ASSESSING THE DESIRABILITY OF MARINE PHOSPHATE MINING AMONGST STRATEGIES FOR A SUSTAINABLE SUPPLY OF PHOSPHATES

A review of the phosphate lifecycle, impacts and strategies for sustainable use in the South African context

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SAFEGUARD OUR SEABED COALITION

THE MARINE MINING OF PHOSPHATE MINERAL RESOURCES IS UNWARRANTED IN SOUTH AFRICA SINCE IT WOULD INTENSIFY PHOSPHATE FLOWS AND IN THE PROCESS CAUSE A RISE IN THE PHOSPHATE QUANTITY ENTERING THE ENVIRONMENT.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Eutrophication	A widespread problem which occurs in water bodies as a result 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 aquatic lifeforms and humans.
Marine phosphate mining	The mining of phosphate minerals from the seabed. Marine phosphate mining would potentially use Trailing Suction Hopper Dredging technologies (TSHD), which involves dredging sediment from the seafloor and removing a layer of sediment of up to 3 meters deep. A dredge-head of around 11m wide is dragged on the seafloor which has cutting teeth and water jets that crush hard sediment. The sediment is then suctioned by a tube, filtered and all excess water and fine particulates are released back into the water column. This process creates a sediment plume.
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.
Sustainable development goals	A list of universal goals aimed at developing and developed countries to improve social, economic and environmental conditions.
Wastewater treatment influent	Refers to the wastewater stream that exits households and enters wastewater treatment works.

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EXECUTIVE SUMMARY

Phosphorus is a key element for the healthy development of plants and animals. Animals achieve their daily phosphorus requirement through meat and plant consumption whereas plants absorb phosphorus from the soil. In South Africa, apatite ore is the most common source of supplementary phosphorus for agriculture and it is processed through various stages into fertiliser, livestock feed and for other industrial processes. With growing demand for phosphates (Cordell, et al., 2009; Smil, 2000), alongside reported dwindling supply (Cooper, et al., 2011; Gilbert, 2009), companies have sought to explore offshore phosphate deposits, with an intention to potentially exploit marine phosphate reserves.

In 2012 and 2014, the Department of Mineral Resources granted rights to three companies to prospect for marine phosphate in South Africa's marine environment; offshore of West Coast and off Mossel Bay, within the Outeniqua Basin. An argument asserted in all 3 applications for those prospecting rights – and applications in other jurisdictions – is that phosphate is critical for food security and terrestrial phosphate supplies are dwindling whilst demand is increasing.

A central aim of this study is to critically analyse this assertion, in the context of the wider phosphate system. The study will take into consideration market dynamics, available supply and demand, phosphate uses and options for improved phosphate resource management.

In response to concern about the impacts of bulk marine sediment mining, the Centre for Environmental Rights (CER) launched its *Safeguarding our Seabed* project. In order to promote rational decision-making on the desirability of marine phosphate mining for phosphate supply strategies, CER asserts that alternatives to bulk marine sediment mining must be openly considered and discussed and new information and knowledge is generated on the subject.

In support of this objective, this study was commissioned to:

i. Investigate the long-term availability of terrestrial phosphate deposits and to provide an understanding of the industries which are dependent on the phosphate supply in South Africa.

ii. Develop a substance flow analysis (SFA) of phosphate in South Africa, documenting the major flows of phosphate back to nature, including accumulation in farmlands.

iii. Summarise the environmental impacts of releases of phosphate into nature.

iv. Investigate potential phosphate loop-closure options based on the SFA.

> There exists more socio-economically and environmentally friendly approaches to sustainably obtaining supplementary phosphates. These approaches involve the recovery of phosphates from human and animal waste and the efficient application of phosphate fertiliser to soils.

The estimations made on the long-term availability of phosphate reserves in South Africa revealed that currently mined reserves would run out in the next 90–220 years if not exported to the rest of the world which might start experiencing shortages within 45 years, depending on the rate of rise in demand. The key industry influencing this rise in demand is the fertiliser industry, which uses approximately 90% of the phosphoric acid produced; animal feed production and other industries each account for 5%.

The SFA showed that a total of approximately 164 kt/year of phosphorus enters the environment, most of it in the form of manures onto grazing lands or into agricultural soils, where it is already useful but not necessarily optimally applied. Some of it ends up in surface waters where it causes environmental damage, particularly eutrophication. Table 1 summarises the findings from the SFA.

TABLE 1 Summary of phosphorus flows entering the environment

Sources of phosphorus released into environment	Estimated flow (kt/year)	Potential recycling option
Manure	87	Chemical processing, direct application to arable soils
Burning and wild animal consumption	12	Direct application to arable soils
Post-harvest losses	3.5	Subsistence or de-centralised farming to reduce travel distance
Food distribution losses	4	Subsistence or de-centralised farming to reduce travel distance
Human waste	27	Chemical processing, direct application
Erosion losses from arable soil	31	Efficient application to arable soils
Total phosphorus entering environment	**164**	

The most widespread impact resulting from the phosphorus releases into the environment is eutrophication of coastal and inland waters. Sources suggest that eutrophication begins to occur to waters with a phosphorus loading rate above 1 g/year/m^2 (Jaworski, 1981). Other impacts are associated with the processing stages and can include radioactive by-product release, carbon emissions and the release of heavy metal pollutants into the environment.

The last section of the report explores phosphate loop-closure options and particularly focuses on options for agricultural and human sanitation waste. Phosphate loop-closure in agricultural production essentially requires the recycling and reuse of plant and animal waste at farm level. Technology has a role in assisting with gaining an advanced understanding of plant growth dynamics so as to improve land-use and fertiliser application to soils. Alternatively, various technologies are available for recovering phosphorus (in the form of phosphate) from waste. Separation techniques for excreta are broadly categorised as physical, chemical and biological and can be applied within operational wastewater treatment works. Lastly, phosphates can be recovered from urine through various other technologies – the most common being collection through urine diversion and subsequently, the precipitation of struvite, a product with a potential for commercialisation as a fertiliser commodity.

The following conclusions can then be drawn:

- The marine mining of phosphate mineral resources is unwarranted in South Africa since it would intensify phosphate flows and in the process cause a rise in the phosphate quantity entering the environment.
- There exists more socio-economically and environmentally friendly approaches to sustainably obtaining supplementary phosphates. These approaches involve the recovery of phosphates from human and animal waste and the efficient application of phosphate fertiliser to soils.

On the basis of the above conclusions, the following recommendations were made:

- The amount of phosphorus available for agricultural soils should be improved by recycling and reprocessing methods and efficient fertiliser use.
- The commercialising of waste-derived fertilisers should be encouraged so as to create a demand.
- Stakeholders should be educated about the use of waste-derived fertiliser products and encouraged to use and produce these fertiliser products for sale.

PHOSPHATE LOOP-CLOSURE IN AGRICULTURAL PRODUCTION ESSENTIALLY REQUIRES THE RECYCLING AND REUSE OF PLANT AND ANIMAL WASTE AT FARM LEVEL. VARIOUS TECHNOLOGIES ARE AVAILABLE FOR RECOVERING PHOSPHORUS FROM WASTE.

1/ INTRODUCTION

Phosphorus is a key nutrient that is essential to all life forms. In its elemental form, phosphorus cannot be absorbed into fauna and flora; it is rather taken up as various phosphate compounds. In South Africa, apatite ore is the most common source of phosphate rock and has been mined since the mid-1900s in Phalaborwa, Limpopo (DMR, 2008). Also abundant in South Africa are sedimentary deposits of marine phosphorites along the west coast and in KwaZulu-Natal (DMR, 2008). Foskor Limited, a key player in the South African phosphate market, consists of subsidiaries that are involved at all phosphate value-addition stages in South Africa; from mining ores to processing significant phosphate rock quantities mainly into phosphoric acid and fertiliser products. A portion of this phosphoric acid supplies animal feed production as well as metal production. The balance of the phosphoric acid is exported to international markets (Foskor, 2014). Mining and processing phosphate-bearing rock is a significant industry, due to the fact that phosphorous-bearing rock is a key requirement for diverse industries and applications, alongside growing demand, mainly due to population growth. This growing demand has provided a motivation for companies to explore offshore phosphate deposits.

A KEY QUESTION THEN EMERGES: HOW DESIRABLE IS MARINE PHOSPHATE MINING IN THE SUSTAINABLE PROCUREMENT OF PHOSPHATES? THIS QUESTION CAN ONLY BE PROPERLY INTERROGATED IN THE CONTEXT OF THE WIDER PHOSPHATE SYSTEM, WHICH TAKES INTO ACCOUNT PHOSPHATE MARKET DYNAMICS, AVAILABLE SUPPLY AND DEMAND, PHOSPHATE USES AND OPTIONS FOR IMPROVED PHOSPHATE RESOURCE MANAGEMENT.

1.1 Project background

In 2012 and 2014, the Department of Mineral Resources granted rights to three companies to prospect for marine phosphate in South Africa's marine environment; offshore of West Coast and off Mossel Bay, within the Outeniqua Basin. There is very limited knowledge of the impacts of marine phosphate mining on the marine environment and society in general. Preliminary studies, however, outline potentially significant impacts to marine ecosystems and fishery resources (Currie, 2013; Allsopp, et al. 2013; NZ EPA, 2015).

Similar to the technology used in the marine mining of aggregates, the proposed technology for marine mining of phosphate deposits involves dredging the seabed. Mining of marine phosphates would probably make use of Trailing Suction Hopper Dredge technologies, which involves removing and dredging large volumes of sediment from the seabed, at a rapid rate. This may result in the direct destruction of benthic habitats and organisms; disturbance of the physical, chemical and biological composition of the benthos; the release of hazardous substances such as heavy radioactive materials, methane and hydrogen sulphide; and the release of a sediment plume that buries and smothers seabed ecosystems (Currie, 2013).

In response to concerns related to the impacts of bulk marine sediment mining, the Centre for Environmental Rights (CER) launched its *Safeguarding our Seabed* project. As part of the project, the CER seeks to gain knowledge on the potential for closing the phosphate loop, as an alternative to tapping into new primary phosphate reserves.

In order to promote informed decision-making on the suitability and desirability of marine phosphate mining on the basis of ensuring continued phosphate supply; CER asserts that alternatives to bulk marine sediment mining must be openly considered and discussed and new information and knowledge is generated on the subject.

1.2 Problem statement

An argument asserted in all 3 applications for the prospecting rights granted by the Department of Mineral Resources – and in applications in other jurisdictions – is that phosphate is critical for food security; conventional, terrestrial phosphate supplies are dwindling whilst demand is increasing; which motivates the need to explore and eventually mine marine phosphate reserves.

The Background Information Document for one of the marine phosphate prospecting applications in South Africa, prepared by Diamond Field International Limited, provides a clear example of such arguments:

> *The offshore phosphate deposits of South Africa comprise a major phosphate resource. A vital and indisputable link exists between phosphate rock and world food supply. Phosphate rock is the source of phosphorus used to make phosphatic fertilizers, essential for growing the food needed by humans in the world today and in the future.*
> (Diamond Fields International Limited, 2013)

A key question then emerges: how desirable is marine phosphate mining in the sustainable procurement of phosphates? This question can only be properly interrogated in the context of the wider phosphate system, which takes into account phosphate market dynamics, available supply and demand, phosphate uses and options for improved phosphate resource management.

In order to promote informed decision-making on the suitability and desirability of marine phosphate mining on the basis of ensuring continued phosphate supply; alternatives to bulk marine sediment mining must be openly considered.

1.3 Objective of study

This study is intended to provide the Centre for Environmental Rights and the broader public, with an understanding of the potential for closing the phosphate loop, as an alternative to tapping into new primary phosphate reserves offshore. The study will achieve this through the fulfilment of the aims that follow:

i. An analysis of the current phosphate supplies in South Africa – shedding light on the long-term availability of phosphate-bearing rock and a break-down of industries that depend on phosphate supply.

ii. A substance flow analysis of phosphate in South Africa, documenting the major flows of phosphate back to nature, including accumulation in farmlands and its long-term impacts.

iii. An investigation into the impacts of excessive phosphate fertiliser exposure to ecosystems, livestock and human health. This section will also investigate the volumes of phosphate in waste water treatment systems and give a verdict on the acceptability of these levels with respect to leaching and run-off into the environment.

iv. An estimate of recoverable phosphate quantities from identified points in the life cycle, also analysing the potential socio-economic and environmental impacts of implementing phosphate recovery strategies for ensuring a sustainable supply of phosphates.

1.4 Scope and limitations of study

It is noted that Centre for Environmental Rights recognises the complex nature of the global phosphate value chain and within this aims to contextualise the case of South Africa. In this study, the focus will be on South African phosphate production and use. However, the international market will be used for comparison. Technologies for phosphate recovery, in use elsewhere, will be included in the scope of the study.

The study is based on a literature review, and will in addition provide some estimates of recoverable phosphate quantities in South Africa. For these estimates, material balancing methods will be used. No primary data gathering, such as measurement of phosphate concentrations in waste streams, was undertaken.

The broader potential socio-economic and environmental impacts of marine phosphate mining are also important factors in considering the suitability of this practice in an overall strategy for the sustainable supply of phosphates. However, such an investigation is beyond the scope of this study.

2/

PHOSPHATE MARKET DYNAMICS

Section 2.1 begins by presenting information relating to the global and South African distribution of phosphate reserves. Thereafter, Section 2.2 sheds light on the processes involved during the production of phosphate product. The main intention of this section is to understand which industries depend on phosphate and thus helps in understanding the importance of this resource. Overall, Sections 2.1 and 2.2 help build a strong understanding of backward and forward linkages associated with the phosphate industry; and aim to promote the improvement of production methods so as to gain competitive advantage, commonly referred to as *upgrading in the value chain* (Fessehaie, 2012). Lastly, Section 2.3 ties up the information in the preceding sub-sections and interprets its implications.

2.1 Phosphate rock reserves

South Africa is estimated to have approximately 2% of the global phosphate reserves – the fifth largest in the world behind Morocco with Western Africa, Algeria, China and Syria. Combined, North Western African countries hold approximately 80-90% of the world's phosphate reserves. Russia, Jordan and the United States also have considerable resources (USGS, 2015). Figure 1 shows a graphic of the geographical dispersion of the world's phosphate reserves.

Although countries such as the United States and China hold significant phosphate reserves; their contribution to the global export market is limited since they consume phosphate amounts similar to what they produce internally. Interestingly, the United States' reserves are expected to be depleted in less than 25 years (Childers, et al., 2011; Cordell, et al., 2009). This is slowly becoming evident by the United States' dependence on imported phosphates which account for approximately 14% of the United States' consumption in 2010 and 2011 (Childers, et al., 2011; USGS, 2015).

South Africa, on the other hand, is a key player in phosphate-based product exports. The largest source of phosphate-bearing rock in South Africa is found at the Phalaborwa mine in Limpopo, as igneous deposit (DMR, 2008). The mine is operated by Foskor Limited Mining

FIGURE 1

World Phosphate Rock Reserves (Adapted from PotashCorp, 2014)

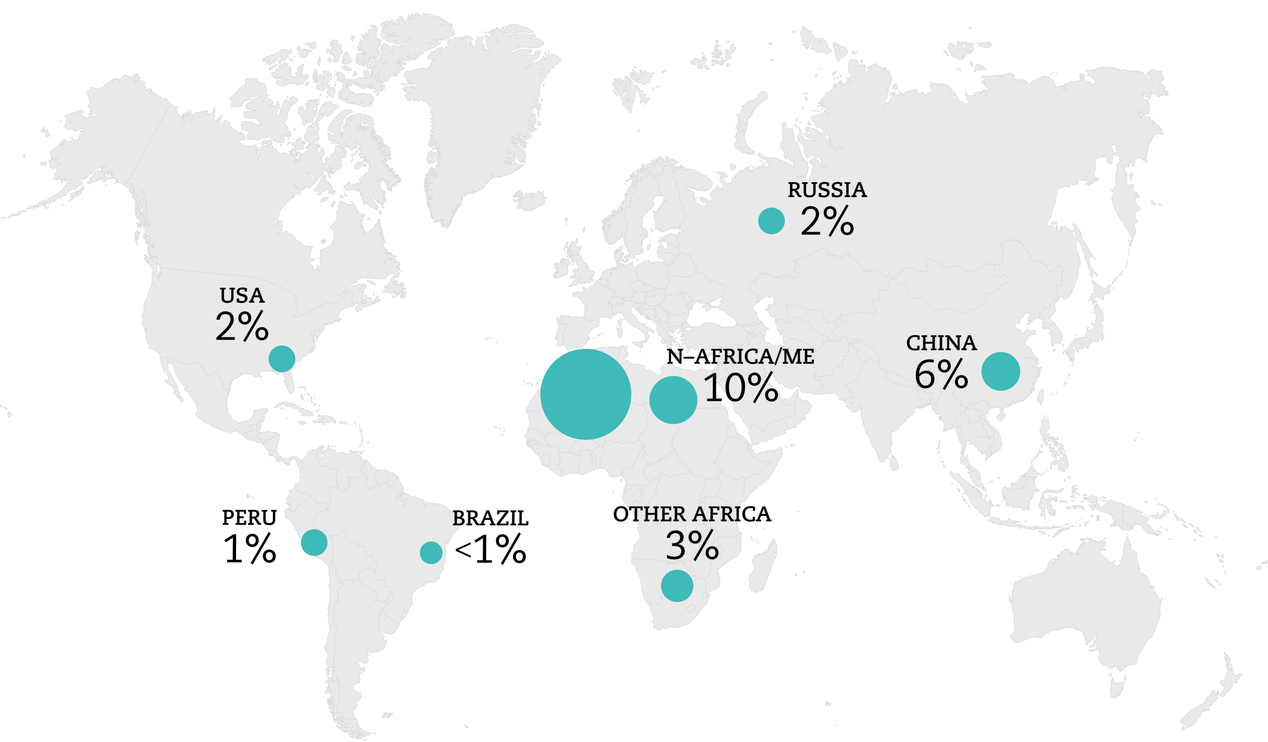
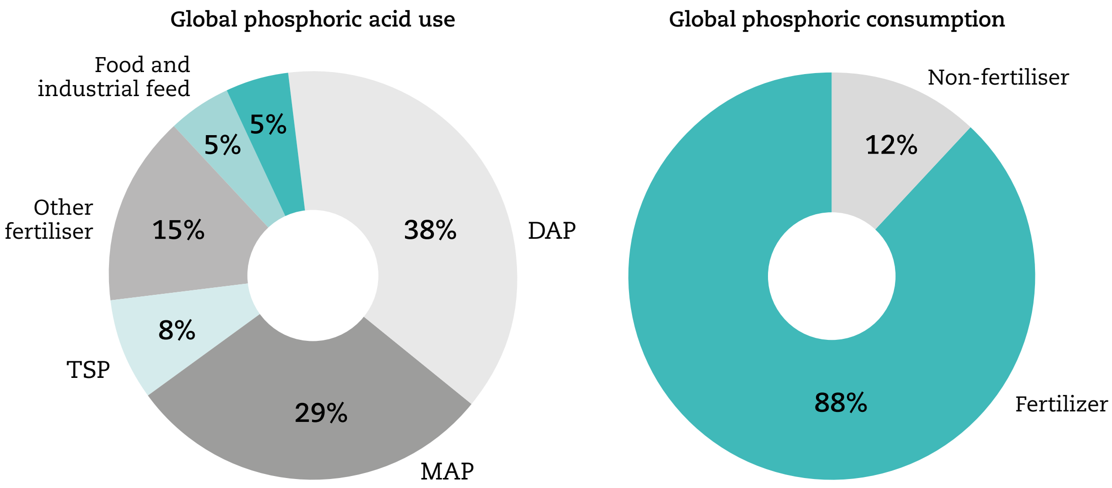


FIGURE 2
World phosphoric acid uses (Adapted from PotashCorp, 2014)



**Note*: *DAP – diammonium phosphate, MAP – monoammonium phosphate, TSP – triple superphosphates*

Division, a subsidiary of Foskor Limited, and the source has been exploited since the mid-1900s. Initially, the mines' target market was limited to local farmers – providing them with phosphate fertiliser. The South African phosphate industry has since grown to a global level. At the mine, apatite, a phosphate-bearing ore, is mined at two of open-cast mines and is transported to Richards Bay for further processing into phosphoric acid and subsequently other end-use products. (Foskor, 2014).

On the West Coast of South Africa exists the Elandsfontein sedimentary phosphate deposit which are currently being explored and developed by Elandsfontein Exploration and Mining (Pty) Ltd. This phosphate deposit holds the second largest reserves in South Africa after the deposits in Phalaborwa. The plant is planned to begin operations in August 2016 and intends to produce 1.35 million tonnes of phosphate concentrate per annum with a concentration above 32% phosphorus pentoxide (P_2O_5) (EEM, 2015).

Montero Mining and Exploration is another company currently exploring phosphate deposits in South Africa under their 'Phosco" project. This project consists of four exploration sites, three of which are located in the Western Cape (Duyker Eiland, Phillips Kraal and Lamberts Bay) and one in Bierkraal, Northwest. The most advanced of the projects is Duyker Eiland which has the potential to produce 490 kt/year of 33% P_2O_5 (Montero Mining , 2011).

The heavy reliance of phosphate procurement on finite phosphate ores together with the diminishing grades of phosphate ores is a global challenge (Cordell, et al., 2012). The finiteness of the mineral resource suggests that alternative sources ought to be explored; this is even more pertinent since diminishing ore grades have made it more difficult to separate and process phosphate ores (Cooper, et al., 2011; Gilbert, 2009).

2.2 Phosphate-dependent industries

Cordell, et al. (2009) and Van Kauwenbergh, et al. (2013) agree that approximately 80-90% of the global phosphate demand is for the production of fertilisers. Furthermore, the demand is expected to increase by 50–100% by 2050 mainly due to population growth. Figure 2 is a global breakdown of phosphate rock dependent industries.

The processing of phosphate rock into various products generally occurs in three beneficiation stages, primary (mining and refinement), secondary (mineral processing) and tertiary (processing into common use products). The primary and secondary stages involve size reduction, separation and mineral processing techniques that are both energy and resource intensive (Childers, et al., 2011; Villalba, et al., 2008). The primary stage refers to the mining and concentration of the phosphate rock into market grade phosphate rock which typically contains 28-39% phosphorus pentoxide (Gharabaghi, et al., 2010; Ortiz, et al., 1999). The secondary step is responsible for the conversion of concentrated phosphate rock into phosphoric acid. The conversion is commonly achieved through the 'wet process' that reacts phosphate rock with sulphuric acid. Importantly Also of importance, the sulphuric acid used in the secondary stage is produced using imported sulphur (Foskor, 2014), rendering the entire process vulnerable to potential disruptions in sulphur supply (HCSS, 2012). Lastly, the tertiary stage(s) processes phosphoric acid, together with other reagents, into end-use products.

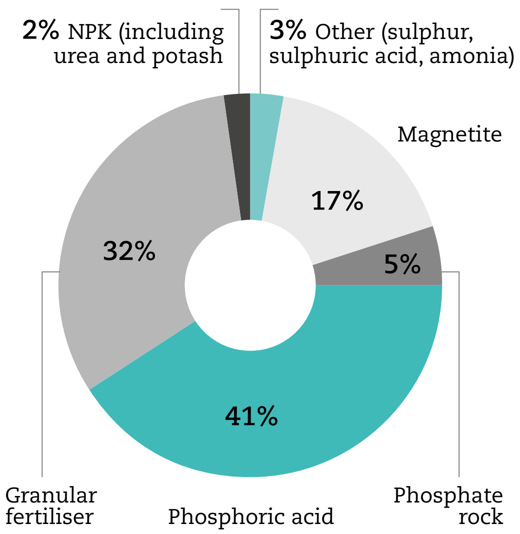
The overall phosphate industry in South Africa is summarised by the revenue shares presented by the Foskor Limited Integrated Report, in Figure 3. The chart sheds light on the detail of the total revenue of R5.1 billion that was generated by Foskor Limited in 2014.

Evidently in Figure 3, phosphoric acid and granular fertiliser constitute 41% and 32%, respectively, of the total revenue. The by-product, magnetite, also makes up a significant percentage of the revenue (even though it is not phosphate-based). Furthermore, the South African market is similar to the global market – shown in Figure 2 – in share of phosphoric acid used to produce fertiliser. It is responsible for consuming approximately 90% of the total phosphoric acid produced (Patel, et al., 2015).

As per Figure 2, the balance of the 10% global phosphoric acid demand is split evenly between industrial phosphate products and livestock feed products (PotashCorp, 2014). Industrial phosphate products are used as food additives, in soft drinks, in metal treatment and in detergents. It is worth noting that the presence of phosphates in detergents ultimatetly contributes about 30–35% of the phosphorus present in wastewater entering treatment works (Quale, et al., 2010). A follow-up study conducted by du Plooy, et al. (2012) observed a significant change in the phosphorus content in wastewater in two of Cape Towns wastewater treatment facilities after the introduction of zero-phosphate detergents by a major detergent producer (du Plooy, et al., 2012).

FIGURE 3

Foskor product revenue breakdown in 2014 (Foskor, 2014; Patel, et al., 2015)



*Note: NPK – Nitrogen, Phosphate and Potassium products

AN ESTIMATE OF THE LONG-TERM AVAILABILITY OF PHOSPHATES SUGGESTS THAT GLOBAL PHOSPHATE RESERVES WOULD LAST FOR APPROXIMATELY 300 YEARS AT CURRENT USAGE RATES.

2.3 The sustainable procurement of Phosphate

A crude estimate of the long-term availability of phosphates suggests that global phosphate reserves would last at most for approximately 300 years at current usage rates – see Equation 1. However, there is no doubt that phosphate demand will continue to grow in the presence of drivers such as population growth, growing preference for meat-rich diets and the growing need for biofuels (Cordell, et al., 2009; Cordell, et al., 2012; Villalba, et al., 2008). With the projected increases for the aforementioned reasons, more sophisticated and thus more accurate estimation methods predict that global phosphate reserves, tabulated in Table 2, could become insufficient to meet demand in the next 45–100 years (Smil, 2000). Using a similar chain of thought, a crude estimation reveals that South African terrestrial reserves could meet current demand for approximately 650 years – see Equation 2. Noteworthy, regarding this estimate, is that it neglects factoring in net exports (and imports). It assumes the South African phosphate industry is closed, meaning it does not contribute to the international market. This of course is not the case and as noted earlier in Section 2.1, South Africa is a key player in the international phosphate market. Secondly, it also fails to factor in growth in demand. As with the global phosphate availability in the long-term, phosphate reserves are also expected to be reduced by a factor in the range 3 to 7. Thus, depletion in South Africa's terrestrial phosphate reserves quoted in Table 1 can be expected in the next 90–220 years.

EQUATION 1

$$\textit{Availability at current usage} \cong \frac{\text{(Land Reserves (kT)}}{\text{(Production (kT/year)}} = \frac{67{,}000{,}000}{225{,}000} = 300 \text{ years}$$

EQUATION 2

$$\textit{Availability at current usage (South Africa)} \cong \frac{1{,}500{,}000}{2{,}300} = 650 \text{ years}$$

TABLE 2 Phosphate rate of production and terrestrial reserves by country

Country	Mine production of marketable phosphate rock product in 2013 (kilo Tonnes/year)	Reserves (million Tonnes)
Morocco and Western Africa	26 400	50 000
China	10 800	3 700
Algeria	1 500	2 200
Syria	500	1 800
South Africa	2 300	1 500
Russia	10 000	1 300
Jordan	5 400	1 300
USA	31 200	1 100
Australia	2 600	1 030
World Total	**225 000**	**67 000**

In order to discuss sustainable procurement of phosphate it is necessary to provide a brief frame for analysing sustainability and sustainable development. The recently adopted Sustainable Development Goals (SDGs) provides the international community with defined goals and a framework to approach and strive towards sustainability. With the anticipated growth in phosphate demand, we can look to the Sustainable Development Goals (SDGs) as a frame to assess the desirability of marine phosphate mining. Most pertinent to this study are Goal 1 and Goal 2 of the SDGs. Goal 1 aims to 'eradicate poverty in all its forms everywhere' and Goal 2 aims to 'end hunger, achieve food security and improve nutrition, and promote sustainable agriculture' (Osborn, et al., 2015). Also of peripheral relevance is Goal 14, which aims to 'conserve and sustainably use the oceans, seas and marine resources for sustainable development'.

The Oceans and Seas SDG, in turn, is highly interconnected with Goal 1 (poverty), Goal 2 (food security) Goal 12 (sustainable consumption and production) and Goal 15 (biodiversity). Increasing reliance on non-renewable mineral resources (through marine phosphate mining) is a linear approach that, like terrestrial mining, fails to recognise the complexity associated with achieving a sustainable phosphate supply. Currently, even though Africa holds the world's largest phosphate reserves, the resource (chemicals and fossil fuel) and energy intensiveness linked with the mining and processing of ores renders fertiliser unaffordable to most farmers in sub-Saharan Africa (Cordell, et al., 2009); and in doing so, limits progress with respect to Goal 1 and Goal 2 of the SDGs.

A crude estimation reveals that South African terrestrial reserves could meet current demand for approximately 650 years.

3/ SUBSTANCE FLOW ANALYSES

3.1 Global flows

Substance Flow Analyses (SFA) enable the tracking of resource flows with the main aim of identifying potential 'intervention' spots for the better management of these resources (Cordell, et al., 2012), in this case phosphate. Cordell, et al. (2012) present a matrix of phosphate SFA that have been conducted in the past; these differ in geographical and temporal scales as well as in scope and sectors.

The phosphorus flow analysis done by Cordell, et al. (2009) is global and uses data from 2005 and importantly, it includes information pertaining to all the different sectors. Four key figures from the study by Cordell, et al. (2009) have been noted and tabulated in Table 3. Most notable is the phosphorus consumed by livestock and this demand, in turn, is due to increased demand for meat diets. Other key processes identified in Table 3 are phosphorus losses; together, these losses make up 18 Mt/year which is similar to what is mined annually worlwide. Section 5 discusses ways to minimise these losses.

3.2 South African phosphate flows

The SFA adopted herein is a simplified version of that found in Smil (2000); it takes on a less complicated form similar to the SFA done by Cordell, et al. (2009) and Childers, et al. (2011). The SFA included eight stages altogether, shown in Figure 4, the processing of market grade phosphate rock into phosphoric acid, fertiliser production, application of fertiliser to arable soil, absorption of phosphate by crops, crop harvesting, food production, and lastly human and animal consumption of phosphorus in different forms (Cordell, et al., 2009). The substance flow presented herein 'begins' with the beneficiated phosphate rock that has been mined; and the main emphasis is on the losses that are represented in streams 8, 10, 14, 16 and 18.

Igneous phosphate reserves in South Africa are estimated at 1 500 million tons (Table 2). The mined ore has an average phosphorus pentoxide (P_2O_5) content in the range 6–7% which has to be processed as per the process explained in Section 2.2. The processing of the mineral ore results in a market grade beneficiated product which contains a phosphorus pentoxide content in the range 30–40%. The phosphorus content of market grade phosphorus pentoxide rock flows within South Africa amounts to 182 kt/year; of this 85 kt/year are exported as phosphoric acid, 5 kt/year used for livestock feed, another 5 kt/year for other industrial processes and 87 kt used for the production of fertiliser. Notable in the phosphate

The SFA in this study suggests that there is an opportunity to close the phosphate loop and that this option is potentially more socially, economically and environmentally responsible than the proposed marine mining.

TABLE 3 Most notable phosphorus release/consumptions processes globally

Process/Sink	Phosphorus (million tonnes/year)	Phosphorus source
Grazing for livestock	13 Mt/year (Consumed, excl.)	Vegetation and livestock feed additives
Animal manure losses	7 Mt/year (Released into natural environment)	Livestock
Erosion from arable soil	8 Mt/year (Released into natural environment)	Arable soil
Crop losses before harvesting	3 Mt (Released into natural environment)	Crops

TABLE 4 Summary of phosphorus losses in cycle

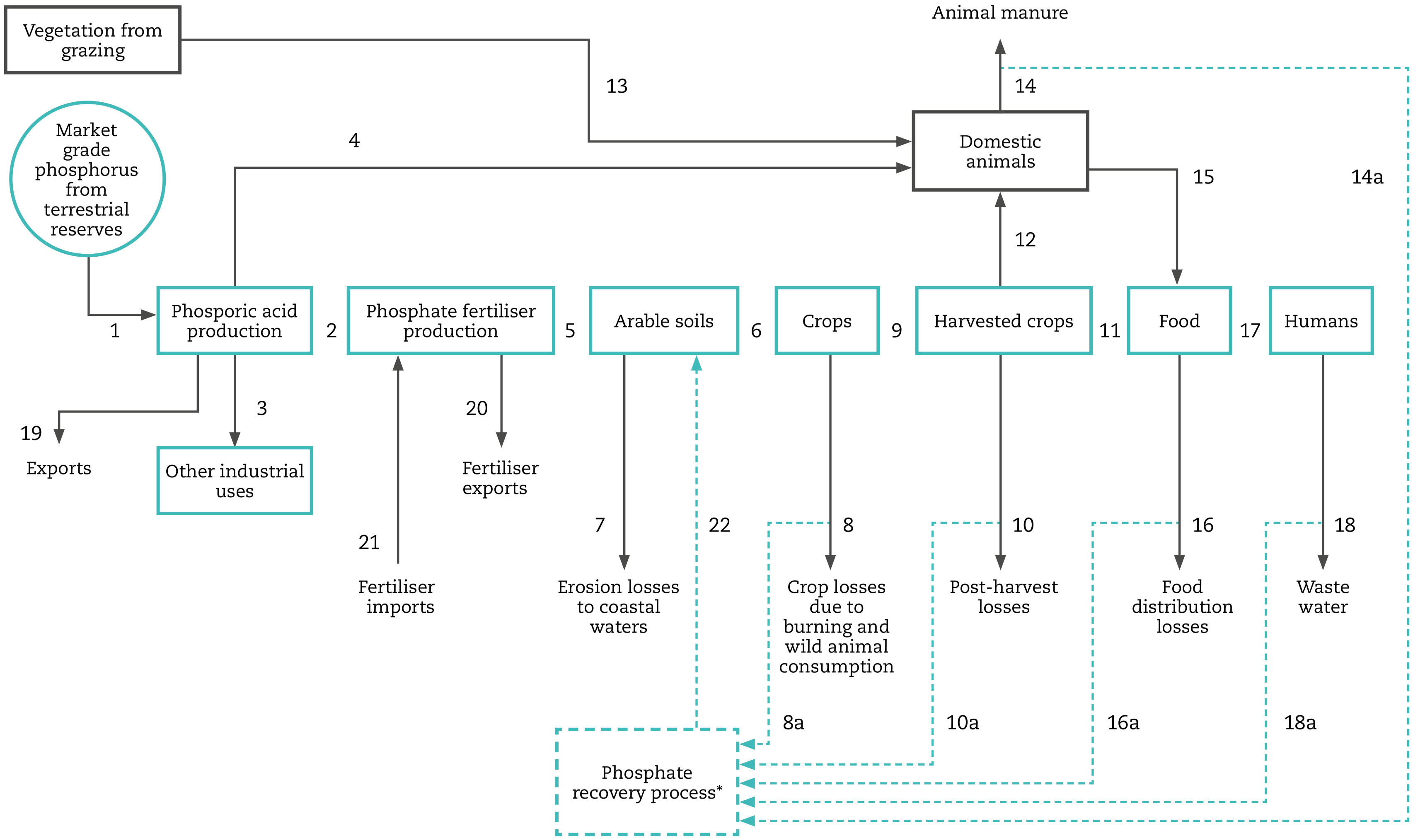
Sources of Phosphorus released into environment (stream number)	Estimated Flow (kt/year)	Potential recycling option
Manure (14)	87	Chemical processing, direct application to arable soils
Burning and wild animal consumption (8)	12	Direct application to arable soils
Post-harvest losses (10)	3.5	Subsistence or de-centralised farming to reduce travel distance
Food distribution losses (16)	4	Subsistence or de-centralised farming to reduce travel distance
Human waste (18)	27	Chemical processing, direct application
Erosion losses from arable soil (7)	31	Efficient application to arable soils
Total phosphorus entering environment	**164**	

ULTIMATELY, A MAXIMUM OF 133 KT/YEAR OF PHOSPHORUS CAN BE RECOVERED, THROUGH SOME SORT OF RECYCLING, FROM THE ENVIRONMENT. THE BALANCE OF LOSSES — APPROXIMATELY 31 KT/YEAR — CAN BE PREVENTED FROM ESCAPING INTO THE ENVIRONMENT BY USING ENHANCED TECHNOLOGIES THAT ARE DESIGNED TO OPTIMISE FERTILISER APPLICATION ONTO SOILS.

fertiliser production stage is the significant amount of phosphorus imported (63 kt/year) and exported (56 kt/year) – leaving 95 kt/year for application onto South African arable soils. Using the global phosphate build-up rate from Cordell, et al. (2009), it is estimated that there is a build-up of 17 kt/year of phosphorus in South African agricultural soils. The phosphorus that is eventually absorbed into crops amounts to 46 kt/year and that lost due to erosion of soils 31 kt/year. Livestock consume approximately 5 kt/year of phosphorus from harvested crops and about 82 kt/year through grazing. The majority of what is consumed by livestock either re-enters grazing lands or agriculture and contributes to vegetation and crop growth or it results in eutrophication. Combined, the phosphorus released into the environment as manure is estimated to amount to 87 kt/year. Lastly, with a South African population of 56 million people, each of whom excretes an average of 1.3 g/day per capita, a combined total of approximately 27 kt/year phosphorus comes from human waste.

Table 4 is a summary of the phosphorus losses shown in the cycle flow in Figure 4 (see over). Furthermore, Table 5 in Section 5 lists the potential phosphorus recovery options from the losses shown in Figure 4. Ultimately, a maximum of 133 kt/year of phosphorus can be recovered, through some sort of recycling, from the environment. The balance of losses – approximately 31 kt/year – can be prevented from escaping into the environment by using enhanced technologies that are designed to optimise fertiliser application onto soils. Section 5 provides more detail for phosphate loop-closure options.

FIGURE 4 *Phosphate cycle (South Africa)*



Stream	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Phosphorus flow (kt/year)	182	87	5	5	95	46	31	12	35	3.5	26	5	82	87	4	4	27	27	85	56	63

THE MOST COMMON IMPACT OF PHOSPHATE PROCESSING AND USE IS EUTROPHICATION. THE OTHER THREE MAJOR EFFECTS, RELEASE OF RADIOACTIVE BY-PRODUCTS, CARBON EMISSIONS AND HEAVY METAL POLLUTANTS ARE MORE ASSOCIATED WITH THE PROCESSING.

4/ LONG-TERM EFFECTS OF NUTRIENT EXPOSURE TO ECOSYSTEM

4.1 Eutrophication

Eutrophication refers to the excess presence of nutrients in surface waters. This results in an over-growth of aquatic microorganisms and consequently, the reduction of the oxygen content in water bodies (Correll, 1999). Typically the phosphorus content should be kept below 100 micrograms per litre (µg/L) of dissolved phosphate to avoid eutrophication (Smil, 2000); however, Correll (1999) stresses that there is no absolute threshold phosphorus content since concentrations of 20 µg/L are also commonly a problem. Alternatively, Smil (2000) and Jaworski (1981) suggest that a better eutrophication barometer is phosphorus loading, measured with the units of mass of per unit area, together with the retention time of that stream or waterbody. The set phosphorus loading rate quotient above which eutrophication is known to take place is 1 gram of phosphorus per square, per annum (g/m^2/year) (Jaworski, 1981). Easily identifiable preliminary key indicators of the nutrient content of a waterbody remain transparency and color.

As a result of a reduced dissolved oxygen (DO) content, eutrophication also tampers with food chains. At low DO concentrations conditions become inhabitable for fish, which leads to low fish yields. Furthermore, humans that depend on these waterbodies face the risk of ingesting neuro- and hepatotoxins that are released by decomposing algal blooms (Jaworski, 1981).

In South Africa, effluent from wastewater treatment works should contain no more than 1 mg/L for release into external waterbodies (DWA, n.d.). However, data collected at a wasterwater treatment works located in the outer skirts of Cape Town by Sikosana (2015) revealed a effluent concentration of 1.11 mg/L soluble phophates (orthophosphates) and 2.44 mg/L total phosphates – both effluent values higher than those set in the guidelines by the Department of Water and Sanitation (DWA, n.d.; Sikosana, 2015).

4.2 Other effects

Release of radioactive by-products
Among other heavy metals, mined phosphate rock also contains uranium (U), radium (Ra) and cadmium (Cd) – all of which are radioactive (EFMA, 2000; Ortiz, et al., 1999). The radioactive nature of these compounds means they constantly emit radiation which is dangerous to animal and plant life. Foskor Limited, a major phosphate supplier, has noted the significance of the presence and thus needs for disposal of radioactive materials.

Carbon emissions
The decoupling of mineral and chemical processing from carbon emissions remains one of the most difficult challenges, more so because of the abundance of resources as well as the growing need to process. Combined, the energy sources used in the mining and mineral processing stages release 465 kt of CO_2 equivalent ($kgCO_2e$) emissions each year (Foskor, 2014).

Heavy metal pollutants
According to Villalba, et al. (2008), the presence of heavy metals in phosphogypsum is site specific. In addition to uranium and cadmium are nickel (Ni), lead (Pb), chromium (Cr) and Copper (Cu) (Ortiz, et al., 1999). The environment is exposed to these heavy metals through phosphogypsum disposal as well as through inefficient processing at the stages leading to phosphoric acid production.

5/ PHOSPHATE LOOP-CLOSURE OPTIONS

Various options are available for closing the phosphate loop. Sections 5.1 and 5.2 explore phosphorus loop-closure options around agriculture and sanitation sectors respectively. The discussion is focused on Figure 5 which has been adopted from Childers, et al. (2011).

5.1 Closing the cycle at agricultural production

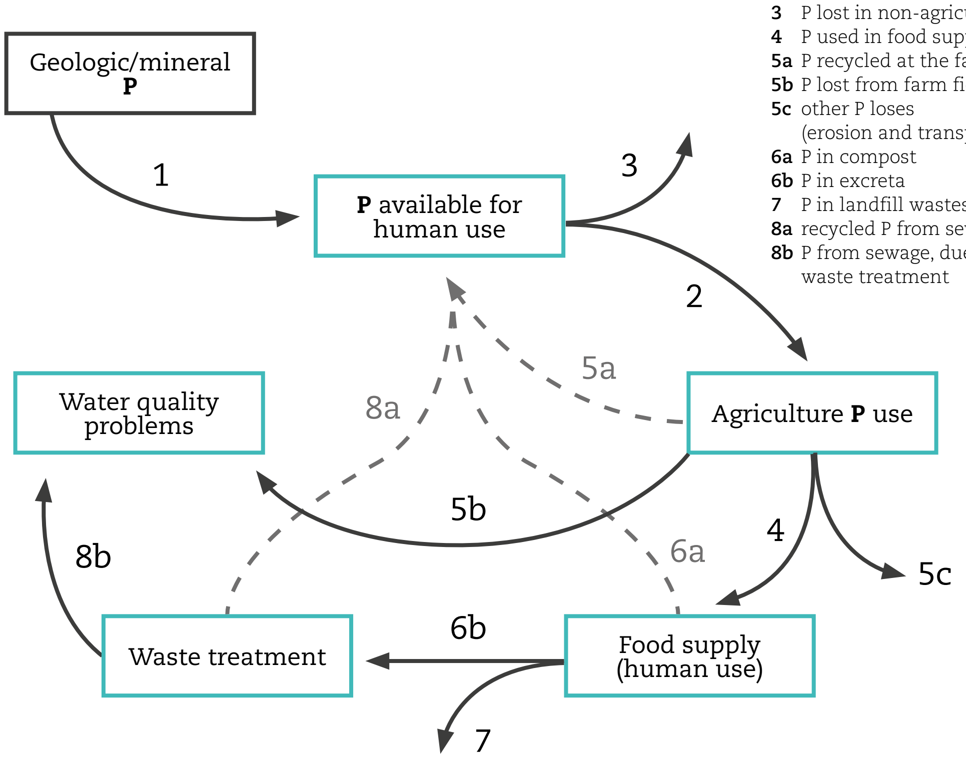
The first potential phosphate loop-closure option involves the enhancement of phosphate flows recycled at farms, depicted by arrow 5a, as well as the reduction of processes 5b and 5c that are shown in Figure 5.

In Figure 5, this option is represented by flow 7. Closing the loop at the agricultural stage would require changes in behaviour since farmers would have to reduce nutrient runoff from farms and recycle crop residue to livestock or crops (Childers, et al., 2011). The former can be achieved by efficient application of fertiliser to soils and land use optimisation which requires a better understanding of crop growth so as to efficiently align phosphate needs with crop growth (Childers, et al., 2011; Schroder, et al., 2011; Cordell, et al., 2009).

5.2 Closing the cycle at human and animal waste production

The following subsections discuss the opportunity for phosphorus recycling using centralised, de-centralised and semi-centralised techniques. Subsection 5.2.1 discusses the potential for phosphorus recovery from human and animal excreta whereas subsection 5.2.2 discusses the opportunity for phosphate recovery from urine.

FIGURE 5
Summarised phosphate cycle with loop-closure options



KEY

- **1** phosphate (P) mined and processed
- **2** P used in agriculture
- **3** P lost in non-agricultural uses
- **4** P used in food supplies
- **5a** P recycled at the farm
- **5b** P lost from farm fields due to erosion
- **5c** other P loses (erosion and transportation)
- **6a** P in compost
- **6b** P in excreta
- **7** P in landfill wastes
- **8a** recycled P from sewage wastes
- **8b** P from sewage, due to inefficient waste treatment

5.2.1 *Centralised treatment of human and animal excreta*

Work by Sikosana (2015) on the Cape Flats Wastewater Treatment Works investigated the techno-economic feasibility of phosphate recovery from this wastewater works. Results found that the effluent wastewater stream entering the environment contained a phosphate content of 1.11 mg/L soluble phophates (orthophosphates) and 2.44 mg/L total phosphates – both not compliant with City of Cape Town phosphate standards of less than 1 mg/L (Sikosana, 2015). According to Nieminen (2010) and Sikosana (2015), wastewater treatment works influent is typically in the region 5-20 mg/L phosphate. This is below the minimum required for an economically viable phosphate recovery which is quoted by Nieminen (2010) as wastewater containing more than 50 mg/L phosphates. However, concentrating the influent stream through the removal of water increases the phosphate content. This therefore results in a stream where phosphates can be recovered economically. An example of a stream that could be exploited is the return stream from anaerobic digesters during wastewater treatment which contains phosphates at a suitable concentration of approximately 190 mg/L orthophosphates (Sikosana, 2015).

Phosphorus may also be recovered from animal manures using at least one of the methods listed in Table 5; and alternatively it could be directly applied depending on the pathogen and micropollutant content. According to data collected from various sources by Sheldrick, et al. (2003), beef cattle and dairy cows excrete phosphorus in the range 6–23 kg/year per animal – depending on age. Horses follow with a yearly phosphorus excretion rates of 8–14 kg/year. Other significant potential recovery sources are sheep and goat manure (Sheldrick, et al., 2003).

Various phosphate recovery techniques are available and the work by Strom (2006) and Sikosana (2015) provides an extensive list. Recovery technologies primarily use physical, chemical or biological techniques to recover phosphorous from wastes and can be applied at different parts of the treatment process (Sikosana, 2015; Strom, 2006).

The implementation of phosphate recovery techniques in wastewater treatment works summarised in Table 5 could therefore be a major motivation for the efficient treatment of wastewaters. This would eliminate the effects associated with inefficiently treating wastewater whilst also providing a sustainable source of phosphates. Additionally, alternative recovery methods may be suitable for phosphate recovery from animal manure.

The study by Nieminen (2010) also sheds light on the various technologies currently being operated industrially and as pilots to recover phosphates, in the form of struvite, from wastes. Table 6 (see over) gives examples of industrial phosphate operations in use Japan and Germany and also that used at the pilot plant in Durban, South Africa to recover phosphates from urine.

5.2.2 *Urine diversion*

Alternatively, the project, *Volarisation of Urine Nutrients* (Etter, et al., 2015), looks at the recovery of phosphates and other nutrients from source-separated urine. Via tests, the project estimated that the typical concentration of phosphorus in fresh urine (undiluted) was 2.1 g/L – approximately 90% of which can be recovered (Etter, et al., 2015). On the other hand water-diluted urine contains a phosphorus content in the range 0.1-0.5 mg/L, depending on the extent to which it is diluted (Maurer, et al., 2006). Furthermore, Pronk & Kone (2009) emphasise that about 50% of the phosphates present in wastewater come from urine therefore giving source-separated urine an advantage over wastewater. Another advantage that further motivates the recovery of phosphates from source-separated urine over wastewater is the potential for direct use (Pronk & Kone, 2009). Additionally, source-separated urine is known to have nutrient

TABLE 5 Potential technologies for phosphorous recovery

Recovery technique	Brief description
Physical phosphate removal	These technologies involve the physical removal of particulate phosphorus. Reverse osmosis and ultrafiltration fall into this category and they commonly used towards the end effluent polishing parts of wastewater treatment (Strom, 2006).
Chemical phosphate removal and recovery process – with a specific focus on chemical precipitation	Given the right temperature, pH and concentration conditions struvite ($MgNH_4PO_4.6H_2O$) can precipitate out, either spontaneously or through induction (Durrant, et al., 1999). Technologies in this category induce precipitation through the strategic addition of metals such as magnesium, calcium, aluminium and iron during the treatment of wastewater (Durrant, et al., 1999; Strom, 2006; Levlin & Hultman, 2004).
Biological methods	This catergory of technologies relies on the usage of bacteria and microalgae in bioreactors. Most common in this category is *Enhanced Biological Phosphorus Removal* (Sikosana, 2015).

TABLE 6 Summary of processes in operation (Nieminen, 2010; Sikosana, 2015)

Location	Feed material	Influent phosphate concentration	Product and product flow rate
Shimane Prefecture Lake, Japan (Industrial)[1]	Sludge liquor	100–110 mg/L	Struvite, 500–550 kg/day
Gifhom, Gemany (Industrial)	Leached digested sludge	600 mg/L	Struvite, 680 kg/day
Durban, South Africa (Pilot plant)[2]	Urine	800–2 000 mg/L (Maurer, et al., 2006)	Liquid fertiliser, 30 L of fertiliser per 1 000 L of urine

concentrations similar to those in commercial fertiliser and to date the only inhibitor of it getting applied to soils directly is its content of micro-pollutants and pathogens. A major opportunity using centralised, decentralised or semi-centralised methods thus exists for the 'conversion' of urine into fertiliser for direct use or the decentralised further treatment into urine derivatives which subsequently can be included in exisiting phosphate processing plants. In the long term, the recovery of phosphates from urine (or its direct application onto farmlands) could prove to be advantageous than current phosphate procurement techniques due to the reduced capital-intensiveness, resource intensiveness as well as its socio-economic contribution.

However, the technical advantage of shifting to sustainable phosphate procurement from source-separated urine still faces a few challenges. Firstly, micro-pollutants and pathogens present in urine are a threat if urine is directly applied onto farmlands as fertiliser. Sources therefore suggest that urine be stored for at least a period of six months prior to use in order to decrease pathogen activity. Struvite precipitation is also commonly perceived as a more effective method of remove micropollutants and recovering high grade product (Maurer, et al., 2006; Pronk & Kone, 2009). Other challenges associated with urine use or phosphate recovery from urine are tabulated in Table 7 together with proposed solutions to these challenges.

THE IMPLEMENTATION OF PHOSPHATE RECOVERY TECHNIQUES IN WASTEWATER TREATMENT WORKS COULD THEREFORE BE A MAJOR MOTIVATION FOR THE EFFICIENT TREATMENT OF WASTEWATERS. THIS WOULD ELIMINATE THE EFFECTS ASSOCIATED WITH INEFFICIENTLY TREATING WASTEWATER WHILST ALSO PROVIDING A SUSTAINABLE SOURCE OF PHOSPHATES.

TABLE 7 Challenges of using urine as a phosphate source (Adapted From Vidima (2016))

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°C to be considered safe to use.	*Storage containers*
Unpleasant smells due to fresh urine storage	Water-flush sanitation.	*(Current water-flush toilet systems)*
Transportation of large quantities of urine	Application of decentralised volume reduction technologies. Evaporation, freeze-thaw and reverse osmosis technologies are available for this (Maurer, et al., 2006).	*Evaporation, reverse osmosis 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*

1 A detailed report on this plant can be obtained from Ueno & Fujii (2001)
2 Covered extensively by Etter, et al. (2015)

IMPROVING THE USE OF PHOSPHATES IN AGRICULTURE, SUPPORTED BY THE RECYCLING OF PHOSPHATES, COULD STRONGLY REDUCE THE NEED OF OPENING UP OF NEW PHOSPHATE RESERVES.

6/ CONCLUSIONS

Based on the foregoing information, the following conclusions have been drawn.

6.1 Sustainable phosphate availability

There are two key points on South Africa's phosphate market dynamics; at current consumption rates, South Africa's phosphate reserves are expected to reach depletion in the coming 90–220 years; and the majority of mined phosphorous rock is used for agricultural purposes. Thus, **improving the use of phosphates in agriculture, supported by the recycling of phosphates, could strongly reduce the need of opening up of new phosphate reserves**.

6.2 Alternative phosphate sources

A significant amount of 164 kt/year phosphorus enters the environment (surface waters arable and non-arable soils) mainly as manure, human waste and due to erosion from soils. Further intensification of phosphorus flows, through marine phosphate mining, will only encourage further environmental contamination – eventually resulting in eutrophication and the escalation of phosphate processing-related environmental impacts. As an alternative to opening up new phosphate reserves, **the SFA in this study suggests that there is an opportunity to close the phosphate loop and that this option is potentially more socially, economically and environmentally responsible than the proposed marine mining.**

6.3 Possibilities of phosphate loop-closure

The two main options identified for phosphorus loop-closure are in **sanitation** and **agriculture**. The most practical and economically viable is the implementation of centralised and/or decentralised phosphate recovery techniques in sanitation which has potential to lead to phosphate loop-closure, thereby reducing environmental damage and encouraging socio-economic upliftment. **Together with phosphates recovered from sanitation, the effect of efficient phosphate use in agricultural soils and recycling of manures have the potential to cause a significant reduction in the demand of primary phosphate resources.**

7/

RECOMMENDATIONS

Improve the amount of phosphorus available for agricultural soils

Several options are available for improving the quantity of phosphorus available for use in arable soils. The techniques associated with phosphate recovery from human wastes are already in use at an industrial scale in countries such as Netherlands, Sweden, Germany and Japan but not in South Africa. On the other hand, phosphate use reduction in agriculture and recycling need attention.

Commercialise waste-derived fertilisers

Struvite is not yet commercialised and it is a widely accepted nutrient source rich in phosphorus and nitrogen. The potential effect of commercialising this nutrient source would be multifold; it would encourage society to see the value in waste – thus challenging the status quo, reduce the nutrient quantity entering the environment – thus reducing eutrophication and compete with current fertilisers that require more processing.

Educate stakeholders and promote waste-derived fertilisers to stakeholders

The success/ failure of waste-derived fertilisers depends how socially accepted the product is. To improve the social acceptance of using such fertiliser, educating the users and end consumers is vital.

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SAFEGUARDING OUR SEABED PROJECT

In response to concerns that unsustainable seabed mining will soon be authorised in South Africa, the Centre for Environmental Rights (CER), with its partner WWF-South Africa, began working on the Safeguarding our Seabed (GT439), a three-year WWF-Nedbank Green Trust funded project. A key objective of the project is to achieve a moratorium on bulk marine sediment mining in South Africa.

THE SAFEGUARD OUR SEABED COALITION

In 2015 a group of organisations that shared the common interest in pursuing a cautious approach towards seabed mining formed a coalition. The Safeguard our Seabed Coalition includes organisations that represent the interests of commercial and small scale fishing and environmental and environmental justice organisations. The Safeguard our Seabed Coalition is made up of 11 organisations:

1	The Responsible Fisheries Alliance (RFA)	www.rfalliance.org.za
2	Food and Allied Workers Union	www.fawu.org.za
3	Fish SA	www.fishsa.org
4	South African Deep-Sea Trawling Industry Association (SADSTIA)	www.sadstia.co.za
5	WWF-South Africa	www.wwf.org.za
6	BirdLife South Africa	www.birdlife.org.za
7	Masifundise Development Trust	www.masifundise.org.za
8	Centre for Environmental Rights	www.cer.org.za
9	AfriOceans Conservation Alliance	www.aoca.org.za
10	International Ocean Institute – Southern Africa	www.ioisa.org
11	Institute for Poverty, Land and Agrarian Studies (PLAAS)	www.plaas.org.za

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