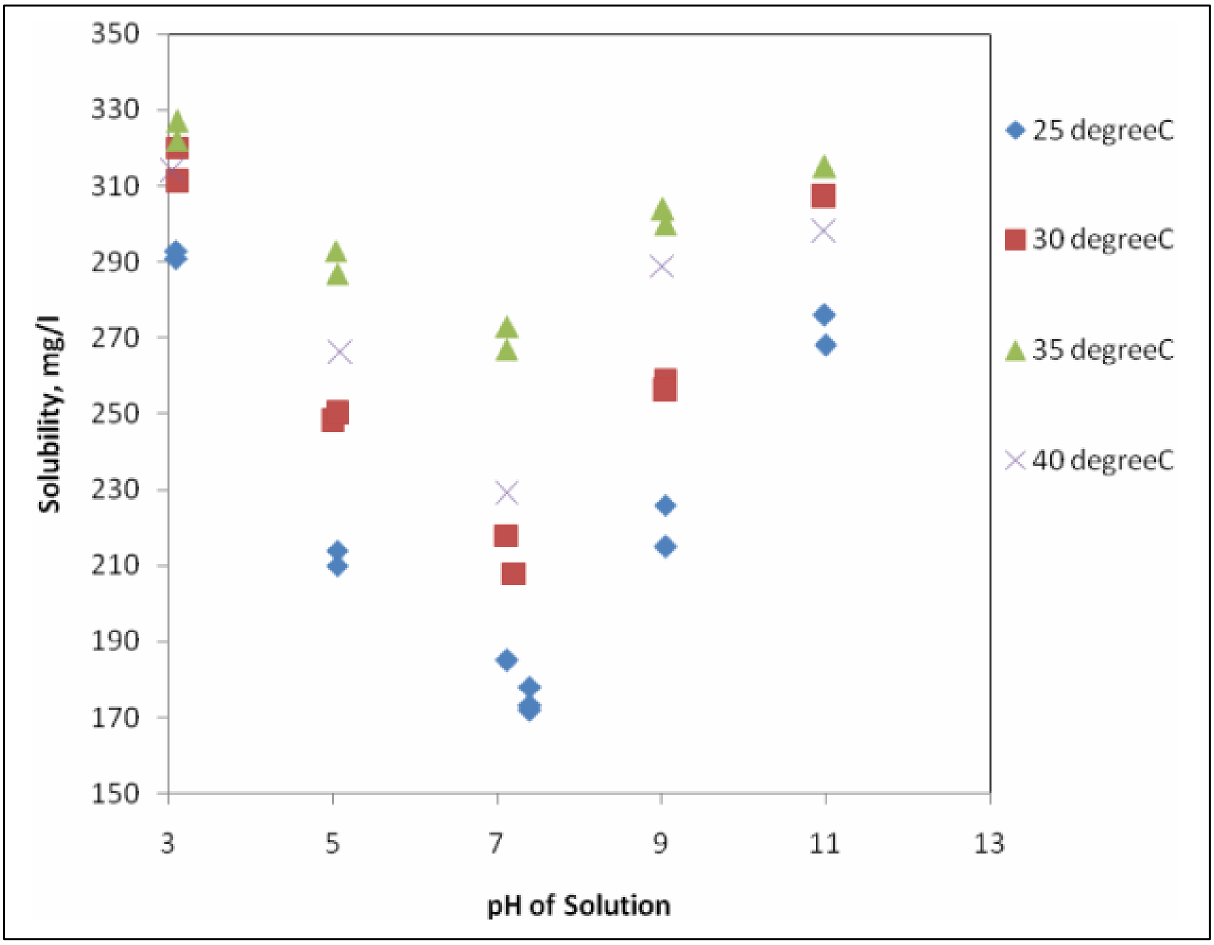
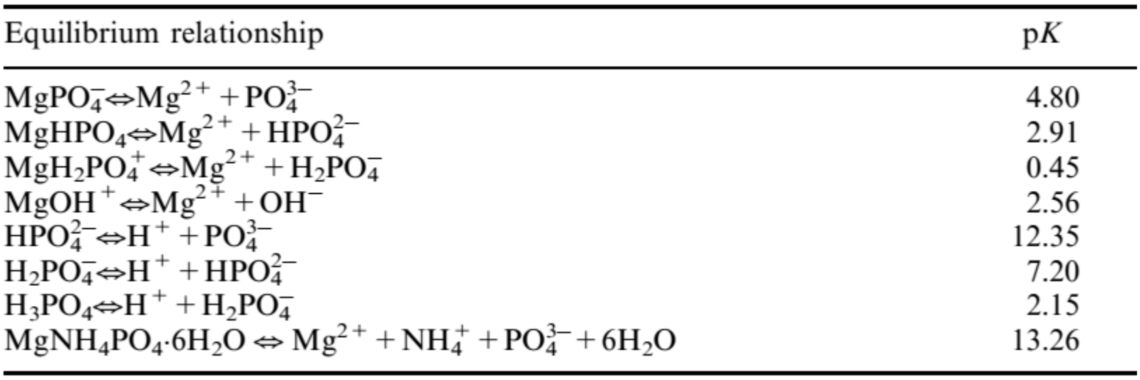


FIGURE 18: STRUVITE SOLUBILITY FOR VARIOUS TEMPERATURES AND INITIAL SOLUTION PH

The solubility of struvite increases with increasing temperature until it reaches a maximum that is between 35ºC and 40ºC and thereafter starts to dip, as shown on Figure 18. The dependence of struvite solubility on pH is parabolic in nature in that it decreases with increasing solution pH until a minimum is reached at a pH of approximately 7.5; after the minimum, the solubility then increases again (Ariyanto, et al., 2011; Doyle & Parsons, 2002; Ohlinger, et al., 1998).

The behaviour of struvite in acidic solutions can then be predicted from Figure 17 and Figure 18. Maximum solubility is found at low pH and, the lower the pH of the solution the more the reaction shifts towards producing phosphoric acid. In addition to the formation of phosphoric acid, various other products may form. In the presence of ammonium and phosphate ions, there is the possibility that ammonium phosphate, di-ammonium phosphate and ammonium hydrogen phosphate may be formed (Andrade & Schuiling, 2001). Furthermore, Andrade and Schuiling (2001) explain that magnesium hex-aquo complex can also be formed at acidic conditions. On the other hand, Ohlinger, et al. (1998) suggest that more complex ions can be formed when struvite is dissolved when the solution pH was corrected to basic at the beginning of the experiment. Table 5 shows equilibrium pK values for the various species available upon struvite dissolution at standard temperature and pressure (Ohlinger, et al., 1998).

Table 5: Equilibrium pK for Ions Present During Struvite Dissolution



Equilibrium relationship	p*K*
$MgPO_4^- \Leftrightarrow Mg^{2+} + PO_4^{3-}$	4.80
$MgHPO_4 \Leftrightarrow Mg^{2+} + HPO_4^{2-}$	2.91
$MgH_2PO_4^+ \Leftrightarrow Mg^{2+} + H_2PO_4^-$	0.45
$MgOH^+ \Leftrightarrow Mg^{2+} + OH^-$	2.56
$HPO_4^{2-} \Leftrightarrow H^+ + PO_4^{3-}$	12.35
$H_2PO_4^- \Leftrightarrow H^+ + HPO_4^{2-}$	7.20
$H_3PO_4 \Leftrightarrow H^+ + H_2PO_4^-$	2.15
$MgNH_4PO_4 \cdot 6H_2O \Leftrightarrow Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O$	13.26

Data in Table 5 further proves that acidic conditions sway the equilibrium towards producing phosphoric acid. In doing so, phosphate ions are depleted as shown in the reactions and in Figure 17.

2.5 LINKING INCLUSIVE BUSINESS TO EXTENDED PRODUCER RESPONBILITY

The base of the economic pyramid (BoP) comprises 4 to 5 billion people living on less than 10US$ per day, most of which live in rural areas and in congested slums (WBCSD, 2016). While the provision of quality services and goods to the BoP is often restricted, inclusive business models have a role in integrating these low-income communities in the core of big business. The report by the Federal Ministry for Economic Cooperation and Development defines inclusive business models as those that *'are intended to circumvent existing market failures and inefficiencies to successfully* ***integrate the poor****, either on the* ***demand side as clients*** *or on the* ***supply sides as distributors****,* ***suppliers of goods and services****, or* ***employees****'* or consumers (Rosler, et al., 2013; UNDP, 2010). The practice of businesses becoming inclusive represents a much-needed paradigm shift from philanthropy to corporate social responsibility (CSR) to shared value creation (CSV) (Porter, 2013). Shared value creation not only benefits low-income communities with steady income creation but also in skills development, innovation promotion and rapid information sharing and utilisation. To businesses, on the other hand, the BoP is a large, untapped source of opportunity where there is room to grow (Porter, 2013; Rosler, et al., 2013). The key to successful inclusive business models lies in the core inclusion of the BoP in key forward and backward business linkages (UNDP, 2010).

One way of encouraging social, economic and environmental progression is through the implementation of extended producer responsibility (EPR). In simple terms, EPR refers to the extension in the producers' responsibility for a product to the post-consumer stage which includes the disposal of the product (Widmer, et al., 2005). The implementation of EPR schemes is often executed through mandatory or voluntary interventions. The former is often driven by the country's agenda to protect the environment and to upskill people through legislation. Although voluntary EPR is primarily reported as that which is driven by industries realisation to be socio-ecologically responsible; there is literature that argues the formation of some voluntary EPR models as ones that are derived from an agreement between government and industry to improve product responsibility (Nahman, 2010; Widmer, et al., 2005). Subsections 2.5.1 and 2.5.2 introduce two distinct EPR cases, one which has been applied in the waste tyre industry and the other in used oils. The introduction provides insight into the inner workings of the EPR cases whose experiences are further studied in Chapter 6.

2.5.1 RECYCLING AND ECONOMIC DEVELOPMENT INITIATIVE OF SOUTH AFRICA

Approximately 275,000 tonnes of tyres, which are often discarded as ‘waste’ after use, are manufactured annually and sold locally in South Africa (REDISA, 2012). Traditionally, most of these tyres were dumped in landfills and slums around the country – further resulting in unhealthy living environments. The Integrated Industry Waste Tyre Management Plan (IIWTMP) by the Recycling and Economic Development Initiative of South Africa (REDISA) aimed to support and promote loop-closure in the waste tyre industry. Through the support and promotion of waste tyre recycling, REDISA had created a circular economy that was funded by a waste management levy of 2.3 R/kg of tyre manufactured and sold to the user (REDISA, 2015).

The REDISA plan, shown in Figure 20, constituted seven mandates, namely: waste diversion from landfill back into a value generation supply chain, skills upliftment and training (technical and business know-how), development of SMMEs, create jobs, drive research and development, participate in social upliftment programmes and to market tyre life optimisation and promote the use of rethreaded tyres. In the annual report of 2015, REDISA reported to have created 1,897 jobs directly, 178 SMMEs, collected 85,133 tonnes of tyres and processed (via crumb and pyrolysis) 43052 tonnes of tyres by February 2015 (REDISA, 2015). From the aforementioned information, a basic socio-economic indicator in the form of a ratio between the total fiscal inflow from the waste management levy and the amount of jobs created can be used. In the case of REDISA it can be deduced that in the year 2015, the creation of one job in the reverse logistics network required funding of 100,000 ZAR annually collected from the levy. Additionally, the environmental impact then depends on the what the waste tyres were used for.

The circular economy that results from the REDISA approach exhibits inclusive business model properties in that the South African BoP is involved in the core tyre recycling business. At the estimated tyre production capacity in South Africa of 275,000 tonnes annually there is R605 million available – through the 2.3 R/kg tyre levy – to facilitate tyre recycling. REDISA sought to distribute these funds as shown in Figure 19 which in turn also shows how REDISA aimed to fulfil their objectives.

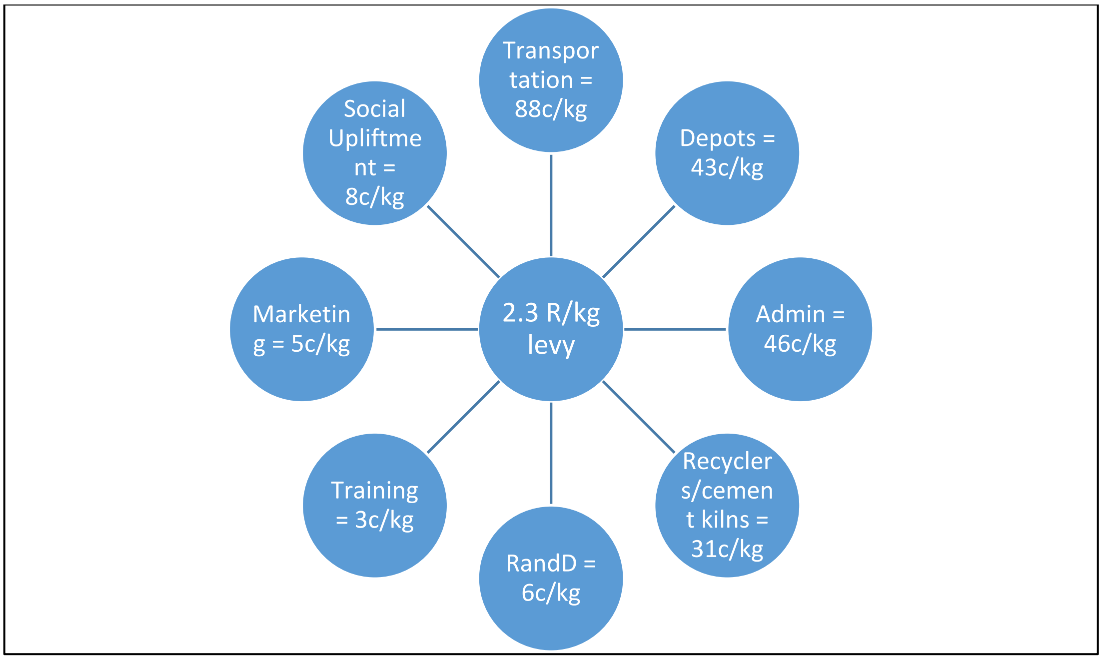


FIGURE 19: TYRE LEVY DISTRIBUTION (REDISA, 2012)

About 71% of the tyre levy was mostly filtered down to low-income communities who were involved in tyre transportation to and from depots, storage at the depots and recyclers. The balance of the tyre levy finances research and development (RandD), marketing, admin etc. (REDISA, 2012). At the time of writing of this work, the supply of tyres into the South African market exceeded the recycling capacity and thus some of the value was being shipped out to countries with established tyre recycling facilities.

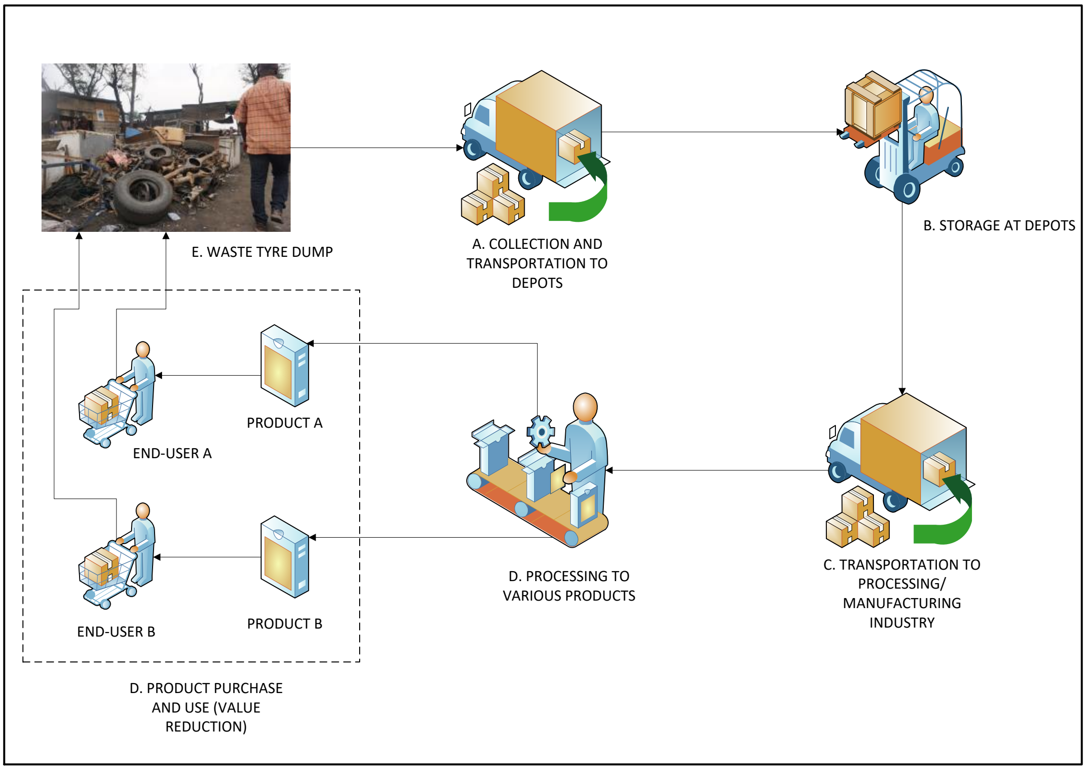


FIGURE 20: REDISA PLAN

As shown in Figure 20, the REDISA plan created shared value by imposing the levy on the end-user of the tyre product which then funds the recycling process.

The loop-closure of phosphates is a somewhat more complex since the waste source is not expected to fund the treatment of the waste. Instead, the model would most likely depend on another form of funding to ensure that the recycling process is sustainable. The discussion is advanced in Chapter 6 of this work.

2.5.2 RECYCLING OIL SAVES THE ENVIRONMENT FOUNDATION

Established in 1994 by lubricant producing companies, the Recycling Oil Saves the Environment (ROSE) Foundation has recycled a total of over one billion litres of used oil in South Africa (ROSE, 2017). Unlike the REDISA model which was largely government attempt at recycling waste (tyres), the ROSE Foundation is backed by oil producers with the intention of re-processing used lubricant oils. The impressive extended producer responsibility model used to achieve this milestone is one that comprises used lubricant oil collection after end-use, transportation, storage and processing thereof. According to the ROSE Foundation, used lubricant oils may be re-processed and re-used as low grade low sulphur industrial fuel oils, or to produced industrial grade furnace fuels (ROSE, 2017).

The common statistic in oil recycling literature is that a litre of used oil can pollute one million litres of water if unsafely released into the environment (Saskatchewan Association for Resource Recovery Corp, 2008; ROSE, 2017). Noting this, there is immense environmental and socio-economic benefit that has been accomplished through the of the ROSE Foundation however, the potential to close the loop almost entirely remains. Even though the ROSE Foundation boasted an 8.9% increase in the volume of recycled oil in 2016; it is estimated that there is still a further 11 million litres of used oil that is not being appropriately disposed and ROSE aims to close this gap (ROSE, 2017).

2.6 SUMMARY OF LITERATURE REVIEWED

The literature reviewed in this chapter has shown that phosphate fertiliser production primarily depends on the mining and subsequent processing of phosphate ores. However, this approach is heavily reliant on the finite mineral ores and centralised processing plants that are material, energy and water intensive. Additionally, phosphate grades have shown increasing impurity amounts – adding onto the resource intensiveness of the processing technologies (HCSS, 2012; Ortiz, et al., 1999).

However, examination of phosphate pathways shows that there is an opportunity for closing the phosphate loop by capturing the phosphates from wastewater and ultimately reuse them in agriculture (Ganrot, 2005; Liu, et al., 2008). Source-separated urine has also become an attractive option for phosphate recovery due to its high nutrient content shown in Table 3. Various technologies have since been developed so as to recover phosphates (and other nutrients) but there exists a gap in using source-separated urine as a raw material in an existing processing plant. In fact, there is limited literature, i.e. it is only the work of Pronk and Kone

(2009) where the reintroduction of urine-derived struvite is considered as an option for integration into phosphoric acid production plants.

In making production processes more circular, extended producer responsibility (EPR) models such as that previously used by REDISA and that currently used by the ROSE Foundation have an imperative role. Not only does EPR a form of better resource management but it also creates employment opportunities and diverts wastes that would otherwise end up in the environment as pollutants.

CHAPTER 3. APPROACH AND METHODS

Having gathered the relevant information from literature on the importance of phosphate, the different phosphate processing options, struvite chemistry as well as extended producer responsibility models, the key questions that aid this work are presented in Section 3.1.

The research undertaken herein investigated the capability and suitability of existing dihydrate and hemihydrate phosphate processing flow sheet options in processing struvite into phosphoric acid. As discussed in Section 3.2, only two of the five processing options presented in the reactor design subsection 2.2.3 were explored. Process flow simulations were used to assess the potential of using a human waste derivative, specifically struvite, as a raw material in the phosphoric acid production process. Secondly, discussed in Section 3.3 is the method behind the investigation into the socio-economic impacts of this approach to sustainable phosphate procurement were explored. This was done by examining the implementation of the extended producer responsibility models by the Recycling and Economic Development Initiative South Africa (REDISA) in the management of waste tyres in South Africa and the Recycling Oil Saves the Environment (ROSE) Foundation. The economics of a urine collection and processing reverse value chain to tie into a centralised phosphoric acid production plant were modelled.

3.1 KEY RESEARCH QUESTIONS

Based on the literature review, the following key questions arise:

i. Can struvite produced from source-separated human urine and/or obtained from centralised wastewater treatment works be used as a raw material phosphate source during the production of phosphate fertiliser?
    a. At which stage of the phosphoric acid production process does it make process engineering sense to use struvite as a raw material?
    b. What economic implications does the addition of struvite into a centralised phosphate processing plant have on the production process?
    c. At what struvite cost is the upstream phosphate processor willing to use struvite over phosphate rock and,
    d. How does the price at which struvite is sold to the upstream processor impact on struvite reverse logistics?
    e. Would the magnesium content of the struvite be lost in the gypsum waste product or could it be cycled or used productively?

ii. How can the loop-closure of a phosphate value chain be achieved? Specifically;
    a. What proportion of primary phosphate, that would otherwise have to be mined, does the reintroduction of a secondary phosphate source account for?
    b. How many potential work opportunities can result from the closure of the phosphate loop?

iii. What learnings can be drawn from the implementation of past EPR strategies and why were these strategies successful or unsuccessful? Additionally;
    a. What are the experiences of people who have been involved in reverse logistics networks with other materials?
    b. What factors can guide decision-making with respect to the implementation of future EPR schemes such as that evaluated in this work?

The dissertation proceeds to detail the approach taken to answer the research questions posed.

3.2 FLOW SHEET ANALYSIS

Dihydrate and hemihydrate phosphate processing flow sheets were simulated according to Figure 21: Flow Diagrams for DH and HH Processing Options. The base case simulation shows only mined phosphate rock to generate phosphoric acid whereas the alternative cases in the DH and HH processing options used both the phosphate rock as well as struvite derived from wastes and neglected the presence of other salts that may precipitate with the struvite.

The base case scenario aimed to achieve a phosphoric acid production rate of about 650,000 tons per year which is approximately 100,000 tons per year more than that published as the aim for Foskor in 2016, even though the plant in Richards Bay does have more capacity. The important parameters in this analysis were the **phosphoric acid production cost** as well as the amount of **phosphogypsum produced per tonne of phosphoric acid produced**. The phosphoric acid production cost referred to herein is that of the raw material demand per unit of phosphoric acid produced – it does not factor in other variable costs which may differ according to production for the two processes.

The operating conditions for the DH and HH reactors are taken to be in the regions of 60-80ºC and 120-140ºC under vacuum conditions, respectively. The operating condition range for the DH option corresponded to a 20-25% phosphoric acid concentration after the DH reactor, as shown in Figure 4, and 38-41% phosphoric acid product concentration as in Figure 6. The same data was then obtained for the HH option whose first pass concentration (after the HH reactor) is between 25-30% (slightly higher than in the DH option) and the phosphoric acid product acid in the range 53-62%. Additional data and assumptions made for the mass balance calculations to be carried out for the DH and HH processing options to meet quality specifications, as per literature, are tabulated in Table 6. Furthermore, the research did not at this stage explore the implication of having chemical Reactions 2 and 3 in the reactor (see subsection 2.2.3).

The base case was then used for assessing the potential of struvite addition to the DH and HH phosphate processing options. Identifiable struvite addition points, as shown in Figure 21 for the two options, are:

a. during pre-reactor mixing where process water and phosphate rock are mixed to form a slurry,

b. at the phosphoric acid plant when sulphuric acid is reacted with phosphate rock concentrate or,
c. at the digestion stage or,
d. further on in the final stage production when phosphoric acid is fed into the fertiliser production process.

Section 4.1 details the choice of addition point for struvite for options a, b, c and d.

As mentioned in Section 2.4.3, the chemistry of struvite, with respect to its reactivity with acids is not well documented in literature. However, Figure 17: Presence of Various Species with Solution pH and Figure 18: Struvite Solubility for Various Temperatures and Initial Solution pH, were essential in predicting how struvite would tend to react when conditions are acidic. From the information gathered in Section 2.4.3 it is assumed that Reaction 5 is the governing reaction when struvite reacts with sulphuric acid at the pre-specified reactor conditions. Furthermore, the mass balance assumes that the reaction kinetics for reacting struvite into phosphoric acid, as per Reaction 5, are similar to those needed to react phosphate rock to form phosphoric acid, as per Reaction 1; that is, the time taken to react one mole of struvite in Reaction 5 is similar to that needed to react one mole of apatite rock, as per Reaction 1.

$$2MgNH_4PO_4.6H_2O(s) + 3H_2SO_4(aq) + 2H_2O(l) \rightarrow 2H_3PO_4(aq) + 2MgSO_4.7H_2O(s) + (NH_4)_2SO_4(aq) \quad \text{Reaction 5}$$

After performing the base case mass balance, the influence of adding struvite on the cost of production as well as the specific phosphogypsum production were analysed. The mass fraction of struvite to phosphate rock in the feed stream was varied from 0 (using no struvite) to only 10% since complete substitution of phosphate rock with struvite is impractical due to limitation in the availability of phosphorus in urine. This is discussed in more detail in Chapter 4. In addition to this, the techno-economic assessment assumed 95% overall equipment effectiveness (OEE) in the plant and a cost of 1320 R/tonne (Sikosana, 2015) of struvite for the initial calculation. Costs for phosphate rock and sulphuric acid of 2115 R/ton and R665 R/ton were obtained from the Foskor price list, for the period 01 July 2016 to 31 July 2016, available on the website (Foskor Limited, 2016).

Following this, the sensitivity of the phosphoric acid production cost on struvite pricing was determined. This was done by varying the price of struvite whilst keeping the total phosphoric acid production rate constant at 650 kilo-tonnes per year for the two processing options.

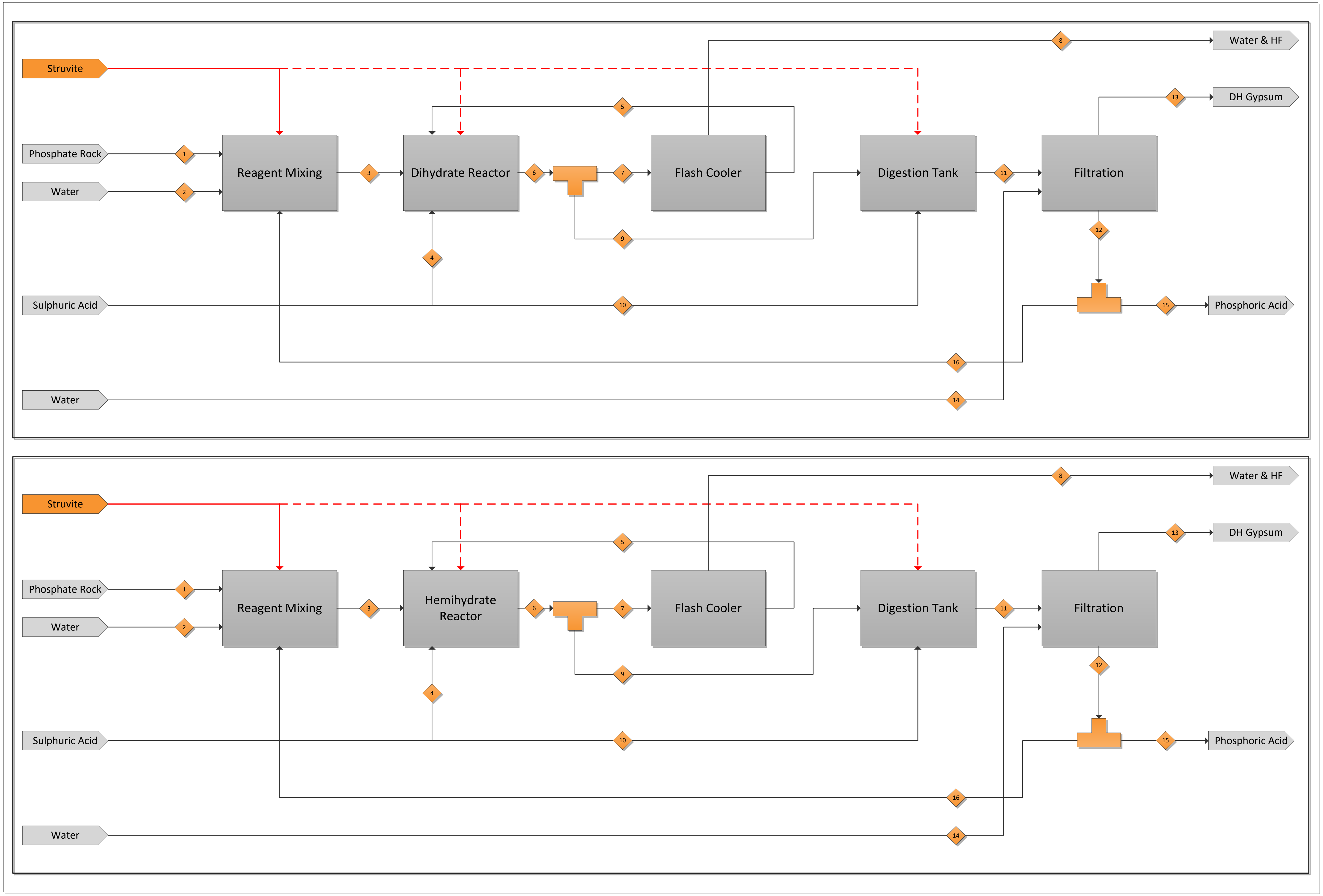


FIGURE 21: FLOW DIAGRAMS FOR DH AND HH PROCESSING OPTIONS

TABLE 6: DATA AND ASSUMPTIONS FOR BASE CASE MASS BALANCE

Option	DH	HH
Phosphate Rock Basis	175000 kg/h	175000 kg/h
Struvite Basis	0	0
Water Flow	1.1 x that required by stoichiometry	0.85 x that required by stoichiometry
H_2SO_4 Flow into Reactor	1 x that required by stoichiometry	1 x that required by stoichiometry
Reactor Conversions	**Conversion in Reactors**	
$NH_4MgPO_4.6H_2O$	N/A	N/A
$Ca_5(PO_4)_3F$	93%	96%
MgO	95%	95%
Recycle Ratio	0.1	0.1
Water Separation Efficiency	80%	80%
HF Separation Efficiency	100%	100%
Fresh H_2SO_4 Flow into DT	1 x that required by stoichiometry	1.2 x that required by stoichiometry
DT Reactor	**Conversion in DT**	
$NH_4MgPO_4.6H_2O$	N/A	N/A
$Ca_5(PO_4)_3F$	83%	86%
MgO	90%	90%
Solids Recovery into Gypsum	95%	93%
Liquids Recovery into Gypsum	7%	7%
HF Recovery into Gypsum	90%	90%
Wash Water (based on rock inlet)	60%	5%
Product Draw	85%	85%

3.3 VALUE CHAIN ANALYSIS

The socio-economic impact assessment of the phosphate circular economy model was carried out through a financial evaluation of collecting and transporting source-separated urine, processing the urine into struvite and transportation of struvite to Richards Bay. It is envisioned that small and medium enterprises (SMMEs) would be responsible for achieving the above-mentioned tasks with the intention of ensuring that the reverse logistics network is optimally operational. The capital and operational expenditure were determined at each of the three beneficiation stages together with the potential retail price to Foskor Limited established. Furthermore, a comparison is made between the struvite price obtained from modelling the value chain against the struvite price obtained from Sikosana (2015).

The analysis was divided into two; the first being at a base case urine collection rate – as per the VUNA study which was briefly introduced in the problem statement (Section 1.2) of this work and the second at a participation rate that would be sufficient to service the population that has no flush toilet system that is connected to the public sewerage system. The two cases were developed and analysed to provide insights on the impact of scale in such a network as well as to establish key parameters whose sensitivity can be tested.

3.3.1 COLLECTION AND TRANSPORTATION COST ASSESSMENT

The capex required for urine collection and transportation at the base case urine quantity of 18,000 litres in a 30-day month comprised the price of a truck and collection containers that would facilitate the process. Furthermore, an 10% contingency was factored in to accommodate possible overheads. The number of trucks that would be needed for this operation was then estimated using typical parameters on the average distance travelled by a collection truck together with the quantity of urine collected per distance travelled by the truck in the VUNA study. The same methodology was then used to obtain the capex required for a collection and transportation fleet that would meet the demand of the larger KZN population.

In addition to the capex, the opex was determined after breaking it down into fixed and variable costs. The former was made up of the labour that is needed for the transportation, the depreciation of the trucks, maintenance as well as other overheads. In both the base case as well as the scaled-up version, the amount of labour, in the number of people needed, required was determined from the number of trucks that were calculated in the capex estimation description above. In both cases, the labour requirement was initially estimated from the VUNA case study which had used one driver, two loaders/collectors and one facilitator per truck in their collection and transportation phase. The driver was initially assumed to earn 10,000 ZAR per month and the rest of the team 5,000 ZAR per month. The depreciation amount was calculated on a depreciation rate assumed at 15% over a 20-year period using the straight-line method. The cost of maintaining the vehicle was taken at 8.05% of the total capex per year and was divided accordingly to obtain a monthly cost (Seider, et al., 2010). Lastly in the fixed cost category were other overheads that were taken to be 13.3% of the sum of the total labour cost with the maintenance cost (Seider, et al., 2010). The only variable cost at this phase of the operation was the fuel consumption of the vehicle. The price of fuel was taken at 13 ZAR per litre, the consumption rate at 11 litres of diesel per 100 km travelled. The last variable needed to obtain a cost was calculated from the amount of urine that needs to be collected in that case and a constant representing the average quantity of urine collected per distance travelled by the vehicle. The total potential cost that can be incurred during the collection and transportation of urine was then determined by summing the fixed to variable cost.

3.3.2 PRE-TREATMENT AND PROCESSING COST ASSESSMENT

The pre-treatment and processing phase of the network required capital investment that would be sufficient to build process units required in the conversion of urine into struvite. The capital investment required was scaled-up following the process detailed by Sikosana, et al. (2016) for the treatment of urine into struvite. The work by Sikosana, et al. (2016) detailed a process option where urine was treated via a precipitation reactor where magnesium chloride and caustic soda are added and allowed to react with diluted urine. Thereafter, the precipitate is filtered and allowed to dry before dispatched. The filtrate on the other hand is byproduct of the process. A process flow diagram of this recovery method is summarised in Figure 22. The six-tenths rule together with CEPCI indexes for 2015 and 2017 were applied to obtain an estimate of the capex required to process the urine quantities in the two scenarios.

The opex of the urine treatment plant was again divided into fixed and variable costs. The following Table 7 is a summary of the parameters used in the costing of urine pre-treatment and processing into struvite.

TABLE 7: SUMMARY OF COSTING PARAMETERS - PRE-TREATMENT AND PROCESSING

Description	Value
Wages	10,000 ZAR per month per person
Plant depreciation	Straight-line method at 15% per year for 20 years.
Maintenance cost	8.05% of total capex (Seider, et al., 2010)
Operating overheads	13.3% x (Labour cost + Maintenance cost) (Seider, et al., 2010)
Variable cost	3.87 ZAR per kg of struvite produced from urine in which Mg:P ratio is kept at 1.2-1.4:1 (Malanda, et al., 2016)
Magnesium chloride	8.3 ZAR per kg
Scale of production and dilution factor	18,000 L urine/day at 26% dilution
Acid needed for pH correction	60 mmol H^+ per litre of fresh urine to maintain a pH below 4 (Maurer, et al., 2006)
Price of sulphuric acid	665 ZAR/ton (Foskor Limited, 2016)

3.3.3 STRUVITE TRANSPORTATION COST ASSESSMENT

The capex required to start-up struvite transportation was determined from the number of vehicles that would be needed to transport a certain quantity of struvite. The distance travelled by one truck was preliminarily capped at 200 km/trip where a trip was the distance taken from the depot/struvite generation process to the phosphoric acid complex but could be adjusted. Secondly, the number of trips that could be made per day by a truck was capped at 2 trips per day per truck. The number of driver/loader pairs required was then calculated by multiplying the inverse of the 2 trips per day per truck by the actual number of trips required per day to transport the produced quantity of struvite; and thus the number of trucks needed for each operation deduced. In the case where the quantity of struvite exceeds 20 tons per month, the cost of one truck was taken at 1,2 million ZAR. The capex then also accounted for a 18% contingency.

The fixed and variable costs for struvite precipitation were obtained using the same method as detailed in the collection and transportation cost assessment.

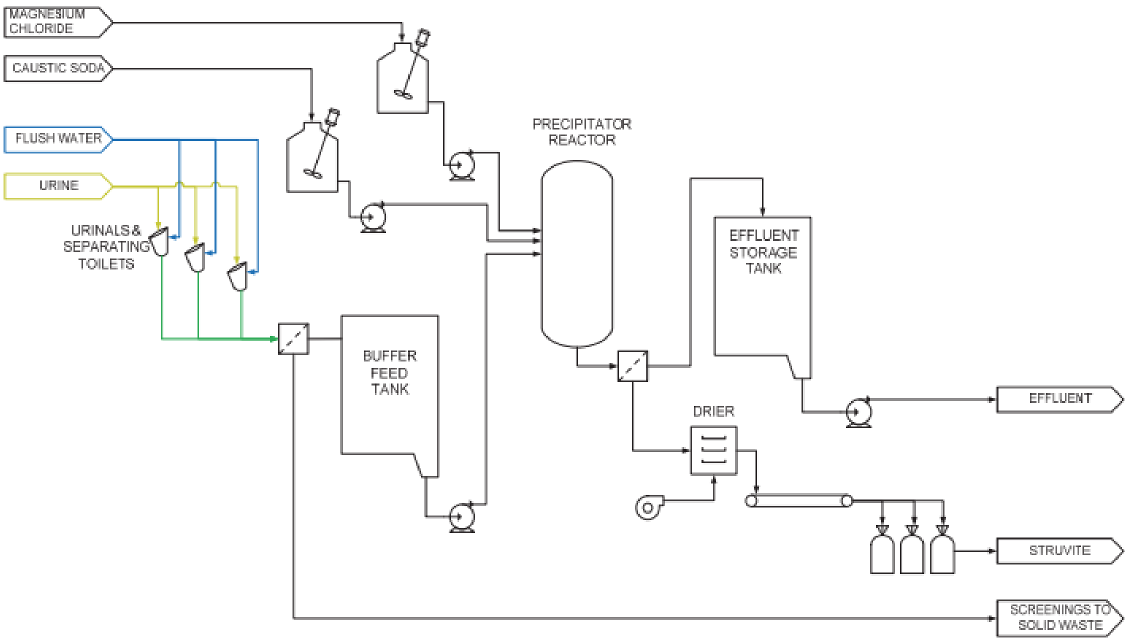


FIGURE 22: PFD FOR STRUVITE RECOVERY FROM URINE

3.4 LEARNING FROM PAST EPR SCHEMES

Schemes studied to understand how an extended responsibility of producers for their products functions in the South African context included REDISA as well as the ROSE foundation. A semi-structured interview with a representative of a used oils recycling company was conducted. The second respondent from the ROSE Foundation was liaised with via email for clarification on some of the functions of the ROSE Foundation. A desktop study was then also used as a mode of data collection to understand how extended producer responsibility schemes have approached recycling in the past.

To ensure the research was carried out in an ethical manner, an application to review the suggested research was put forth to the Engineering and Built Environment Ethics in Research Committee. This application was approved.

CHAPTER 4. PHOSPHATE PROCESS FLOW SHEET ANALYSIS

Chapter 4 draws heavily from the technical insights discussed Section 2.2 and 2.4, specifically detail on wet process phosphoric acid production as well as struvite chemistry. The chapter is arranged in a manner which tackles the process engineering design, process economics and points out key environmental considerations. The process engineering design aspect of the chapter unpacks the HH and DH processes thereby establishing key entry points for struvite into the generic HH and DH processes. Additionally, the process engineering aspect informs the process economics through a mass balance which accounts for the material substitution of mined phosphate rock with struvite derived from urine. It is important to note that at this stage, the process economics are largely preliminary due to the cost of struvite procured through a reverse logistics network not being fully understood at this stage of the study; Chapter 5 provides further insight in this regard. Lastly, the material balance also provides insight into the key environmental considerations that would result from the above-mentioned material substitution.

Based on the methodology detailed in Section 3.2, the results obtained from the flowsheet analysis are presented and discussed.

4.1 CONCEPT DESIGN – STRUVITE SUBSTITUTION

The objective of the concept design is to understand the ideal stage at which struvite can be introduced during the processing. As shown in Figure 21, both flow sheets follow the same process sequence under different reaction conditions which thus brings about different reactions and products. In both DH and HH processing options struvite can be added into the reagent mixing stage (Option A), DH or HH reactor (Option B), at the digestion stage (Option C) or further on in the fertiliser production stage when phosphoric acid is used as a reactant (Option D). Practically, the optimal addition point is one where the maximum amount of struvite is used while producing the maximum amount of phosphoric acid with an ‘acceptable’ change in product quality for the downstream processer to use with little to no further processing in the product acid.

Blending phosphate rock, struvite and water reagents at the mixing stage of the process favours feed of a homogenous mixture with little process variations if designed with sufficient residence time. Having a homogenous reagent mixture is an advantage in that there is better control of the relative quantities of reagents added into the reactor where sulphuric acid is introduced. Furthermore, the addition of struvite at an earlier stage of the process ensures that all reactants have sufficient time to effectively collide thus maximising the probability of reaction. Even though Option B has the advantage of not having to input energy to mix reagents it has the added cost of mechanical and electrical equipment that would be needed to get the product to the reactor. Additionally, Option B (without the reagent mixing stage) has the potential for loss of production should a process upset occur at any of the water, phosphate rock or struvite supplies (upstream pump, conveyor or instrument failures for example). This would then upset the relative ratios of reactant entering the reaction and therefore the reaction itself whereas the mixing stage of Option A buffers process related deviations. Option C alone is unfavourable to this process as the contact time of struvite with sulphuric acid would be minimal before the product is separated at the filtration stage. A combination of options is also possible and has the potential for better efficiency; however, no combinations are explored in this study. Option D was not investigated as it is beyond the scope of this research, however, it is anticipated that this option could also have the potential to eliminate bacteria and other pathogens that might be found in struvite since it uses ammonia to make MAP and DAP. The dynamics of Option D are different from those of Options A, B and C since the addition is not during the phosphoric acid production stage but rather at the fertiliser production stage.

4.2 STRUVITE SUBSTITUTION ANALYSIS

4.2.1 BASE CASE PROCESS FLOW SIMULATIONS

The base case mass balances where based on an existing process that is equipped to handle 175,000 kg/h of phosphate-bearing raw material (phosphate rock and/or struvite). Hereon, the processes that do not use struvite are identified as DH and HH and those using struvite as a reactant are identified as the '*struvite'* DH/HH or sDH/sHH processes. Material balance results for the process flow diagrams shown in Figure 21, representing the DH and HH processes for phosphoric acid production are summarised in Table 8 and

Table 9, respectively.

Using the data / inputs shown in Table 6, the process flow simulations of the processes represented in Figure 21 (DH and HH processes) noticeably showed that there was a difference in the concentration of phosphoric acid product between the two processes. Even though the HH process was able to achieve a higher final product concentration at 54% H_3PO_4 (aq) than the DH process at 38% H_3PO_4 (aq), the concentration of magnesium impurity in the final product of the DH process (6000 ppm) was lower than that of the HH process (9000 ppm). The previous statement is further supported by the saturation solubility characteristics of magnesium sulphate which indicate that the solubility of the salt increases with increasing temperature (Ting & McCabe, 1934). The saturation solubility of magnesium sulphate is quoted by Ting and McCabe (1934) as ranging from roughly 20.9 g $MgSO_4$ / 100 g H_2O at 2ºC to 33 g $MgSO_4$ / 100 g H_2O at 48ºC. The material balances of the HH and DH options suggested that the two processes would achieve dissolved magnium sulphate contents below 5%, therefore indication undersaturated solutions containing the salt (Ting & McCabe, 1934). This observation is imperative as it has the potential to affect the quality of phosphoric acid in the sDH and sHH processes knowing that struvite is rich in magnesium. Furthermore, there exists the additional factor of high pH in the digestion unit which could also have the potential to improve the solubility of the magnesium salt formed during the reaction and therefore further impact the quality of product phosphoric acid. The solubility characteristics described above therefore prompt the questions on the practical impact of introducing struvite to the process and product quality. The section that follows untangles this condition further after a materials balance of the sDH and sHH processes.

TABLE 8: DH PROCESS MATERIAL BALANCE – BASE CASE

Stream	1		2		3		Struvite		4		5		6		7		8	
Flow	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h
H_20	0	0	70400	3910	88200	4900	0	0	605	34	588	33	29400	1630	2940	163	2350	131
H_2SO_4	0	0	0	0	1920	20	0	0	161000	1650	1340	14	13400	136	1340	14	0	0
H_3P0_4	0	0	0	0	14900	152	0	0	0	0	11300	116	113000	1160	11300	116	0	0
HF	0	0	0	0	86	4	0	0	0	0	0	0	6010	300	601	30	601	30
$(NH_4)_2SO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Ca_5(PO_4)_3F$	159000	316	0	0	159000	316	0	0	0	0	1120	2	11200	22	1120	2	0	0
MgO	2630	66	0	0	2630	66	0	0	0	0	13	0	132	3	13	0	0	0
Fe_2O_3	840	5	0	0	846	5	0	0	0	0	94	1	940	6	94	1	0	0
SiO_2	2100	35	0	0	2120	35	0	0	0	0	235	4	2350	39	235	4	0	0
Al_2O_3	210	2	0	0	212	2	0	0	0	0	24	0	235	2	24	0	0	0
Other	9980	N/A	0	N/A	10100	N/A	0	N/A	0	N/A	1120	N/A	11200	N/A	1120	N/A	0	N/A
$NH_4MgPO_4.6H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$MgSO_4.7H_2O$	0	0	0	0	2610	11	0	0	0	0	2000	8	20000	81	2000	8	0	0
$MgSO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.2H_2O$	0	0	0	0	2030	12	0	0	0	0	28500	166	285000	1660	28500	166	0	0
$CaSO_4.0,5H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	175000	424	70400	3910	285000	5520	0	0	162000	1680	46400	343	493000	5040	49300	504	2950	161

Stream	9		10		11		12		13		14		15		16	
Flow	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h	kg/h	kmol/h
H_20	26500	1470	38	2	23200	1290	119000	6620	8970	499	105000	5830	101000	5630	17900	994
H_2SO_4	12000	123	10100	103	13700	140	12800	130	961	10	0	0	10900	111	1920	20
H_3P0_4	102000	1040	0	0	107000	1090	99300	1010	7480	76	0	0	84400	861	14900	152
HF	5400	270	0	0	5740	287	574	29	5160	258	0	0	488	24	86	4
$(NH_4)_2SO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Ca_5(PO_4)_3F$	10100	20	0	0	1720	3	86	0	1630	3	0	0	73	0	13	0
MgO	119	3	0	0	12	0	1	0	11	0	0	0	1	0	0	0
Fe_2O_3	846	5	0	0	846	5	42	0	804	5	0	0	36	0	6	0
SiO_2	2120	35	0	0	2120	35	106	2	2010	34	0	0	90	2	16	0
Al_2O_3	212	2	0	0	212	2	11	0	201	2	0	0	9	0	2	0
Other	10100	N/A	0	N/A	10100	N/A	503	N/A	9550	N/A	0	N/A	427	N/A	75	N/A
$NH_4MgPO_4.6H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$MgSO_4.7H_2O$	18000	73	0	0	18700	76	17400	71	1310	5	0	0	14800	60	2610	11
$MgSO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.2H_2O$	257000	1490	0	0	271000	1570	13500	79	257000	1500	0	0	11500	67	2030	12
$CaSO_4.0,5H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	444000	4530	10200	105	454000	4500	264000	7950	295000	2390	105000	5830	224000	6760	39500	1190

TABLE 9: HH PROCESS MATERIAL BALANCE – BASE CASE

Stream	**1**		**2**		**3**		**Struvite**		**4**		**5**		**6**		**7**		**8**	
Flow	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**
H_20	0	0	54400	3020	60700	3370	0	0	604	34	834	46	41700	2320	4170	232	3340	185
H_2SO_4	0	0	0	0	1280	13	0	0	161000	1650	796	8	7960	81	796	8	0	0
H_3P0_4	0	0	0	0	15000	153	0	0	0	0	11600	119	116000	1190	11600	119	0	0
HF	0	0	0	0	86	4	0	0	0	0	0	0	6180	309	618	31	618	31
$(NH_4)_2SO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Ca_5(PO_4)_3F$	159000	316	0	0	159000	316	0	0	0	0	640	1	6400	13	640	1	0	0
MgO	2630	66	0	0	2630	66	0	0	0	0	13	0	132	3	13	0	0	0
Fe_2O_3	840	5	0	0	849	5	0	0	0	0	94	1	943	6	94	1	0	0
SiO_2	2100	35	0	0	2120	35	0	0	0	0	236	4	2360	39	236	4	0	0
Al_2O_3	210	2	0	0	212	2	0	0	0	0	24	0	236	2	24	0	0	0
Other	9980	N/A	0	N/A	10100	N/A	0	N/A	0	N/A	1120	N/A	11200	N/A	1120	N/A	0	N/A
$NH_4MgPO_4.6H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$MgSO_4.7H_2O$	0	0	0	0	2610	11	0	0	0	0	2000	8	20000	81	2000	8	0	0
$MgSO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.2H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.0{,}5H_2O$	0	0	0	0	2420	17	0	0	0	0	24800	171	248000	1710	24800	171	0	0
TOTAL	**175000**	**424**	**54400**	**3020**	**257000**	**4000**	**0**	**0**	**162000**	**1680**	**42200**	**359**	**461000**	**5750**	**46100**	**575**	**3950**	**216**

Stream	**9**		**10**		**11**		**12**		**13**		**14**		**15**		**16**	
Flow	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**	**kg/h**	**kmol/h**
H_20	37500	2080	27	1	36800	2050	42400	2350	3190	177	8750	486	36000	2000	6360	353
H_2SO_4	7160	73	7060	72	9150	93	8510	87	641	7	0	0	7240	74	1280	13
H_3P0_4	105000	1070	0	0	107000	1100	99900	1020	7520	77	0	0	84900	866	15000	153
HF	5560	278	0	0	5760	288	576	29	5180	259	0	0	489	25	86	4
$(NH_4)_2SO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Ca_5(PO_4)_3F$	5760	11	0	0	806	2	56	0	749	1	0	0	48	0	8	0
MgO	119	3	0	0	12	0	1	0	11	0	0	0	1	0	0	0
Fe_2O_3	849	5	0	0	849	5	59	0	789	5	0	0	51	0	9	0
SiO_2	2120	35	0	0	2120	35	149	2	1970	33	0	0	126	2	22	0
Al_2O_3	212	2	0	0	212	2	15	0	197	2	0	0	13	0	2	0
Other	10100	N/A	0	N/A	10100	N/A	706	N/A	9380	N/A	0	N/A	600	N/A	106	N/A
$NH_4MgPO_4.6H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$MgSO_4.7H_2O$	18000	73	0	0	18700	76	17400	71	1310	5	0	0	14800	60	2610	11
$MgSO_4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.2H_2O$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$CaSO_4.0{,}5H_2O$	223000	1540	0	0	230000	1590	16100	111	214000	1480	0	0	13700	95	2420	17
TOTAL	**415000**	**5170**	**7090**	**74**	**422000**	**5230**	**186000**	**3670**	**245000**	**2040**	**8750**	**486**	**158000**	**3120**	**27900**	**551**

4.2.2 STRUVITE PROCESS FLOW SIMULATIONS

For this analysis the struvite composition in the feed was varied and the total phosphate-bearing mass feed kept constant at 175,000 kg/h. As the struvite content of the feed varied from 0 to 100%; the phosphoric acid produced in the sDH and sHH processing options declined at rates represented by the gradients of the trendlines shown in Figure 23.

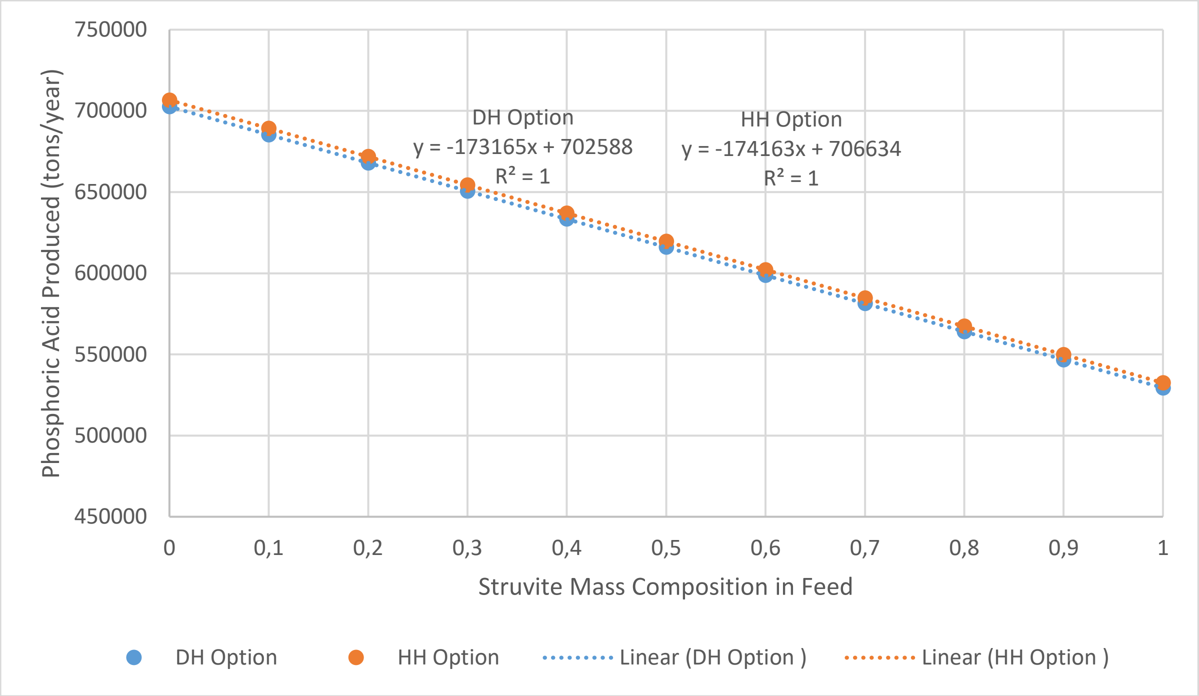


Figure 23: Impact of Struvite Addition on Phosphoric Acid Production Rate

The rate of decline of phosphoric acid produced was found to be in the region of 173-175 kt/year for every 10% increase in struvite content at the feed when keeping the total solids feed at 175000 kg/h. The rate at which phosphoric acid is produced declined *slightly* faster, as represented by the gradients in Figure 23, in the sDH option than in the sHH option. A key factor which contributed to this is the assumption made in the mass balance on the reaction kinetics and therefore conversions given specifications on existing product acid and phosphogypsum in the two processing options. It was noted that process specialists Prayon Technologies suggest that the product acid concentration leaving the DH and HH processes are at 39-45% and 28.5%, respectively. In both the DH and HH processing options the reactions are exothermic (Prayon, 2012). Since the DH reaction is designed and controlled to occur at lower temperatures than the HH reaction, as shown in Figure 4, the kinetics of the DH option bottleneck the raw material conversion rate and hence the production of phosphoric acid. Thus, the HH option achieves an insignificantly higher rate of acid production compared to the DH option which can be expressed as the ratio R throughout the different struvite contents:

$$R = \frac{-174163x+706634}{-173165x+702588} \quad for\ x\ \varepsilon\ [0;1] \text{ where x is the struvite composition in the feed} \qquad \text{Equation 1}$$

The decline in phosphoric acid production with increasing struvite content in the feed material in both options lies in that the specific mass of phosphate material present in

$MgNH_4PO_4.6H_2O$ is less than that present in $Ca_5(PO_4)_3F$. Struvite as $MgNH_4PO_4.6H_2O$ contains 39 wt% recoverable phosphate whereas $Ca_5(PO_4)_3F$ contains 57 wt% recoverable phosphate. The potential benefit of introducing struvite as in sDH and sHH processing options as a raw material primarily depends on how fast the struvite would be converted into phosphoric acid product. If the conversion is fast as the mass balance assumes then there is potential benefit of effective phosphoric acid production without the need for extra capital investment to increase plant capacity so as to accommodate the decline in recoverable phosphate. However, if the conversion is much lower than that assumed in the balance herein there is a greater chance of struvite being incompatible to an existing phosphate processing complex of this sort. The kinetics combined with the relative costs of struvite vs. phosphate rock as well as phosphoric acid product quality ultimately dictate whether there will be benefit in using struvite over phosphate rock.

The results of the material balance investigation can now be used in a cost analysis whose results presented in Figure 24. The production cost was calculated based on the raw material demand of the two processing options as:

$$\begin{aligned} Production\ Cost\ ({}^{R}/_{ton}) \\ &= Cost\ of\ [Struvite + Phosphate\ Rock + Sulphuric\ Acid \\ &+ Process\ Water]\ ({}^{R}/_{ton}) \end{aligned} \quad \textbf{Equation 2}$$

Evidently in Figure 24, as the struvite content in the feed is increased, the cost to produce phosphoric acid comes down. However, this comes at the cost of losing the quantity of phosphoric acid produced as shown in Figure 23.

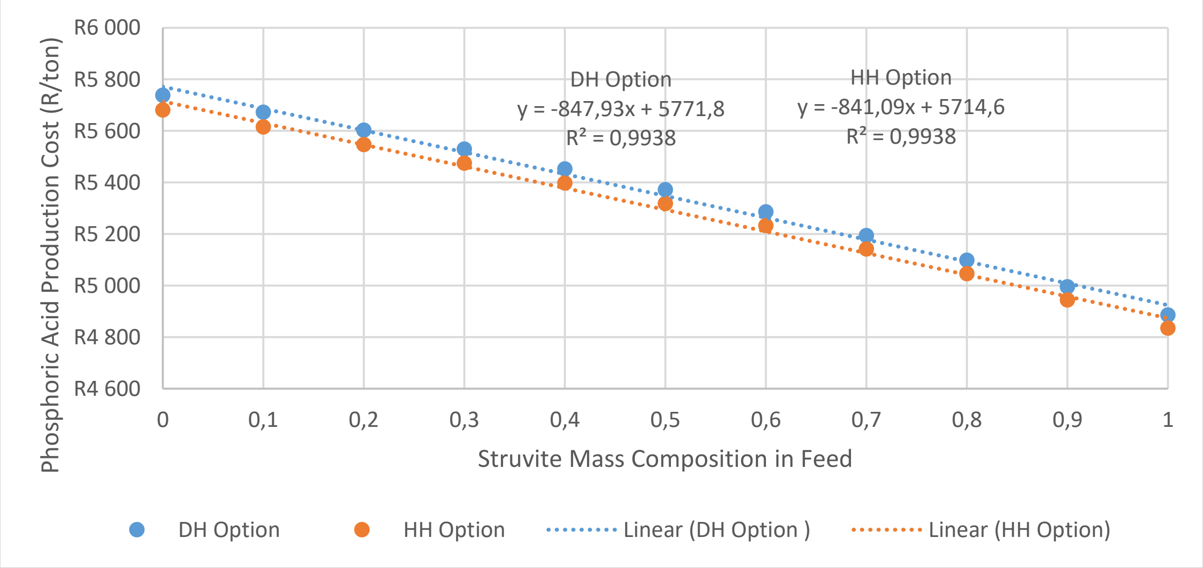


FIGURE 24: IMPACT OF STRUVITE ADDITION ON PHOSPHORIC ACID PRODUCTION COST

Equations that predict how the phosphoric acid production cost changes as the feed struvite content changes are shown in Figure 24. The decline in production cost is due to the assumption that struvite costs less than phosphate rock. The initial cost analysis used a struvite cost of 1320

R/ton (Sikosana, 2015) of struvite whereas that of phosphate rock is 2115 R/ton (Foskor, 2016). The assumption of pricing struvite being lower than phosphate rock is justified in the initial cost analysis seeing as struvite contains less phosphate than phosphate rock. Production costs for the sDH option were found to be higher than those of the sHH option. This was due to the excess sulfuric acid that would be used in the sDH option compared to the sHH option because of its lower conversion rate in the reactor.

At first, the phosphoric acid production rate of 650,000 tons/year (refer to Section 3.3) in the two processing options, the ideal struvite contents were found to be 30% and 33% for the sDH and sHH processes, respectively. This was done by equating the equations shown on Figure 23 to the required production rate of 650,000 tons/year and solving for the ideal struvite content in the feed. The task however did not prove meaningful because of a limitation in the available struvite that can be fed back into the network. The limitation is further discussed in Section 5.1. Acknowledging the limitation on the available phosphorus recoverable from wastewater, a maximum of 10% struvite in the feed was used in the sensitivity analysis. The results of the sensitivity analysis are then presented in Figure 25.

As the price of struvite increases from 0 R/ton to 2700 R/ton the production cost of phosphoric acid increases as shown in Figure 25.

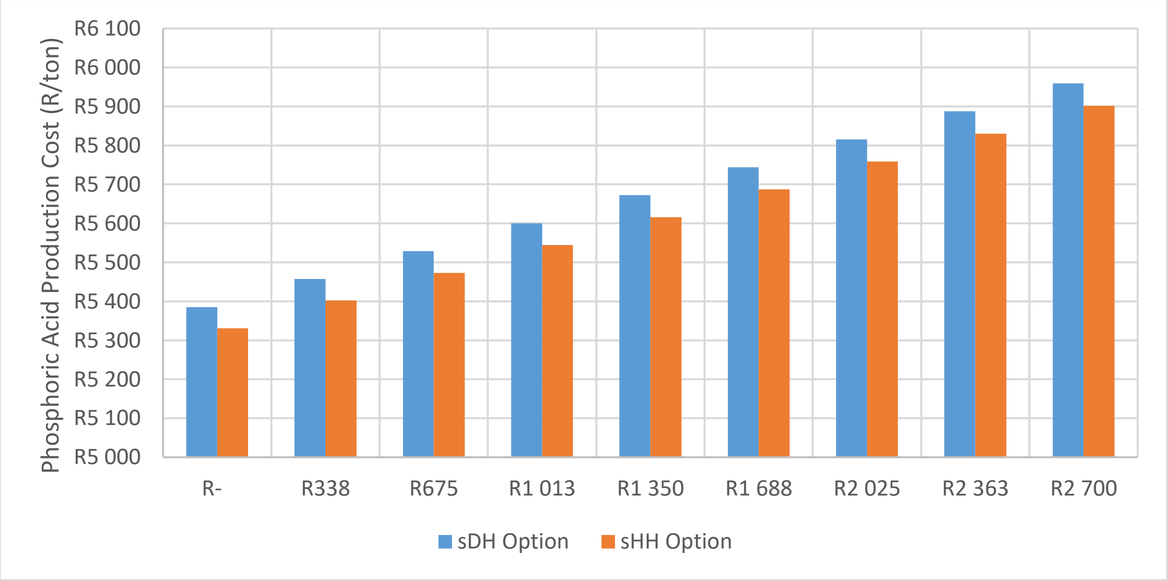


FIGURE 25: RELATION OF PHOSPHORIC ACID PRODUCTION TO STRUVITE PRICE

In both processing options, the potential benefit of using struvite in the process as a substitute for phosphate rock declines as the cost of struvite approaches that of the phosphate rock. Furthermore, there exists the potential to end up with phosphoric acid product containing a magnesium content that may be out of the required specification when struvite is introduced into the process.

The material balance executed using the 10% struvite and 90% phosphate rock process inlet showed that the product concentration in the sDH process decreased to 36% and that of the sHH process decreased to 49%. When the product concentrations were compared to those recommended by Prayon Technologies of 38% in the DH process and 53-63% H_3PO_4, the variance is manageable. A more detailed analysis of this impact would be necessary for the downstream processes. In addition to this, the content of magnesium in the products from the sDH and sHH processes was determined to be 13,000 ppm and 17,000 ppm, respectively. There is evidence in literature that higher magnesium contents in the phosphoric acid product leaving the reactor has an adverse effect on the formation of gypsum crystals and negatively impacts the filtration process (Rashad, et al., 2004). As such, there exist methods to deal with the negative impacts of high magnesium contents such as the addition of fluoride donating compounds such as hydrofluoric acid thereby forming crystalline compounds such as $MgAl_2F_8$ (Parks, et al., 1981). The method of removing magnesium from solutions of phosphoric acid presents opportunity for further use of the exhaust stream from the process in the treatment. Additionally, there is further potential to increase the concentration of the acid before it is sent onto the next process.

4.3 ECO-EFFICIENCY

The two other noticeable waste by-products generated during the phosphoric acid production from phosphate rock are phosphogypsum as well as hydrogen fluoride gas. Their analysis follows.

The material balance in the sDH and sHH processing options showed that the absence of calcium in struvite has the potential to reduce the amount of phosphogypsum that results compared to the conventional DH and HH processes. At the chosen struvite composition of 10% for the sDH and sHH options, respectively; the resultant phosphoric acid product to phosphogypsum by-product ratios are 0.31 wt/wt and 0.38 wt/wt, respectively. At the above-mentioned struvite inlet composition, it is anticipated that both sHH and sDH processing options would achieve 10% decreases in phosphogypsum generation compared to DH and HH options. Minor continual improvements in the wet processes have ample potential to reduce environmental burden, specifically the generation of phosphogypsum wastes. According to literature most of the phosphogypsum generated during the wet process is stockpiled or released into the oceans (Bituh, et al., 2009; Szlauer, et al., 1990). Foskor currently disposes by-product gypsum at sea but also has a tailings dam which it hopes to rehabilitate (Foskor, 2011). Although it is often common practice for phosphogypsum producing plants to dispose of it in the ocean because of its rapidly dissolving nature, strict restrictions for effluent cadmium content exist (Department of Mineral Resources, 2009). Furthermore, in March 2016 Foskor set aside a budget of R450 million for the cost to completely close the dam (Foskor, 2016). Using a published phosphoric acid production of 307000 t/a in the 2016 Foskor financial year as well as the maximum phosphogypsum of 5.5 tons PG per ton phosphoric acid, Foskor could have disposed approximately 1.7 million tons of PG into the sea. An estimate of 170,000 tons of PG would have been avoided from being released into the sea.

Although it is expected that no calcium sulphate ($CaSO_4.2H_2O \ or \ CaSO_4.{}^1/_2 \ H_2O$) will form in the extreme case where phosphoric acid is only generated from struvite there is potential to still generate an alternative waste in the form of a magnesium sulphate by-product which is much more soluble in water than PG. Because of the high solubility of the magnesium sulphate salt in water, especially at high temperatures and acidic pH (Ting & McCabe, 1937; Kramer, 2004), most of it would most likely need to be separated from the phosphoric acid solution as per discussed in earlier sections. This would require an extra processing step before the filtration process blocks in Figure 21 that would facilitate the separation of the salt from the rest of the phosphoric acid product. At high enough struvite feed compositions, it remains to be investigated whether the magnesium sulphate by-product could be used in other industries. Various uses of magnesium sulphate have been documented in literature including pharmaceuticals, flocculants, pulp and paper industries and agriculture (Kramer, 2004). Due to the presence of radioactive material, depending on the phosphate rock source, in the product stream it is unlikely that magnesium sulphate could be used for pharmaceutical applications. However, there is possibility for use as a reagent during the conversion of source-separated urine into struvite.

The generation of hydrogen fluoride (HF) gas is also unavoidable when using the conventional approach to phosphoric acid generation. However, the inclusion of struvite in the reaction with sulphuric acid reduced the generation of the gas. The effect of using struvite as a secondary phosphate source on the generation of HF reduces the quantity of HF containing gases because of the substitution of fluoride containing phosphate rock with struvite. Furthermore, there is potential to reuse the gas in the process needed to precipitate magnesium sulphate from solution before it enters the filtration process.

It can then be deduced that phosphoric acid product purely generated from phosphate rock only exhibits the lowest eco-efficiency. As the amount of struvite in the feed is increased, the eco-efficiency indicator, expressed as the ratio of phosphoric acid to HF gas (ton/ton), increases exponentially and then becomes meaningless when no phosphate rock is used. The complex chemistry of how HF gas reacts with other compounds in the system has not been fully explored herein, however, in this preliminary study it is important to fully acknowledge the potential of such a recycling strategy in decision-making.

CHAPTER 5. PHOSPHATE LOOP-CLOSURE MODEL DEVELOPMENT

Chapter 5 proceeds to unpack the cost implications of phosphorus loop-closure in the urine context through a struvite recovery process followed by conversion into phosphoric acid. The evaluations presented in Chapter 5 only cover financial costs that would result from the collection and transportation of urine, conversion into struvite and lastly, the transportation of struvite to a phosphoric acid producing complex such as the one discussed Section 2.2.3.

Figure 26 is a representation of the mostly linear nature of phosphorus flows in the South African context which has already been critiqued in Chapter 1. From the substance flow diagram (Figure 26), most beneficiation unit blocks leading to the consumption of food by the end-user (humans) exhibit a quantity of phosphorus which ends up in nature as a waste. Although not explicitly shown in Figure 26, possibly avoidable losses are also incurred in the production of phosphoric acid from phosphate rock, animal feed production as well as in the production of phosphate-based fertiliser. Figure 26 also shows the potential for phosphorus/phosphate recycling in South Africa. To determine the phosphorus flows as shown in Figure 26, mass balance calculations were done using the assumptions and data summarised in Table 10.

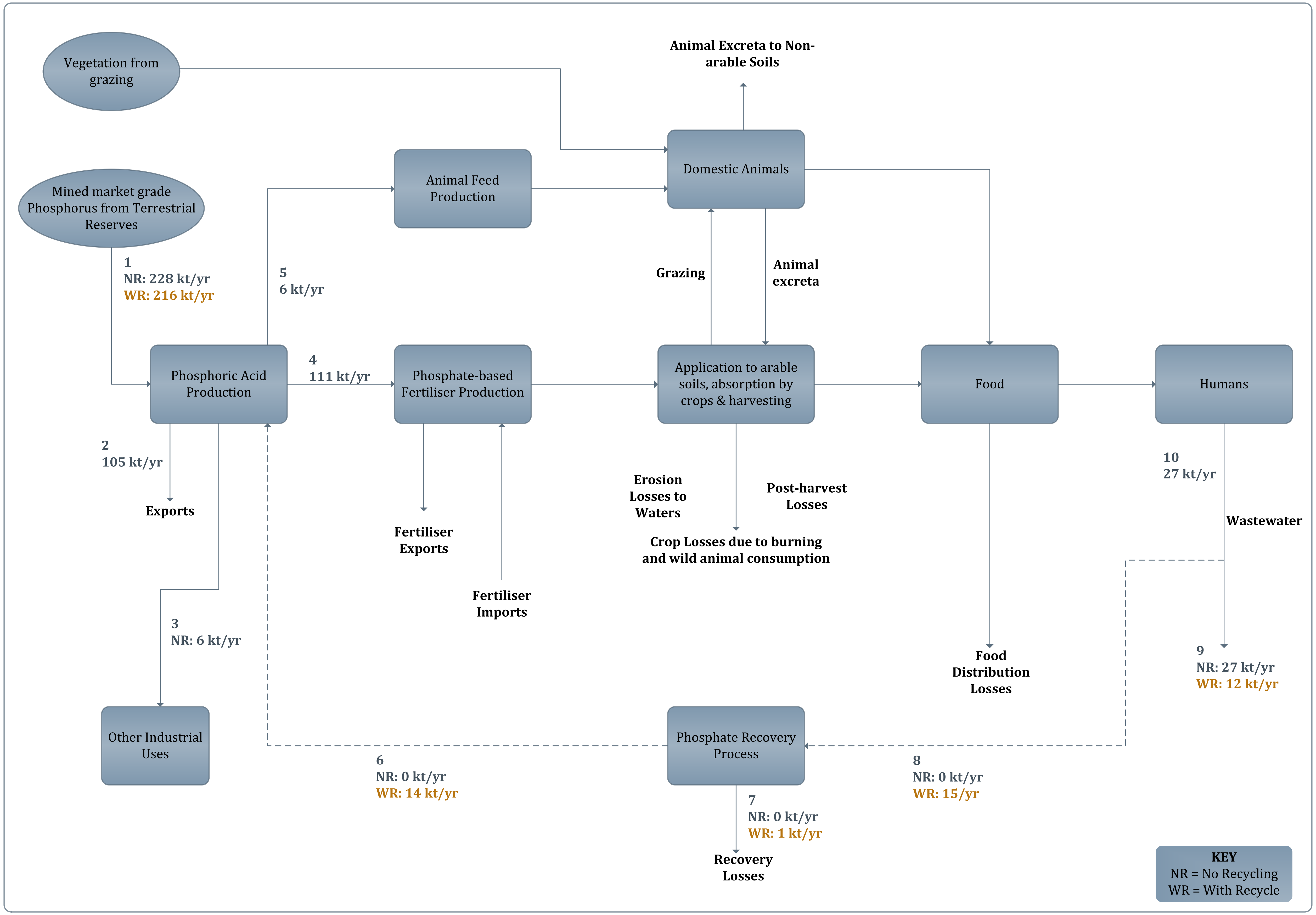


FIGURE 26: PHOSPHORUS FLOWS IN SOUTH AFRICA – POTENTIAL FOR LOOP-CLOSURE (FLOWS ARE KT/YEAR OF P)

TABLE 10: ASSUMPTIONS AND DATA USED FOR SFA

Description	Value	Comment/Source
Total Phosphoric Acid Produced by Foskor (tons/year)	650,000	Target Phosphoric acid production in South Africa (Foskor, 2014)
Foskor Market Share of Phosphoric Acid Production	90%	Estimated from phosphate rock mined in 2013 (Foskor, 2014; USGS, 2015).
Phosphoric use breakdown:		
Exported	46% of production	(Foskor Limited, 2016)
Fertiliser production	90%	(Patel, et al., 2015)
Other industrial uses	5%	(Patel, et al., 2015)
Animal feed	5%	(Patel, et al., 2015)
Phosphate in Urine relative to wastewater	55%	(Ganrot, 2005; Pronk & Kone, 2009)
Phosphate recovery efficiency	93%	(Etter, et al., 2015)
South African Population	56 million people	Obtained from www.worldometers.info
Daily phosphorus excretion from humans	1,3 g/person.day	(Gilmour, et al., 2008)

5.1 PHOSPHATE LOOP-CLOSURE IMPLICATIONS – AFRICA

The simulation of phosphate flows in South Africa found that without loop-closure, an estimated 27 kt/year phosphorus from human excreta lands up in the sanitation system which splits it roughly into one half ending in sludge (which in certain areas is returned to agricultural soils) and the other half in waterbodies – leading to environmental degradation. With urine-diversion alone and subsequent processing of the urine into struvite there is potential to recover at least 50% (Etter, et al., 2015; Ganrot, 2005) of the phosphorus present in the wastewater, in the form of phosphate. The benefits of having a circular phosphate economy are multi-layered but there are limitations to the model.

The phosphorus flow analysis shown in Figure 26 would be able to achieve a reduction in the amount of phosphate rock that is mined in South Africa. If all urine in South Africa is diverted, approximately 15 kt/year of the phosphorus can be reintroduced into a phosphate recovery process such as struvite precipitation. As investigated by Etter, et al. (2015) in KZN, the struvite precipitation process is currently able to achieve a maximum phosphorus recovery efficiency of 93% and therefore approximately 14 kt/year of phosphorus can be reintroduced into a phosphoric acid production process, such as that used in Richards Bay. The mass flows were modeled assuming that phosphorus exports, other industrial use, animal feed and fertiliser production flows would be constant as when there is no loop-closure. Furthermore, the diversion of urine would benefit current WWTP in that it would reduce the phosphate and nitrogen loading i.e. the mass flow as well as the volume that is treated which results in reduced operational costs associated with running the WWTP. In addition, WWTPs could become net producers of energy instead of energy consumers by adopting source separation since energy can be saved in biological nutrient treatment processes (Wilsenach & van Loosdrecht, 2003). Traditionally, WWTP’s follow the well-documented enhanced biological phosphorus removal (EBPR) process or chemically induced phosphorus removal via addition of metal salts (Morse, et al., 1998). Although the former usually achieves less phosphorus removal compared to the chemical precipitation, there is potential benefit for both methods in reducing or eliminating urine presence in WWTP influent. These benefits would have to be investigated further.

In the broader phosphate loop-closure context, the recycling of urine-bound phosphate alone does not have the potential to contribute significantly to a decrease in the mined phosphate throughput. It is important to realise that the phosphorus flow analysis depicted in Figure 26 used the entire South African population to estimate the expected contribution that the recovery of waste-bound phosphates would have. In the case of KZN, the population is only a fraction of the population used in the determination of the phosphate flows in Figure 26. Because of this, there is a population quantity limitation and a potential population density limitation in recovering phosphates from human wastes in KZN for use in the existing phosphate processing complex in Richards Bay. The former is explored in more detail sections that follow.

Whilst it may be impractical to consider recovering urine-bound phosphate from the entire population in South Africa for processing in Richards Bay, there is an opportunity in the context of African cities infrastructure needs to import urine waste-derived phosphates from neighbouring countries, especially from those whose untreated effluent would flow into the Indian Ocean. The benefits of such an extension to the model backward linkages are multifaced in that employment opportunities would result and that sanitation services can be provided to those that are not currently equipped with them. Developing countries often do not have adequate sanitation facilities and therefore, the creation of value through a reverse logistics network that depends on wastes, which would otherwise get treated in conventional WWTP's, could prove useful. The study carried out by the World Health Organisation and UNICEF on worldwide sanitation progress against the previous Millennium Development Goals (MDG) is depicted in Figure 27. From this data, it can be said that the opportunity for phosphate loop-closure is substantial in Africa. Much of the African continent suffers a heavy sanitation backlog with more than 50% of the population with sub-standard sanitation (UNICEF & WHO, 2015).

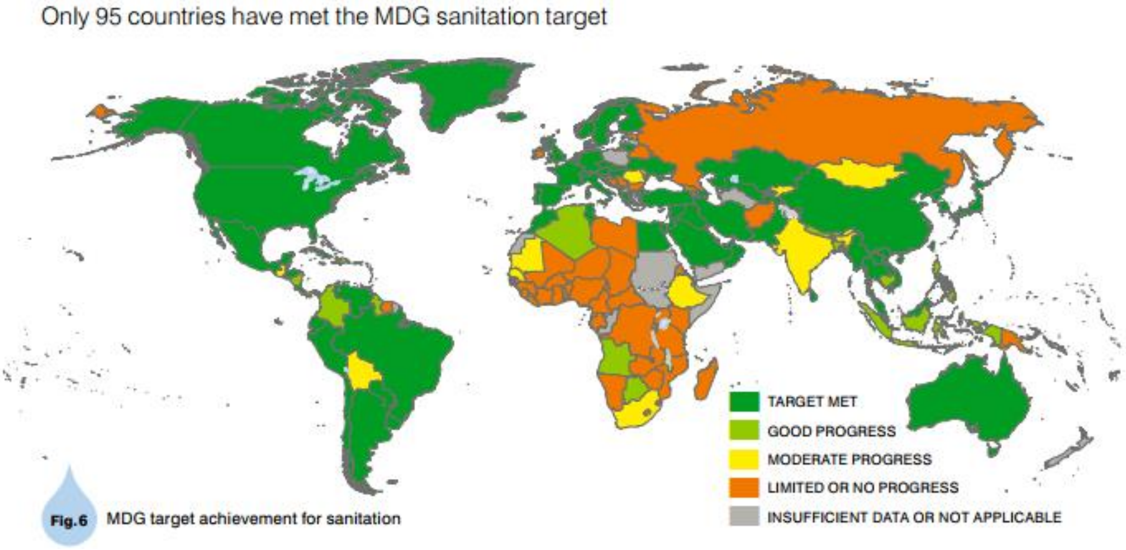


FIGURE 27: PORTION OF POPULATION WITH IMPROVED SANITATION IN 2015

Foskor's major processing complex in Richards Bay is conveniently located close to the port of the east coast. This makes the importing of struvite in bulk from neighbouring countries much more attractive than if the complex were located inland. The option to extend the supply of struvite to the South African market so as to meet the demand required may very well depend on struvite imports from sub-Saharan and East African countries.

5.2 REVERSE LOGISTICS IN STRUVITE PRODUCTION

The process block labelled "Phosphate Recovery Process" in Figure 26 consists of several stages from urine collection and transportation from households to depots, pre-treatment and processing into struvite and lastly, transportation to Richards Bay. Thereafter, the struvite would then be processed into phosphoric acid alongside phosphate rock, according to the analysis conducted in Chapter 4. Capital (capex) and operating (opex) expenditure requirements for the aforementioned processes as well as job creation opportunities are determined in the subsections that follow. As introduced in Chapter 3, two cases were analysed: one that uses base case data gathered from the VUNA case study that trialled urine collection and its subsequent conversion into struvite over a period of six months within a population of 600 people; and the scaled-up version which uses sanitation and population statistics of KZN.

5.2.1 URINE COLLECTION AND TRANSPORTATION

The data summarised in Table 11 was used to establish a capex and opex base case for source-separated urine collection and transportation. Base case data presented was obtained from the VUNA pilot scale study of urine collection networks in KZN (Etter, et al., 2015).

TABLE 11: BASE CASE DATA FOR CAPEX AND OPEX MODELLING

Description	Value
Population	600 people
Average urine excreted per person per day	1 L urine/person per day
Urine collected per average distance collected	5 L urine/km
Diesel Consumption	11 L diesel/100 km
Price of Diesel	13 ZAR/L diesel
Average distance travelled per truck per day	200-300 km/day

The VUNA case study in KZN was conducted on about 100 rural households, each of which had an average of 6 people per household. The average urine emission rate for humans typically ranges from 0.5 to 1.4 litres per person per day (Whitney, et al., 2013) which corresponds to that used in the analysis by Etter, et al. (2015). The analysis by Etter, et al. (2015) found that the collection team travelled between 200-300 km per day whilst the maximum urine quantity during the pilot study was 1,500 litres per week. The collection team comprised four people; namely the truck driver, two collectors and a local facilitator. The study also experimented with incentivising urine collection to encourage users to participate in reverse logistics network and found improved participation when collectors were incentivised (Etter, et al., 2015).

The scaled-up version of the analysis used a population of 6,27 million people in KZN without flush toilets connected to the public sewerage system (StatsSA, 2017). All other key variables tabulated in Table 11 were common in both the base case and the scaled-up version. The value of the scale-up exercise is in understanding how the scale of such a wide operation network can affect economics and thus, a cost comparison was done on a per ton basis. Furthermore, the exercise provided estimates into the kind of financial commitment that would need to come from decision makers regarding such a reverse logistics network. It is also important to note that the financial evaluation modelled in this section does not factor in the purchasing of urine diversion toilets and the collection containers which would need to be installed for the collection of urine.

5.2.1.1 CAPEX

Base Case Scenario

The capital expenditure required to kick-start the reverse logistics network in the collection and transportation phase in the base case scenario comprises the cost of the transportation vehicle/s as well as other unforeseen costs for which a 10% contingency has been made. The number of transportation vehicles required to collect the estimated 18,000 litres of urine per month (in a 30-day month) was calculated based on the urine quantity as well as the typical distance travelled by a truck per day of 200-300 km/day as per the VUNA trial data. Using a vehicle cost of 450,000 ZAR, the total capex required is estimated to be 495,000 ZAR due to one truck being sufficient for this scale of operation.

Scaled Up Scenario

In the case where the network serves a non-sewered population of 6,27 million people (the majority of which are rural areas), in other words 57% of the KZN population (StatsSA, 2017), the number of transportation trucks needed was estimated to be 4,700. Using a vehicle cost of 450,000 ZAR per truck, as in the base case, the total capex required amounted to 2,4 billion ZAR after factoring in a 10% contingency factor. The most important factors in the calculation are the limitation which has been made on the distance that each truck can travel per day as shown in Table 11. Secondly, the quantity of urine collected and the average collection rate per distance travelled which was kept at 5 litres of urine collected per km of distance that is travelled by the collection truck – refer to Table 11. Furthermore, there could be opportunity to further decrease the number of transportation vehicles required by increasing the collection capacity per truck alongside the factors mentioned above as key parameters in the cost estimation.

It is worth comparing such a cost of 2,4 billion ZAR for purchasing transportation trucks for urine collection from households, together with opex cost, to an alternative of using pipeline transportation means for the source-separated urine. From a sustainability point of view, investing an amount of 2,4 billion ZAR for assets with a lifespan of 10-15 years does not seem like a more attractive option compared to building a pipeline network which would be likely to have a longer lifespan and smaller operational costs. However, the very reasons the rural population in KZN, which makes up the majority of the non-sewered population, is not connected to a sewer network include but are not limited to: the hilly landscape which would make the installation of the pipe network exorbitantly expensive as well as the additional requirements of expanding or building new WWTP's to deal with the extra waste volume (Etter, et al., 2015).

5.2.1.2 OPEX

Base Case Scenario

The potential operating costs that can be incurred during the collection and transportation of source separated urine were broken down into fixed and variable. The former comprises labour, depreciation, maintenance and other overheads. Variable cost on the other hand only account for the fuel cost incurred during the transportation. For the operation at the base case urine collection rate of 18,000 litres of urine per month, the opex amounted to 470,000 ZAR per annum; 87% of which are the fixed costs and 13% variable costs. The breakdown of operational costs can be seen in Figure 28.

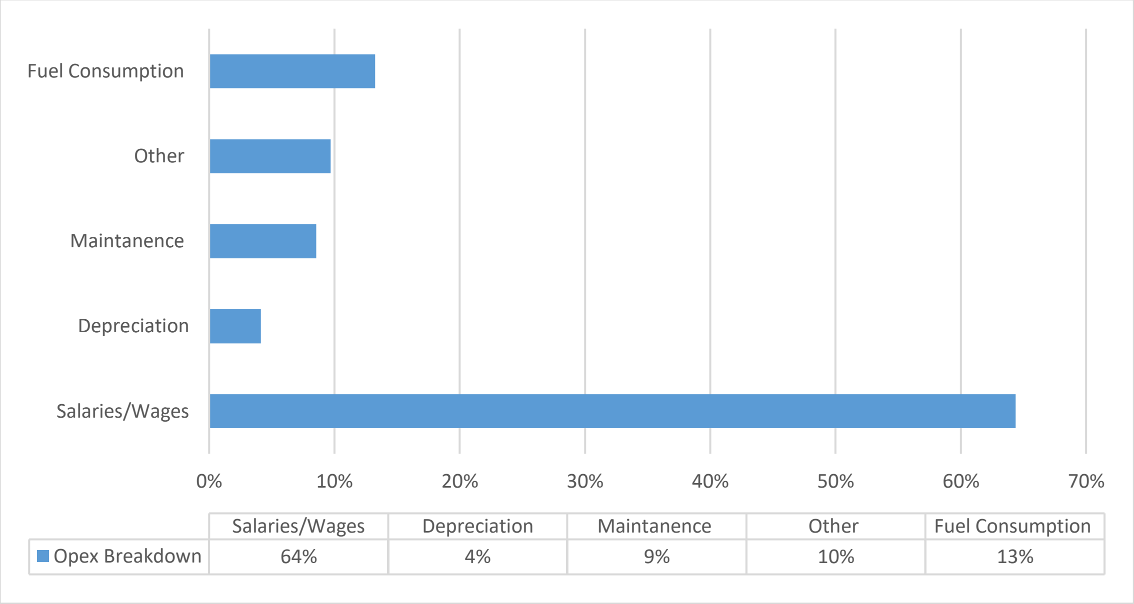


FIGURE 28: URINE COLLECTION AND TRANSPORTATION OPEX BREAKDOWN – BASE CASE

In the base case scenario, the total annual cost (C_t) of collection and transportation in Rand appears to follow the following linear relationship:

$$C_t = 17 * \frac{Q}{d_a} + 40400 \; for \; \frac{Q}{d_a} = 3600 \; km \qquad \text{Equation 3}$$

In Equation 3, (Q) is the quantity of urine collected annually in litres and (d_a) is the average quantity of urine collected per distance (in litres per kilometre) travelled by the collection truck to collect $'Q'$ litres of urine in total. Although the relationship in Equation 3 is only applicable at the base case production parameter of $\frac{Q}{d_a} = 3600\ km$, it reveals three important features of the total annual cost at this production rate. That is, the ratio $\frac{Q}{d_a}$ ultimately depends on the absolute quantity of urine collected within a known timeframe. With an increase in urine, there is also an increase in the cost incurred during collection; however, there is also opportunity to optimise this cost in the broader loop-closure context if on-site volume reduction methods are employed. Secondly, the population density of the area in which urine is collected dictates the average distance that must be travelled by the collection truck before collecting a certain quantity of urine. A truck collecting urine from an area that has a greater population density has the potential to travel a shorter total distance in total compared to that which collects urine from an area that is not as densely populated. Thirdly, the distance between the collection households and the depot impacts the total distance travelled by the truck and therefore will contribute to the total cost accordingly. An optimisation exercise on fixed and variable cost in the collection and transportation phase would have to involve the following:

(i) **maximum participation** from involved communities for maximum urine collection,
(ii) collection from communities of **high population density**,
(iii) and a **distributed network** of urine processing plants where collectors can supply whichever processing plant that comes at the lowest collection and transportation cost; although this is expected to be the one closest to the collection point.

A distributed collection network typically exhibits less risk in terms of a continuous urine supply for processing into struvite and struvite into phosphoric acid; however, a trade-off exists between the extent to which the network is distributed and the size of processing plant. Economies of scale come into play. In the extreme case where the collector has *infinitely* many processing plants that they can supply, the processing plants would have to become smaller and tend to, for example, *one processing plant per household* since the size would be limited by the absolute quantity of urine that can be collected in a specific community/area. In that case, the fixed cost, and therefore the total cost per ton of processing the urine would dramatically increase due to economies of scale – making it more expensive to run a processing enterprise than if the unit was able to process a larger amount of urine. Importantly, the capex requirement for a smaller plant also increases as per the 6/10 power rule of total capital investment cost. For the transporter, however, the cost optimisation primarily lies in minimizing the distance travelled per ton of urine collected. In the extreme opposite case where the collection network is centralised the total cost of processing the urine is expected to decrease however, collectors would be forced to travel longer distances to transport urine thus causing a rise in total transportation costs. The high capex requirement associated with smaller processing plants declines.

Lastly, the total collection and transportation cost of 2200 ZAR per 1000 litres of urine compared well with that found during the VUNA pilot study of 820-2000 ZAR per 1000 litres of urine – depending on the scale and optimisation (Etter, et al., 2015). A notable feature in the VUNA case study is the use of four labourers in the collection and transportation of urine. The impact of employing four labourers in place of two is discussed in the economic assessment of the scaled-up scenario of urine collection and transportation.

Scaled Up Scenario

The total operational cost of collecting and transporting 188 Ml of urine per month amounted to 2,6 billion ZAR per year. The opex breakdown is shown in Figure 29. At the urine volume collected in this scale of operation, it was found that salaries and wages accounted for 55% of the total cost. The 55% attribution to salaries and wages provides a total of approximately 18,000 jobs to those involved in the urine collection phase. Depreciation, maintenance and other overheads accounted for 19% of the total cost. Lastly, the variable cost, which was solely made up of fuel consumption costs, was found to account for 25% of the total operational cost. A higher variable cost composition of the total cost was noted in the scaled-up case compared to the base case.

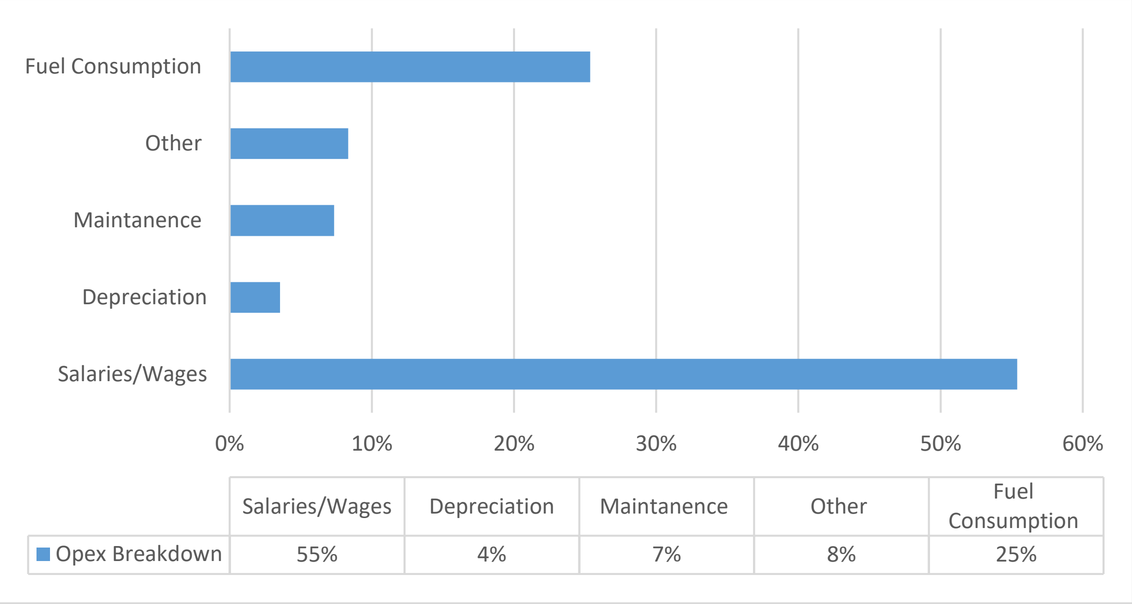


FIGURE 29: URINE COLLECTION AND TRANSPORTATION OPEX BREAKDOWN – SCALE-UP

Even at a large operation scale, fixed costs still make up most of the total cost compared to variable cost. The limiting variable preventing further increase of variable cost vs. fixed cost is the quantity of urine collected per distance travelled by the collection truck. As discussed in the base case opex discussion, population density is imperative in the optimisation of variable cost relative to fixed cost as well as total cost. From an economic perspective it is likely that SMME owners would also look at downsizing the collection team. The cost breakdown represented in Figure 29 was projected for a collection team which comprises one driver, two collectors/loaders and one local facilitator. However, downsizing the collection team to just one driver and one collector/loader would have a significant impact on the fixed cost and hence the total cost of the operation. Noting that the total cost has been projected based on 5,000 ZAR per month each for the collectors and for the facilitator; downsizing the collection team would offer a 40% decrease in the salaries and wages cost to the SMMEs. From an employment creation perspective, this would significantly cut the number of employment opportunities created by the reverse logistics network from 18,000 to 9,400 jobs in total.

Lastly, the total cost to collect and transport 1,000 litres of urine was found to be 1,100 ZAR which was only 50% of the total cost in the base case scenario. The economics of this scale of operation also show potential to further decrease the collection and transportation cost, particularly the salaries and wages component of the total cost. When the collection team is reduced in size, the total cost for collection reduces from the above mentioned 1,100 ZAR per 1,000 litres to 700 ZAR per 1,000 litres of urine. Additionally, the outlay of the opex breakdown represented in Figure 29 changed to increase variable cost relative to fixed costs.

5.2.2 PRE-TREATMENT AND PROCESSING

The two pre-treatment methods investigated in the study for urine stabilisation are by acidification or by the addition of a base so as to prevent the evaporation of nitrogen, in the form of ammonia, from urine. Thereafter, the processing stage requires the conversion of urine into struvite by precipitation through addition of magnesium chloride according to Reaction 4.

Key parameters used in the capex and opex cost estimations were obtained from the study by Sikosana et al. (2016) and have been summarised in Table 12.

TABLE 12: KEY PARAMETERS FROM SIKOSANA ET AL. (2016)

Description	Value	Source / Comment
Fresh urine dilution factor	1 litre urine : 2,85 litre water	(Sikosana, et al., 2016)
Total phosphorus composition at dilution factor of 2,85 l water per litre of fresh urine	76 mg/l	(Maurer, et al., 2006)
Struvite Recovered : Fresh Urine	1 kg:371 kg	(Sikosana, et al., 2016)
Magnesium Chloride required for precipitation[2]	1 kg $MgCl_2$:251 kg Fresh Urine	(Sikosana, et al., 2016)
CAPEX required for process treating 27832 kg/d of urine at given dilution factor	6,9 million ZAR	(Sikosana, et al., 2016)
Chemical Engineering Plant Cost Index CE (2015) CE (2017)	556 562	(Chemical Engineering Online, 2017)

5.2.2.1 *CAPEX*

Base Case Scenario

The capex required to build a precipitation facility that processes 27,832 litres of urine per day that has been flushed using 79,213 litres of water per day amounted to 6,9 million ZAR according to the study by Sikosana, et al. (2016). Excluding the cost of a new sewer pipework, the capex requirement amounts to 4,5 million ZAR and produces approximately 75 kg dried struvite per day. A capital investment scale-down using the six-tenths factor as well as chemical engineering plant cost indexes resulted in a total capex requirement of 537,000 ZAR for the base case which processes 216,000 litres of fresh urine annually. It is important to note that since the study by Sikosana, et al. (2016) was carried out assuming a dilution factor of 26%, as shown in Table 12; the knock-on effect on the capex estimate is that it is a conservative one since there is no water dilution prior to processing into struvite in this case. It is expected that the dilution of fresh urine as per the dilution parameter of 26% requires larger process

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[2] Density of fresh urine taken to be the same as that of water at 1kg/l

equipment as well as more energy and would be a more chemical intensive process than one that would treat fresh urine, hence the capex and opex would be impacted. Furthermore, a process using fresh undiluted urine has the potential to yield higher phosphate recovery compared to one using diluted urine.

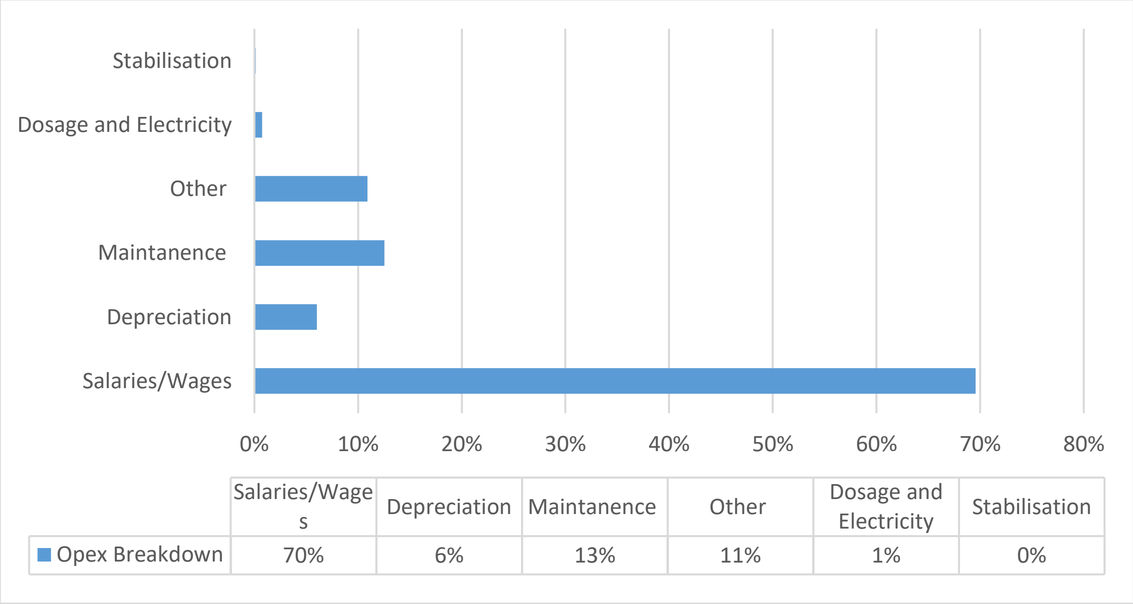
Scaled Up Scenario

The number of struvite processing plants was initially set at six processing facilities, each of which would be capable of producing 1,200 tons dry struvite per year at different locations around the KZN province. Using the six tenths rule together with the cost estimate by Sikosana et al. (2016), the total capex required to erect and commission six struvite processing facilities with the above-mentioned capacity was calculated to be 310 million ZAR. Meaning, each facility would cost approximately 52 million ZAR.

5.2.2.2 OPEX

Base Case Scenario

Just as with the capex assessment, the opex determination for the struvite precipitation processing unit was also a conservative one because of the dilution factor in the initial study by Sikosana et al. (2016). The total cost to operate the precipitation and recovery process was estimated to be 345,000 ZAR per year; approximately 99% of which were fixed costs and the balance 1% variable costs. A cost breakdown is shown in Figure 30.



	Salaries/Wages	Depreciation	Maintanence	Other	Dosage and Electricity	Stabilisation
■ Opex Breakdown	70%	6%	13%	11%	1%	0%

Figure 30: Pre-treatment and Processing Opex Breakdown – Base Case

Most of the fixed cost can be attributed to salary payments. In this estimate, a total of two operators per shift (with the plant running ca. 8 hours for 5 days in a row) has been used and a conservative salary estimate of 10,000 ZAR per month per operator used to obtain an initial figure. Maintenance, depreciation and other overheads are projected to make up the remaining 29% or so, of the fixed cost. Dosage and urine stabilisation were also costed, and it was found that their combined contribution toward the total cost only amounts to approximately 1% of the total cost. At a constant struvite selling price per unit of struvite produced, the high fixed cost relative to variable cost means that the business is likely to have to produce and sell a significant amount of struvite to break-even. The phenomenon is best explained using the break-even formula shown by Equation 4.

$$Q = \frac{FC}{SP-VC} \qquad \text{Equation 4}$$

In Equation 4, Q represents the quantity in tons of struvite that can be produced and sold, SP is the selling price of struvite per unit in ZAR/ton and VC is the variable cost of producing a single unit of struvite (ZAR/ton). At the base case production, where the fixed costs are much greater than the variable costs, the analysis suggests that processing more struvite can help bring fixed costs down relative to variable cost. Furthermore, the cost distribution in this case implies that 100% of the struvite revenue would only come from 1% of the total cost which again points out that Q must be significant for the business model to begin to breakeven.

Scaled Up Scenario

The total operating expenditure for the urine-to-struvite processing facility amounted to 130 million ZAR per annum for all facilities, approximately 22 million ZAR per annum for each facility, assuming a total of six facilities in the province. The opex breakdown for the scaled-up scenario is summarised in Figure 31 and can be compared to that of the base case in Figure 30.

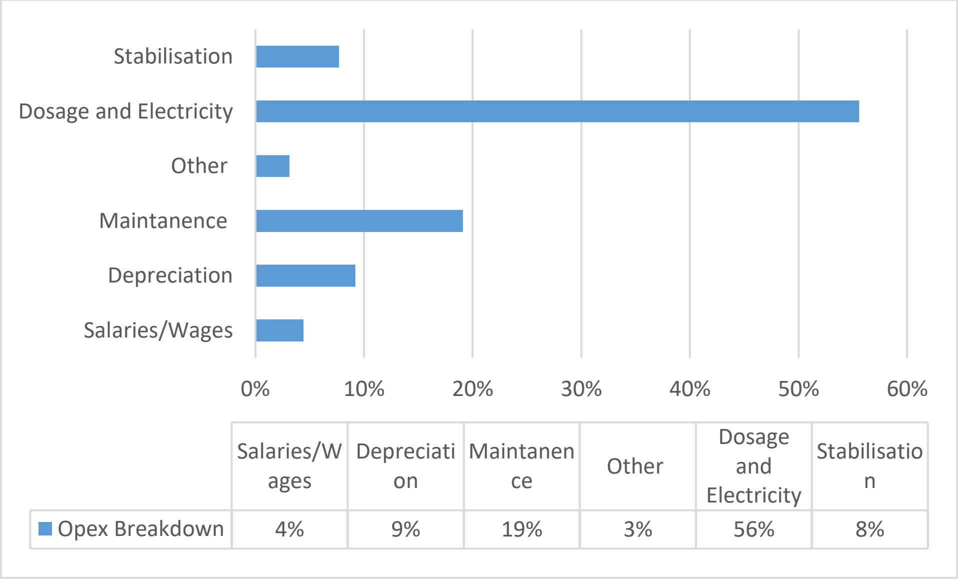


Figure 31: Pre-Treatment and Processing Opex Breakdown – Scale-Up

In the scale-up scenario, fixed costs made up a total of 32% of the total cost compared to 99% of the total cost in the base case. The significant decrease in fixed cost composition was brought about by a decrease in the salaries and wages relative to the struvite produced due to the scale of the operation. The notable difference between the base case and the scaled-up version of the financial modelling was the requirement of extra labour that would be needed to cope with the volume of urine being processed. In the base case, salaries and wages were modelled for 2 process operators whereas the scaled-up scenario required 50 process operator salaries. Because of the increase in volume of valuable material being processed, the fixed cost per ton of struvite was also found to significantly decrease from 510,000 ZAR per ton of struvite in the base case to 2,500 ZAR per ton in the scaled-up scenario. The variable cost was found to increase from only 1% of the total cost in the base case to 63% in the scaled-up scenario. Importantly, in both cases, variable costs per ton were found to be approximately 4,500 ZAR per ton. This was mainly due to the opex cost estimate, which was estimated by Malanda et al. (2016) to be 3.87 ZAR per kg of struvite, being the same for both operations.

Using Equation 4 it is evident that a significant decrease in fixed cost per ton would equate to a significant drop in the quantity of struvite that needs to be processed by the facility if the selling price were to be kept constant in the two cases. In doing so, the price of struvite is more likely to compete with the price of phosphate rock for phosphoric acid producers when it is produced at higher volumes.

5.2.3 TRANSPORTATION TO PHOSPHORIC ACID PROCESSING UNIT

The data summarised in Table 13 was used to establish the capex and opex requirements at the base case urine quantity for the transportation of struvite to a single existing industrial phosphoric acid processing unit. It was initially assumed that the distance between the urine processing facility and that which converts struvite into phosphoric acid is 200 km. Additionally, the size of truck that would be needed would differ according to the quantity of struvite that would need transportation. Because of this, the fuel would also differ according to the struvite quantity collected as shown in Table 13. When the quantity of urine to be collected is less than 20 tons per month, it is assumed that trucks with a carrying capacity below 20 tons can be used for the collection, noting that the truck would have to make several trips to the processing facility. When the quantity is larger than 20 tons per month it was assumed that bigger trucks would be the more viable option.

TABLE 13: BASE CASE DATA FOR CAPEX AND OPEX MODELLING

Description	Value
Distance travelled to phosphoric acid processing facility	200 km/trip
Fuel Consumption:	
If struvite collected > 20 tons per month	0.5 l/km
If struvite collected < or = 20 tons per month	0.23 l/km
Price of Diesel	13 ZAR/l diesel

5.2.3.1 CAPEX

Base Case Scenario

The base case processing rate produces a conservative 52 kg of struvite per month from 18,000 litres of urine collected per month. Thus, trucks with a carrying capacity below 20 tons would be most likely used for such an operation. The capex for transportation of struvite would require only the cost to purchase a single truck. The cost to purchase a single truck whilst allowing for a 18% contingency (Seider, et al., 2010) amounted to 531,000 ZAR. A more cost-effective method of transportation for this scale would of course be a courier.

Scaled Up Scenario

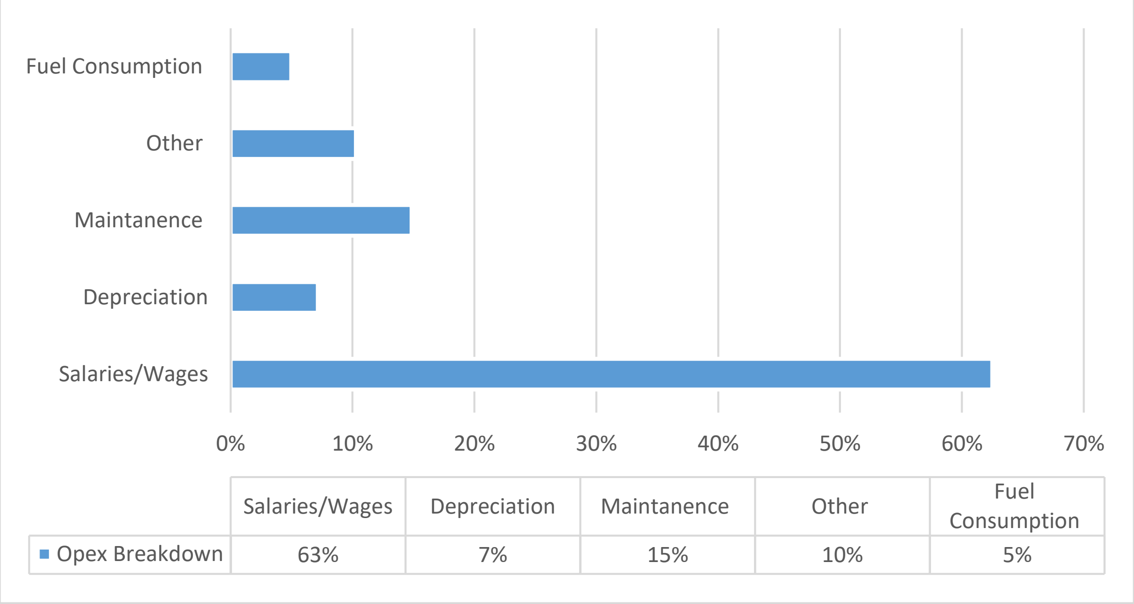
The reverse logistics network collecting 188 Ml of urine per month was estimated to be able to produce approximately 100 tons of struvite per month. In total, this would amount to 7000 tons of struvite per annum, if a total of 6 processing plants is used. The capex required to kick-start such an operation amounted to 4,3 million ZAR in truck costs after allowing for an 18% contingency in capex. The capex for the scaled-up scenario was determined using costs for trucks with a 20-ton capacity and therefore was substantially higher than that of the base case scenario.

5.2.3.2 OPEX

Base Case Scenario

The scale of the base case scenario does not warrant opex financial evaluations. Realistically, a more cost-effective mode of transportation suited for transporting 52 kg of struvite would be by courier and hence only courier fees would be incurred.

A hypothetical opex breakdown for the transportation of struvite to the phosphoric acid processing plant can be seen in Figure 32. The total operational cost was determined to be 288,000 ZAR per year. Fixed cost made up 95% of the cost and the balance was made up of variable cost as fuel consumption.



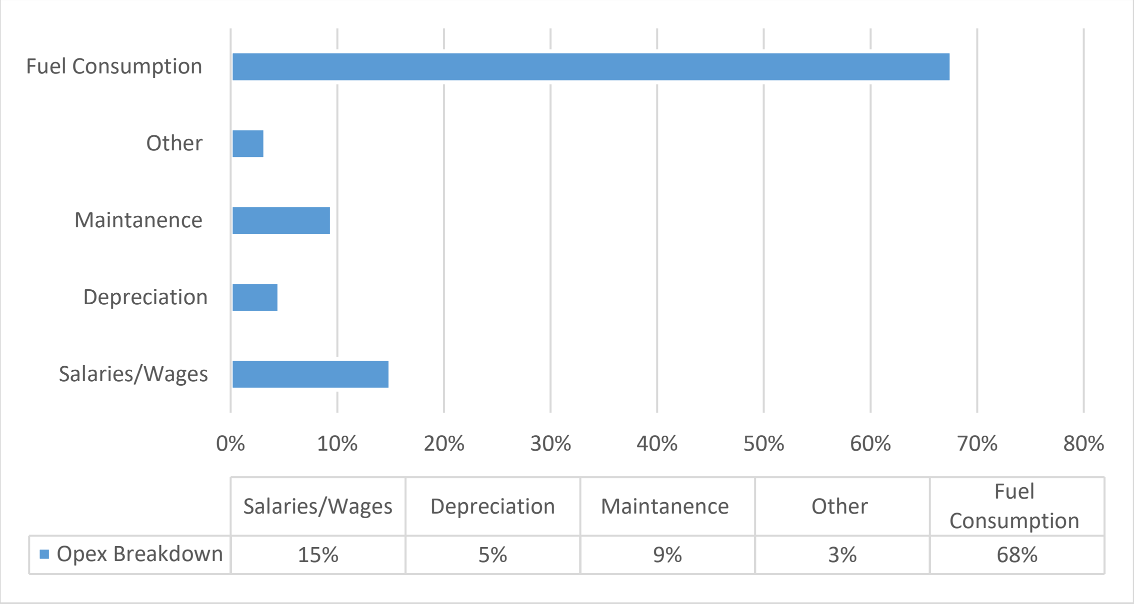
	Salaries/Wages	Depreciation	Maintanence	Other	Fuel Consumption
■ Opex Breakdown	63%	7%	15%	10%	5%

FIGURE 32: STRUVITE TRANSPORTATION OPEX BREAKDOWN – BASE CASE

In the hypothetical evaluation, most of the fixed cost is made up of salaries and wages. The salaries and wages of this phase was based on the driver and loader combination being able to handle the 52 kg of struvite. Lastly, the specific total cost in such a case amounted to 430,000 ZAR per ton of struvite.

Scaled Up Scenario

The opex for an operation of such a scale amounted to 3,6 million ZAR per year – significantly lower than the collection and transportation and processing costs. The breakdown of the opex for struvite transportation is shown in Figure 33. It was found that variable costs made up most of the costs at 68% and fixed costs made up the balance 32%



	Salaries/Wages	Depreciation	Maintanence	Other	Fuel Consumption
■ Opex Breakdown	15%	5%	9%	3%	68%

FIGURE 33: STRUVITE TRANSPORTATION OPEX BREAKDOWN – SCALE-UP

The size of the scaled-up operation again diminishes the fixed cost per ton relative to the variable cost per ton. The result can be seen by doing a comparison between the composition of the total costs in the two cases, i.e. Figure 32 and Figure 33. The total cost per ton of struvite transported at this scale amounted to 1,000 ZAR per ton and thus is significantly lower than that found in the base case. It is anticipated that the scale of the operation would also benefit the breakeven due to the significantly lower fixed costs per ton compared to the base case.

5.3 SUMMARY OF FINDINGS

A summary of findings is presented in Table 14. The findings of the cost assessment without doubt prove how economically unfavourable the reverse logistics network could be. Although notable operational cost reductions could be achieved by simply increasing the scale of operation, as shown in the preceding sub-sections in the comparison of the base case with the scaled-up scenario, the reductions are still not attractive enough for the phosphoric acid producer to favour purchasing struvite over mined phosphate rock. The other possibility is volume reduction of the collected urine by evaporation or freeze-thaw; however, these are not in the scope of this study. Notably, the base case was modelled to cost 1,65 million ZAR per ton of struvite whereas the scaled-up case resulted in a total cost of 147,000 ZAR per ton of struvite. Thus, the specific production cost was modelled to decrease 11-fold when the urine collected and processed catered for the greater KZN population without a connected sewer system.

In Chapter 4, the assumed price of struvite used was 1,320 ZAR per ton compared to that modelled to be 147,000 ZAR per ton of struvite for a network collecting and treating urine around the KZN province. The economics without the inclusion of a volume reduction stage are essentially thrown-off by the collection and transportation phase without which the costs are modelled at 8,000 ZAR per ton of struvite. When the collection and transportation cost is excluded, most of the cost comes from pre-treatment and processing; more specifically the dosage of magnesium chloride and electricity usage costs. Additionally, the collection phase further made up most of the capital expenditure requirement compared to the other phases of the network.

TABLE 14: SUMMARY OF ANNUAL FINANCIAL EVALUATION FINDINGS

Process Stage	**Collection and Transportation of Urine**	**Pre-treatment and Processing of Urine**	**Transportation of Struvite**
Item	**Base Case (216,000 l urine/year)**		
Capex	495,000 ZAR	537,000 ZAR	*Not required*
Opex	470,000 ZAR	345,000 ZAR	*Insignificant*
No. of jobs	4	10	*None*
Struvite production cost breakdown	700,000 ZAR/ton struvite	520,000 ZAR/ton struvite	430,000 ZAR/ton struvite
Item	**Scaled-up Scenario (2,300 Ml urine/year)**		
Capex	2,4 billion ZAR	310 million ZAR	4,3 million ZAR
Opex	2,6 billion ZAR	130 million ZAR	3,6 million ZAR
No. of jobs	9,000-18,000[3]	50	6
Struvite production cost breakdown	139,000 ZAR/ton struvite	7,000 ZAR/ton struvite	1,000 ZAR/ton struvite
Total cost of producing struvite	147,000 ZAR per ton struvite produced		

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[3] A total of 9000 jobs were created when using a driver and loader only pairing whereas the number of jobs created doubled when using a driver, two loaders and a facilitator team.

CHAPTER 6. EXTENDED PRODUCER RESPONSIBILITY–LESSONS FROM PAST EXPERIENCES

Having carried out the technical and economic assessments in Chapter 4 and Chapter 5 respectively, a third objective of the study was to engage with the experiences and outcomes of existing similar loop-closure models in albeit different materials. The work presented in Chapter 6 therefore sought to unpack the questions: "*What learnings can be drawn from the implementation of past EPR strategies and why were these strategies successful or unsuccessful? Furthermore, what are the experiences of people who have been involved in reverse logistics with other materials and how can these experiences guide decision-making into the implementation of future EPR schemes?*" The presented key question is approached by considering two case studies; the first being the REDISA experience in waste tyre management and the other being that of the ROSE Foundation in used lubricant oil recycling. The two approaches in EPR apply reverse logistics in different materials as discussed in Section 2.5. Chapter 6 proceeds to extract key information from the two experiences with the intention of understanding the key parameters in the sustainability reverse logistics scheme giving effect to extended producer responsibility (EPR).

6.1 CASE STUDY IN LOOP-CLOSURE: WASTE TYRES EPR

The mandatory approach taken by the government to encourage the execution of EPR in waste tyres dates back to the publication of the South African Waste Information System (SAWIS) in 2005 and later on, the government gazette notice 425 of 2008 (DEAT, 2005; DEAT, 2008). Soon after that was the establishment and implementation of the REDISA EPR programme which was short-lived and unsuccessful. In the timeframe within which this work was written, REDISA had been fully operational until the Minster of Environmental Affairs made the decision to withdraw REDISA's Integrated Waste Tyre Management plan, effective 1 June 2017. Furthermore, the Minister also outlined that the responsibilities of the REDISA would be transferred over to the Waste Bureau. The decision to withdraw the REDISA plan resulted from audit reports in which there were concerns around **governance**, **performance**, **deviations** from the original plan, the **misuse of public funds** and **operation non-alignment** with reviewed Waste Act, pricing strategy and waste tyre regulations (PMG, 2017). The failure of REDISA, as a Producer Responsibility Organisation (PRO), which then resulted in the ineffectiveness of the EPR reflects the importance of a PRO in a reverse logistics value chain.

A Producer Responsibility Organisation's role is generally defined as being a cooperative industry effort to collectively shoulder the responsibilities of its member companies so as to ensure that the member industries meet their respective EPR goals (Mayers, 2007; Nahman, 2010; Widmer, et al., 2005). As emerges from the work by Nahman (2010) regarding the effectiveness of government initiated EPR against voluntary EPR in the South African packaging industry; special attention is needed regarding the role of PRO's in facilitating the EPR process.

In any corporate institution, '*corporate governance is a processs that aims to allocate corporate resources in a manner that maximizes value for all stakeholders – shareholders, investors, employees, customers, suppliers, environment and community at large and holds those at the helms to account by evaluating their decisions on transparency, inclusivity, equity and responsibility'* (Raut, n.d.). Generally, there are two approaches to corporate governance, namely internal and external. Of most importance in this work are internal mechanisms which focus on:

i. agreeing on a board of directors, through which shareholders exert influence, to best represent the intentions of the shareholders;
ii. the alignment of the interests of managers with those of shareholders through compensation linked with accounting based key performance indicators;
iii. the effective dispersion of the firms shares and;
iv. transparent financial and information disclosure (Bai, et al., 2003).

In the case of REDISA, the concern in terms of poor corporate governance primarily came from the selection of Kusaga Taka Consulting (Pty) (KTC); a private firm that was appointed to handle operational aspects of the REDISA plan (PMG, 2017). This appointment alone was not the main course for concern, but rather, the fact that some REDISA directors were shareholders at KTC, and therefore were able to influence decisions taken by the management of KTC. This appointment of KTC then prompted various questions around conflict of interest with respect to those REDISA directors that were also shareholders at KTC. An article from the Business Report quoted that there had been evidence of "*unlawful misappropriation of public funds*" by REDISA in the implementation of its model (Cokayne, 2017). In December 2016, REDISA published a set of responses to claims of poor governance in which it described the relationship between REDISA and KTC as being strictly regulated by contract and professionalism. Furthermore, the response cited that REDISA directors with shareholding roles in KTC had already declared their roles as required by the Companies Act, 2008. However, at the REDISA liquidation briefing the Department of Environmental Affair's (DEA) minister emphasised requests that had been made for the contracts but had not been made available to the DEA to view.

It is unclear why REDISA, as a producer responsibility organisation, opted to contract KTC to run the REDISA plan. The flexible, yet well-defined and well-governed roles of PRO's are described by Nahman (2010) with specific reference to the packaging industry. In all South African EPR cases discussed by Nahman (2010) and more generically by Mayers (2007), PRO's have been tasked to oversee the EPR process thereby improving cost efficiency as well as supporting the collection and processing (directly or indirectly) of the wastes in accordance to predefined deliverables (Nahman, 2010).

Additionally, during the REDISA liquidation briefing with the Minister of Environmental Affairs, concerns regarding the exporting of tyres were raised and discussed. In the attempt to promote in-house recycling, the Department of Environmental Affairs maintained that the exporting of tyres should cease (PMG, 2017). On the other hand, REDISA defended its position on the matter, citing that South Africa had insufficient recycling capacity to be able to absorb the entire volume of waste tyres.

The key lessons learned in the case of REDISA are the importance of the establishment of a producer responsibility organisation which shares the objectives of the founder so as to avoid goal misalignment and confusion. Coupled with the goal alignment is the importance of strong governance of the PRO that can regularly produce detailed governance, financial and performance reporting.

6.2 CASE STUDY IN LOOP CLOSURE: USED LUBRICANT OILS EPR

The approach taken by the Recycling Oil Saves the Environment (ROSE) Foundation to loop-closure is an inspirational one whose success has thrived for more than 20 years. The role of the ROSE Foundation as a PRO in the recycling of used oils has not been limited to the management of recycling incentives from major lubricants companies; but extends to raising '*…awareness to the general public about the management and laws of applicable to collection and processing of used lubricant oil. The ROSE Foundation does not deal directly with collection nor processing of used oil instead it accredits the compliant players within the used oil recycling industry. The collectors and processors are independent companies. They receive various forms of support from the ROSE Foundation other than the incentives e.g. Operations Manual with Safety Data Sheet, Waste Manifest books, Spill kits, First Aid kits, Training (Dangerous goods, oil spill, first aid and fire fight, PPE* (personal protective equipment), *Bulking Point support, Legislation support, Placarding, Audits Environmental Advice…*' explained a ROSE Foundation representative in an email response.

Notably, the above-mentioned explanation of role aligns well and is seemingly derived from the ROSE Foundations strategic objectives. As emphasised before, clear communication of goals between board members with top management (at the PRO) and independent SMMEs is fundamental in achieving a well-governed and well-aligned PRO. Evidence of good governance in the case of used oils is in the regular communication of progress by the ROSE Foundation and general updates around recycling industries with the public and its board of directors. The former is primarily done through documented newsletters on the ROSE Foundation website. The newsletters generally cover a variety of topics ranging from information on how to get involved in the oils collection / processing industry to success stories of those involved in the process as well as information on legislation in and around waste management. The foundation reports that communication between the board of directors and top management (CEO) primarily occurs at the board meetings which occur four times annually with the intention of tracking progress and discussing operational and strategic objectives. In light of this, it is important to note that the composition of board members for the ROSE Foundation includes seven members, each of which are selected from member companies on an annual basis.

Comparing the success of used oils recycling against the short-lived REDISA model for waste tyres, a key contributing factor identified is the funding model. Although the ROSE Foundation is now only funded and supported by the private sector; prior to its establishment in 1994, used oil recycling was mainly enforced and driven by the government. The shift from used oil recycling being a mandatory scheme into a voluntary scheme not only meant that it had to be funded differently, but also meant that the responsibility had entirely shifted to the producers. The study by Nahman (2010) highlighted the significance of this difference whilst also providing substantiated evidence from case studies in EPR's in South African packaging. To further unpack the argument that industry driven approaches (i.e. voluntary approaches) to EPR are more effective than those that are government driven (mandatory approaches) at delivering the needed recyling rates, it is instructive to consider the relationships between key entities as shown in Figure 34.

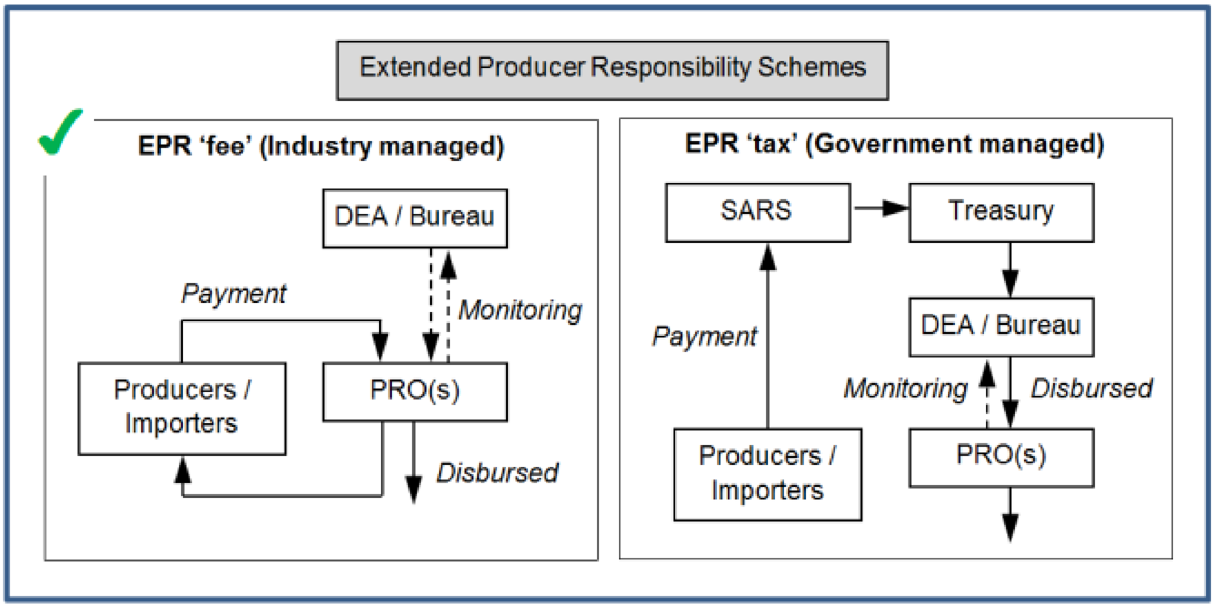

FIGURE 34: FUNDING STRATEGY MODELS FOR EPR'S; ADAPTED FROM (DEPARTMENT OF ENVIRONMENTAL AFFAIRS, 2016)

In both industry managed as well as government managed EPR schemes, the funding method for handling of 'waste' is in line with the polluter pays principle. This means that ultimately, the financial burden for waste recycling is paid by the consumer to the producer. In the industry managed approach, funds are collected through the inclusion of a fee in the product price. This fee is then paid to the PRO so as to achieve pre-determined recycling objectives of the product by the producer. In the case of used oils this is 5 cents per litre of lubricant oil sold by each of the major lubricants companies in South Africa. The fee is then used to facilitate and incentivise the handling of the waste oils. In the case of government managed schemes, the fees are collected in the form of tax by the South African Revenue Services (SARS). Budgetary allowance is then made by the Treasury to channel the funds to the DEA or the newly established Waste Bureau. Lastly, the funds are disbursed to the PRO which manages the waste stream of interest. In the government managed scheme, the flow of money is more likely to experience various forms of inefficiency as it gets disbursed to the PRO. A Rose Foundation report in 2018 highlighted three main causes for concern with government managed EPR schemes. These can be summarised as follows (ROSE Foundation, 2018);

- the implementation of administrative fee that can amount to 25% of the total collected fees, thereby reducing the funds available to facilitate recycling,
- the uncertainty of the funds being ringfenced towards the waste stream for which they were collected and lastly,
- the eventuality that the consumer must pay more for a product whose EPR scheme has to be managed by government as opposed to that managed by industry due to the laborious process between the collection of the funds from the consumer and the eventual redistribution to the PRO managing the EPR.

The concerns are not only limited to those mentioned above but may extend to the 'extra' responsibilities of the PRO such as those mentioned in the opening paragraph of this section. In the case of used oils, the board of directors (all of which are oil specialists) provide sound input in the form of technical, environmental and handling in the oil industry. In doing so, it can be argued that an industry managed EPR brings more to the table in the form of strategic and operational directorship compared to a government managed scheme. Hence, it is critical that waste producers hold a proactive role in ensuring the loop-closure of respective products.

In closing, an interview with a representative of an oil recycling company provided valuable insight into the day-to-day running of the oil recycling business as well as the typical challenges faced. The company has been involved in the transportation and processing of used oils for more than 10 years and operates in the eThekwini Municipality. The company employs more than 10 workers in its operation whilst it is equipped to handle more than 5,000 litres of used oil daily. Although the company's representative was unable to provide data on the price at which they typically purchase used oil and the price at which it is sold for to the downstream user/processor, they were able to confirm that the business was profitable. Furthermore, the company envisages that the business will continue to thrive in the future for at least another 5 years. The positive outlook with regards to business profitability and sustainability painted by the representative is important to note as it suggests success in the way the EPR scheme was rolled out in used oils. Moreover, according to the interviewee, the lubricant oil recycling line of business has "*given the company the exposure to other bigger companies which in return helps with the growth of our company. The busier we are the more throughput through the business. The more profit and exposure we get and the more room there is to grow and expand our network*".

To quantify the contribution of recycling incentives, which are funded through the collection of taxes or fees, to job creation in any EPR scheme the following variables are defined; $'X'$ is defined as the quantity of waste in litres per year or kilograms per year for which the PRO incentivises the recycling of the material at a rate of $'F'$ ZAR per litre or ZAR per kilogram of waste collected for recycling. Additionally, $'N'$ is defined as the number of jobs created directly from the operation that recycles $'X'$ amount of waste. The indicator $'C'$ can be used to signal the amount of funding currently being disbursed into the recycling company to generate one job in a specific recycling industry; this indicator can be calculated using Equation 5. Moreover, the indicator defined through Equation 5 can be used to inform future implementation of EPR schemes.

$$C = {}^{X\,x\,F}\!/_{N} \qquad \text{Equation 5}$$

From the interview with the oil recycling company and information gathered from the ROSE Foundation representative, a generalisation can be made for a company with a throughput similar to that of this company. Noting that the ROSE Foundation incentivises the processing of used lubricant oil at 5 South African cents per litre and that the company processes approximately 5,000 litres of oil daily, whilst assuming insignificant losses during processing; using Equation 5, it can be calculated that the incentive provided by the ROSE Foundation contributes approximately 4,300 ZAR per year for the creation of each job (assuming that the company has 15 employees) that exists in the company. Not only does the company that processes the waste contribute to job creation, but it is important to note that the diversion of the used lubricant oil from waterbodies significantly impacts the prevention of pollution of water as well as land.

6.3 INFORMING DECISION-MAKING IN PHOSPHATE LOOP-CLOSURE

This chapter sought to identify some key considerations that should be known upfront when deciding on an implementation strategy for phosphate loop-closure using an EPR scheme. This final section complements the information derived from the two case studies by using the holistic approach developed and used in scrap metals recycling by Chitaka (2015), on how a decision-making framework could be used to inform the potential to close the phosphate loop by means of EPR. It is investigated whether such an EPR could drive the value-addition of urine-bound phosphates into a high-end phosphoric acid market, as discussed in detail in Chapter 4 and Chapter 5, whilst being potentially more environmentally responsible than the status quo and bringing about the development of society. The framework notes **access to raw materials**, ***contribution to economic development***[4], **economic performance**, ***energy consumption***[5], **environmental performance**[6] and **socio-economic performance** as key considerations prior to reaching a decision (Chitaka, 2015). The key points that have been ascertained through this study have been summarised in Table 15; and the discussion follows.

As presented in Table 15, issues that are expected not to change include the capacity to produce phosphoric acid, the amount of phosphates produced as well as the proportion of phosphate-based fertiliser that is produced (as represented in Figure 26). The potential to close the phosphate loop then presents the opportunity to reintroduce 350 tons of phosphorus per year

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[4] Not considered in this study due to limitation in scope.

[5] Not considered in this study due to limitation in scope.

[6] Not considered in this study – more work needed to make conclusive judgement.

into the value chain, and if this were implemented throughout South Africa, a total of 14 kilotons of phosphorus would be recoverable. In closing the loop, it is expected that 9,000 to 18,000 jobs could be created whilst there would be a need to fund the reverse logistics network with at least 152,000 ZAR per job per year to cover the expenses incurred in the transportation (urine and struvite) and treatment of urine. Notably, the cost of 152,000 ZAR per job per year is significantly higher than that estimated in the used oils recycling system. It is however important to understand that this discrepancy in the cost is due to the fact that the cost estimated at 4,300 per job per year only accounts for what the PRO contributes as an incentive to the processor only whereas the cost of 152,000 accounts for all three phases of the recycling network.

Table 15: Sustainability Performance Assessment of Phosphate Loop-closure

Aspect	Issue	Indicator	Unit	Deviation from Status quo[7]
Access to raw materials	**Capacity**	Capacity to produce phosphorus in SA	kt phosphorus per year	0
	Access to raw materials	Total phosphorus recoverable in KZN	t phosphorus per year	+350
		Total phosphorus mined in SA	kt phosphorus per year	-14
Economic performance	**Production costs**	Phosphoric acid prod. cost in closed loop divided by prod. costs in status quo	ZAR/ZAR	+6.4
	Production quantities	Amount of phosphates produced when substitution occurs	kt phosphate per year	0
	Funding requirement	OPEX required to close phosphate loop	ZAR per litre urine treated	+1.3
	Funding requirement	CAPEX required to close phosphate loop	ZAR per litre urine treated	+1.3
	Market risk	Proportion of product currently imported	kt per year of phosphate bearing fertiliser imported	0
	Funding requirement	Subsidy required to create one job in reverse logistics	ZAR required per job per year	+152,000[8]
Socio-economic performance	**Job creation**	Labour intensity	employment per ton struvite produced	+9000 to +18000 jobs directly
	Skills availability	Proportion of jobs requiring skilled labour	description	Creation of skilled and unskilled labour in reverse logistics network.

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[7] The deviation referred to compares the status quo to the loop-closure option. A positive deviation signals a requirement in the loop-closure option and a negative deviation signals a saving/surplus due to loop-closure.

[8] Signals the minimum amount of subsidy required to fund processes to close the loop and create one employment opportunity.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This dissertation set out to generate knowledge needed to close the phosphate/phosphorus cycle. To achieve this, the phosphate beneficiation process flowsheet was analysed, the process economics of collecting, transporting and processing urine into struvite modelled, thereafter, past EPR models were studied and used in understanding the key parameters needed when implementing a recycling strategy.

Having presented and discussed the results of the study in Chapter 4, Chapter 5 and Chapter 6, this final Chapter 7 draws conclusions and provides recommendations to further supplement this work.

7.1 CONCLUSIONS

The conclusions of this study are directly linked to the key questions posed in Chapter 3 and have been structured around the techno-economic suitability for the (partial) material substitution of phosphate rock with source separated urine-derived struvite in the production of phosphoric acid and the impact this material substitution would have on the people involved in the reverse logistics of phosphate recycling.

Can struvite produced from source-separated human urine and/or obtained from centralised wastewater treatment works be used as a raw material phosphate source during the production of phosphate fertiliser?

From the process options analysed in Chapter 4, Section 4.1; Option A (struvite addition at the reagent mixing stage – refer to Figure 21) was selected for reasons explained in the relevant chapter – the main one being the prolonged increase in reaction time compared to the other options. The choice then prompted flow sheet simulations from which it can be concluded that it should possible, from a technical standpoint, to integrate struvite into an existing phosphoric acid production process.

However, this introduction of struvite into either the DH or HH process comes with various challenges, the first of which is the loss of phosphoric acid production when the substitution occurs. The loss in production that occurs is due to struvite containing 39 wt% phosphate whereas phosphate in fluorapatite is 57 wt%. Therefore, in order to maintain phosphoric acid production whilst also using struvite in an integrated system, the operation would have to feed ±1.5 times more struvite in mass than they would fluorapatite. It can also be argued, using Figure 24, that substitution with struvite does not pose any significant financial benefit with regards to the fiscal benefit in production cost as defined by Equation 2 (this was particularly true when the cost of struvite was estimated at 1,320 ZAR per ton of struvite). There is, in fact, minimal financial benefit in relation to the lost phosphoric acid produced. Secondly, the integration of struvite into the process results in the dissolution of magnesium ions into the product-containing liquid stream. There is evidence in literature that the presence of magnesium ions in the process has been known to adversely impact on the formation of gypsum crystals (Rashad, et al., 2004), and hence limit the optimal removal of gypsum from the product acid. In addition to this, the presence of magnesium in the product acid prompts the question of the product acid quality required further downstream as well as that of the potential need for an extra processing stage for the removal of magnesium, if there exist stringent magnesium content requirements downstream.

How can the loop-closure of a phosphate value chain be achieved? What proportion of primary phosphate, that would otherwise have to be mined, does the reintroduction of a secondary phosphate source account for?

The reintroduction of source-separated urine or struvite derived from it into a phosphoric acid processing complex presents an opportunity to partially close the phosphate loop. As discussed in Chapter 5 and shown in Figure 26, phosphoric acid generation in South Africa processes 228 kt/year of phosphorus for various uses. Without recycling, 27 kt/year of the processed phosphorus reports to sanitation systems of which a significant portion is released into the environment, however with loop-closure; a total of 14 kt/year of phosphorus may be introduced back into the value chain.

For this opportunity to thus prolong the life of the phosphate-bearing rock deposit to be harnessed, there is the imperative requirement that a well-defined urine collection, urine transportation, struvite recovery and struvite transportation reverse logistics network structure with a fit-for-purpose funding model be established. Such models have been represented in Figure 34. The need for such a structure exists due to the cost of at least 147,000 ZAR per ton of struvite produced that is needed to ensure the success of the processes represented in Figure 35.

In addition to diverting waste-bound phosphates from the environment thereby reducing ecosystem impact and improving resource use efficiency, loop-closure of phosphates presents an opportunity to promote entrepreneurship and job creation. Essential to the success of phosphate recycling are the people that drive the processing of value creation from waste. It is through this process that jobs can be created in skilled and unskilled domains of the labour force. Evidently from the financial evaluation, approximately 18,000 employment opportunities can be created from phosphate loop closure in KZN alone, the vast majority of which would be associated with transportation of source separated urine from homesteads to primary treatment facilities. Importantly, however, the costs required to setup and operate such a network are prohibitively high, making this approach unattractive in relation to the value of the recovered phosphate. The imperative for sanitation services and protecting sensitive environments from phosphate-induced eutrophication might, however, necessitate such a recovery scheme.

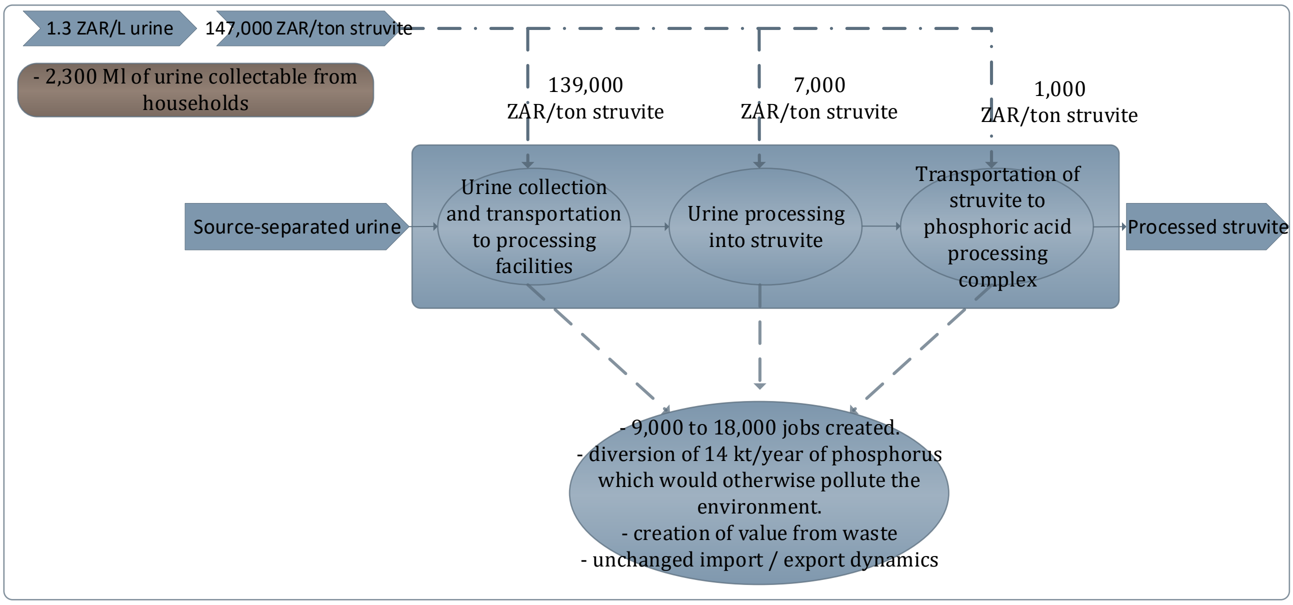

FIGURE 35: PROPOSED PHOSPHATE LOOP-CLOSURE APPROACH

What learnings can be drawn from the implementation of past EPR strategies and why were these strategies successful or unsuccessful?

As shown in Figure 35, there is potential to create value and jobs by reintroducing urine-derived phosphate into the phosphate value chain. Some insights on the jobs that could be created was drawn from the experiences of other Producer Responsibility Organisations (PRO's) viz. REDISA and the ROSE Foundation, complemented by the findings of Chapter 5 in this study. Firstly, the two experiences showed the importance of the establishment of a well-governed PRO with its goals aligned to those of the producers. Secondly, the critique on the mandatory and voluntary approaches to obtaining recycling fees revealed flaws in taking the mandatory approach to loop-closure. Therefore, one of the biggest challenges that remain to be investigated is with regards to how a voluntary approach could be integrated into a provincial strategy for phosphate loop-closure. The collection of EPR funds generally relies on fund collection from the end-user/polluter, however the 'polluter' in this case are the individuals in rural communities. Ironically, phosphate recycling is aimed at providing employment and business opportunities for those individuals. This therefore means that funding for the EPR model would need to be external, perhaps in the form of a 'nutrient efficiency levy on food produce, or by those with existing sanitation facilities as some sort of waste treatment levy.

7.2 RECOMMENDATIONS FOR FUTURE WORK

Whilst phosphate loop-closure by way of recovery of phosphate in the form of struvite from waste water treatment works or the collection and processing of urine into struvite was shown to be possible though at significant cost for the latter, there is an opportunity for improving the rigour of the technical analysis. This would be important since it dictates the economics of the phosphate value chain. It is therefore recommended, from a technical perspective, that rates of reaction of struvite with sulphuric acid be empirically established with the intention of gaining a better basis for the modelling of techno-economically optimal conversions and reactor sizing implications. Furthermore, there is concern with respect to the excessive presence of magnesium in phosphoric acid when struvite is substituted into the process. Further work is needed to fully understand the complexities that result from this presence; most importantly regarding quality specifications (as per downstream requirements) and extra purification options, if necessary. As per the discussion detailed in Chapter 6, it is also evident that further work is required to establish a method through which the reverse logistics would be funded. Noting that EPR schemes are generally funded through a fee or tax, as detailed in Chapter 6, an investigation into the suitability of such funding models in urine recycling should yield valuable insight.

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