ECONOMIC AND AGRONOMIC EVALUATION OF USING EXCRETA-DERIVED PLANT NUTRIENT SOURCES (LATRINE DEHYDRATED AND PASTEURISED PELLETS, STRUVITE AND NITRIFIED URINE CONCENTRATE) AS AGRICULTURAL FERTILISERS

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agricultural Economics, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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FIRST DECLARATION: PLAGIARISM

I, Benjamin Chapeyama, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my own original research,
2. This thesis has not been submitted for any degree or examination at any other university,
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from those persons,
4. This thesis does not contain other author(s) writing, unless specifically acknowledged as being sourced from other author(s). Where other written sources have been quoted, then:
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SECOND DECLARATION: PUBLICATIONS

The following publication forms part of the empirical research presented in this thesis.

Publication – Chapter 3 of this thesis

Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. 2018. The cost-effectiveness of using latrine dehydrated and pasteurization pellets and struvite: Experimental evidence from South Africa. *African Journal of Science, Technology, Innovation and Development*, 10(4): 451-461.

The data collection, analyses and discussion of empirical results for the above-listed publication were conducted in their entirety by B. Chapeyama with the technical advise from Prof. E. Wale and Dr A.O. Odindo. All figures, tables and graphs were produced by the same, unless otherwise referenced in the respective publications.

THIRD DECLARATION: LIST OF CONFERENCE PRESENTATIONS

1. Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. Quantifying the economic benefits of using human excreta-derived plant nutrient sources: ‘LaDePa’ pellets and struvite. *“The University of KwaZulu-Natal, College of Agriculture, Engineering and Science Postgraduate Research Day.”* 22nd of September 2015. University of KwaZulu-Natal Pietermaritzburg Campus, Pietermaritzburg, South Africa.

2. Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. Quantifying the Economic benefits of using human excreta-derived plant nutrient sources: ‘LaDePa’ pellets and struvite. “*International Conference on Post-Graduate Students’ Research on Indigenous Knowledge Systems in Southern and Eastern Africa.”* 20th – 21st of November 2015. Westville, Durban, South Africa.

3. Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. Analysing the cost-effectiveness of using Latrine Dehydrated and Pasteurised (‘LaDePa’) agricultural pellets and struvite as new fertilizers: Experimental evidence for maize, wheat and sugarcane in KwaZulu-Natal, South Africa. *“The 54th conference of the Agricultural Economics Association of South Africa.”* 14th – 16th of September 2016. Misty Hills Country Hotel, Conference Centre and Spa, Muldersdrift, Johannesburg, South Africa.

4. Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. Analysing the cost-effectiveness of using Latrine Dehydrated and Pasteurised (“LaDePa”) agricultural pellets and struvite as new fertilizers: Experimental evidence for maize, wheat and sugarcane in KwaZulu-Natal, South Africa. *“The University of KwaZulu-Natal, College of Agriculture, Engineering and Science Postgraduate Research Day.”* 29th of November 2016. University of KwaZulu-Natal Howard College, Durban, South Africa.

5. Benjamin Chapeyama, Edilegnaw Wale and Alfred Odindo. Economic evaluation of using human excreta and urine-derived materials as agricultural fertilizers. *The “Ukulinga Howard Davis Memorial Symposium.”* 22nd – 23rd May 2018. University of KwaZulu-Natal, Ukulinga Research Farm, Pietermaritzburg, South Africa.

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DEDICATION

This work is dedicated to my parents Mr and Mrs Chapeyama. You have always believed in me, showed me the way, encouraged, supported and sacrificed a lot for me and the happiness of my family. May God bless you abundantly!

ABSTRACT

Faecal sludge can be recycled and processed into usable products such as the Latrine Dehydrated and Pasteurised (“LaDePa”) pellets and urine into Nitrified Urine Concentrate (NUC) and struvite, which can be used as fertilisers. The financial costs and benefits and the agricultural-effectiveness of using LaDePa, NUC and struvite as fertilisers in South Africa and the wider sub-Saharan African region have not been empirically quantified. A study was carried out using experimental data to quantitatively establish the cost-effectiveness of using LaDePa, NUC and struvite for maize production. The costs per hectare of using these products to meet crop nutrient requirements for maize and achieve a specified target yield were determined and compared with the costs per hectare of using recommended commercial fertilisers. The financial feasibility was determined using partial budgets. The income per hectare of using these products was determined and compared with that of the commercial fertilisers. Pot trials in a tunnel were also carried out to determine the agricultural-effectiveness of the products compared with the commercial fertilisers and crop growth parameter results analysed statistically using GenStat. The results showed that LaDePa, NUC and struvite are financially viable, if used in place of the organic fertiliser studied. Their net income (gross income less total calculated costs) per hectare was also higher compared with that of commercial fertilisers analysed. On the agronomic side, the products also proved to be very effective for crop growth and might be better than the assessed commercial fertilisers. On top of being a viable nutrient source, LaDePa is even more cost-effective if it is used as a soil amendment to improve soil physical properties. The use of NUC and struvite as nitrogen and phosphorus sources, respectively, was shown to be financially viable. If one is to add the environmental benefits of recycling waste products as fertilizers, the products will be even more economically viable. However, there is a need for more research on consumer acceptance of the agricultural goods produced this way.

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ACRONYMS

CSA –	Climate-Smart Agriculture
DAFF –	Department of Agriculture, Forestry and Fisheries
DEWATS –	Decentralised Wastewater Treatment System
EWS –	eThekwini Water and Sanitation
FAO –	Food and Agriculture Organisation
FERTASA –	Fertilizer Association of South Africa
GDP –	Gross Domestic Product
GROSSP –	Gromor Accelerator and Single Super Phosphate
H.I. –	Harvest Index
HEDM –	Human Excreta-Derived Materials
IWMI –	International Water Management Institute
LaDePa –	Latrine Dehydrated and Pasteurised (agricultural pellets)
LADSSP –	Latrine Dehydrated and Pasteurised pellets and Single Super Phosphate
LADSTR –	Latrine Dehydrated and Pasteurised pellets and struvite
LAN –	Lime Ammonium Nitrate
LANSSP –	Lime Ammonium Nitrate and Single Super Phosphate
LANSTR –	Lime Ammonium Nitrate and struvite
MAP –	Mono Ammonium Phosphate
N_2O –	Nitrous Oxide
NUC –	Nitrified Urine Concentrate
NUCSSP –	Nitrified Urine Concentrate and Single Super Phosphate

NUCSTR – Nitrified Urine Concentrate and struvite

NGO – Non-Governmental Organisations

PRG – Pollution Research Group

SBSA – Standard Bank of South Africa

SDG – Sustainable Development Goal

SSA – Sub-Saharan Africa

SSP – Single Super Phosphate

UDDT – Urine Diversion Dry Toilet

VIP – Ventilated Improved Pit latrine

VUNA – Valorisation of Urine and Nutrients in Africa

WHO – World Health Organisation (of the United Nations)

WTP – Willingness to Pay

CHAPTER 1 : INTRODUCTION

1.1. BACKGROUND

1.1.1. The state of sanitation provision, input use and crop production in Africa

Food security is one of the major concerns in the African continent because of low levels of food crop production (Yanggen et al., 1998). It may be achieved, when all the involved players participate at full capacity in their respective areas, especially agriculture. Sub-Saharan Africa (SSA) populations are continuously growing at a very fast rate of greater than 2% annually, more than any region in the world, which will likely see its population doubling or more by 2050 from what it was in the first century of the third millennium (Ezeh et al., 2012). This might also add pressure on governments to enhance food production, since most of the SSA countries are also considered poor and experience socio-economic and environmental problems. There is a need for improvement in agricultural productivity as most of the SSA population relies on farming for a living. To achieve this, proper and adequate levels of inputs should be mobilised to attain higher yields.

Subsistence farming using traditional methods with little or no technical advancement in use of improved seed or irrigation is common in SSA (Croppenstedt et al., 2003; Baiphethi and Jacobs, 2009). Moreover, the per-capita crop production in the SSA region is decreasing as a result of population increase and livestock volumes, which leads to high land strain and serious land degradation (Yanggen et al., 1998). These cultivation practices further contribute to deterioration, loss of fertility of the soil by nutrient mining [unreplenished removal by crops of soil nutrients, such as the basic nutrients, nitrogen (N), phosphorus (P) and potassium (K)] and continuously declining crop yields.

Nutrient mining across Africa ranges from 9 to 88 kg $(\text{hayear})^{-1}$ for nitrogen, phosphorus and potassium. The use of chemical fertilisers to replenish this loss for successful crop production in SSA is extremely low [8 - 12kg $(\text{hayear})^{-1}$ compared with 303 kg $(\text{hayear})^{-1}$ in East Asia and 107 kg (hayear) in North America) (Sommer et al., 2013). Organic nutrient sources, such as crop residues and animal excreta, are also not commonly used. Therefore, farmers in SSA, including South Africa, work hard to produce less and crop yields continue to decline. Sub-Saharan Africa is also overwhelmed by a multitude of diseases that have a negative impact on the level of some of the population's productivity levels due to ill-health. This also leads to poor physical and cognitive development which cause the households not to realise their productive potential, especially when physical work is required such as in agriculture. For all these reasons, some residents are highly food-insecure and undernourished, especially children (Liu et al., 2008).

The use of fertilisers enhances the productivity of crops, some of which, however, are getting scarce as in the case of phosphorus (Neset and Cordell, 2012). The world's phosphorus reserves are continuously depleting which could in future worsen the food shortages that SSA and the globe at large face, if alternative phosphorus sources are not discovered. Alternative means for phosphorus preservation such as higher consumption for plant-based foods and meats (such as cocoa, oysters, beef liver, cheese etc.) as substitutes of the ordinary dishes could result in less production of some crops which require more phosphorus and could help reduce the demand of phosphorus fertilisers thereby, extending the durability of the reserves.

This has resulted in the discovery of alternative sources of plant nutrients, rich in all basic nutrients for successful crop production, human excreta,, urine and faecal matter, that can be recycled to produce potentially-effective and nutrient-rich agricultural plant nutrient sources (Grau et al., 2012; Henderson and NewsRx, 2014). Urine is mainly rich in nitrogen and phosphorus, while faecal matter may also be processed into an organic plant nutrient source containing the basic crop nutrients, especially nitrogen (Karak and Bhattacharyya, 2011; Harrison and Wilson, 2012). A pilot programme was implemented in Durban, South Africa, to recover these nutrients, which saw successful nutrient recovery from human excreta, some in high concentrations, thereby making human excreta-derived materials (HEDM) potentially highly productive in agriculture.

Using waste in agriculture is not a new concept as different kinds of waste material such as animal excreta and crop residues, have been used as plant nutrient sources in agricultural fields since time immemorial as they contain nutrients that boost crop growth. However, most of the agricultural practices that use waste as fertiliser sources normally use them as supplements or additional material to other fertiliser sources (e.g. chemical) that they will be using in their fields. However, others use waste as their primary nutrient source, as most people, especially in the SSA region, cannot afford the chemical fertilisers, hence, they have to find alternative plant nutrient sources to boost crop productivity (Place et al., 2003).

Recycling of human excreta has also presented an opportunity of a better, effective and potentially cheaper way of waste management. Sanitation provision is highly important and is also an area of main focus on the United Nations' (UN) Sustainable Development Goals (SDGs) (Sachs, 2012). Less than 50% of the global population have proper sanitation and most of the populations without proper sanitation services are from developing countries (Mara, 2003). Sanitation provision in Durban, in KwaZulu-Natal, South Africa and its peri-urban communities has become a problem due to population increase. With the high urbanisation rate, water stress and scarcity and an increase to about 3.5 million residents who all require sanitation services, an increase in sanitation provision costs is also expected. The municipality is struggling to keep up with this demand (Roma et al., 2010).

The Durban Metro municipality [eThekwini Water and Sanitation (EWS)] is considering extending its existing sewerage network so as to serve thousands of new customers. However, due to the uneven topography in the service areas, the process becomes very expensive and also adds pressure on the existing treatment plants, as it implies that more chemicals, electrical energy and time will be needed for treating the increased waste volumes. This calls for the construction of more treatment plants, thereby increasing the currently high costs.

This chapter explores waste management systems together with economic and environmental implications associated with the creation and use of HEDMs. It also outlines the research problem and objectives and gives an outline of the study.

1.1.2. Waste management in the city and peri-urban areas of Durban

The most common waste management systems in urban areas, including in the EWS service areas, are the centralised waterborne sewerage networks that chemically treat wastes before they are disposed. However, this process incurs huge costs from the specialised chemicals and high amounts of electrical energy used to eliminate all infectious organisms and elements that lead to environmental degradation upon disposal. It is also evident that even after the treatment process, traces, mainly of phosphorus and nitrogen, will still be present in the final effluent to be disposed, as these elements are difficult to completely eliminate. Disposing such effluent is environmentally unfriendly and these nutrients, upon disposal, cause damage, such as environmental and groundwater contamination or may lead to eutrophication and possibly health threats to the public (Molinos-Senante et al., 2010; Uggetti et al., 2011).

Due to this main disadvantage posed by the centralised waterborne systems, alternative ways of disposing wastes have to be devised as the conventional way is unsustainable. This has led to a new approach and development of decentralised waste collection systems for sustainable waste disposal and potential reuse. Researchers have confirmed the presence of a wide range of nutrients in human wastes that can be captured and used for agricultural production, the reuse of hence, faecal sludge is highly important for sustainable development (Grau et al., 2012).

Instead of disposing of this valuable resource and contaminating the environment, human waste recycling is a viable and sustainable option as it also presents advantages such as business development and cheaper sanitation provision. Various institutions around the world focus on ways and means of waste disposal, but only a few concentrate on sustainable waste disposal, which calls for increased participation across the globe to achieve an advanced waste disposal solution. In KwaZulu-Natal province, the EWS unit in partnership with the University of KwaZulu-Natal's (UKZN) Pollution Research Group (PRG) is working towards achieving this sustainable waste disposal solution with the help and support of various local and international institutions.

Construction of decentralised sanitation facilities for waste management has since begun which includes the Decentralised Wastewater Treatment Systems (DEWATS) and the Dry (waterless) Toilets which have been established in Durban's urban and peri-urban communities, respectively, surrounding. The DEWATS is a small imitation of the normal sewer (waterborne) network, except that a smaller number of units (houses e.g. a hundred) will be interconnected to the same sewer network and have their own (normally smaller than the waterborne sewer treatment plant) treatment facility (Eales, 2010). A city can have as many DEWATS facilities as possible as they are cheaper and easier to construct compared with the conventional wastewater treatment facilities.

The DEWATS facility is preferable, because it is cost-effective as wastes will be treated without the use of specialised chemicals or electrical energy, but by the process of anaerobic respiration in treatment cells. The process of anaerobic respiration deactivates all pathogens contained in the wastes (Udert et al., 2003), such that the effluent will not have any infectious agents. Filtration and nutrient uptake from the effluent by plants before it can be disposed with accepted effluent standards are also used in the process (Robbins, 2011). The settled solid wastes at the bottom of this treatment system may be collected for safe disposal or can possibly be treated and used to develop organic plant nutrient sources.

The dry toilets on the other hand come in two types, namely, the Ventilated Improved Pit (VIP) latrines and the Urine Diversion Dry Toilets (UDDT) for effective faecal matter and urine collection, respectively, and are very efficient especially on saving water. These are reinvented toilets that collect all wastes in containers for recycling, also providing the user with comfort, space, enough air and light (Udert, 2015). Compared to the conventional toilet that uses about twelve litres of water on a normal flush, a dry toilet uses no or at most 500ml of water, hence saving water. Dry toilets are actually not new but are modified versions of old toilet systems that give an opportunity of easy and separate collection of raw solid and liquid wastes that can be used as inputs in waste fertiliser production.

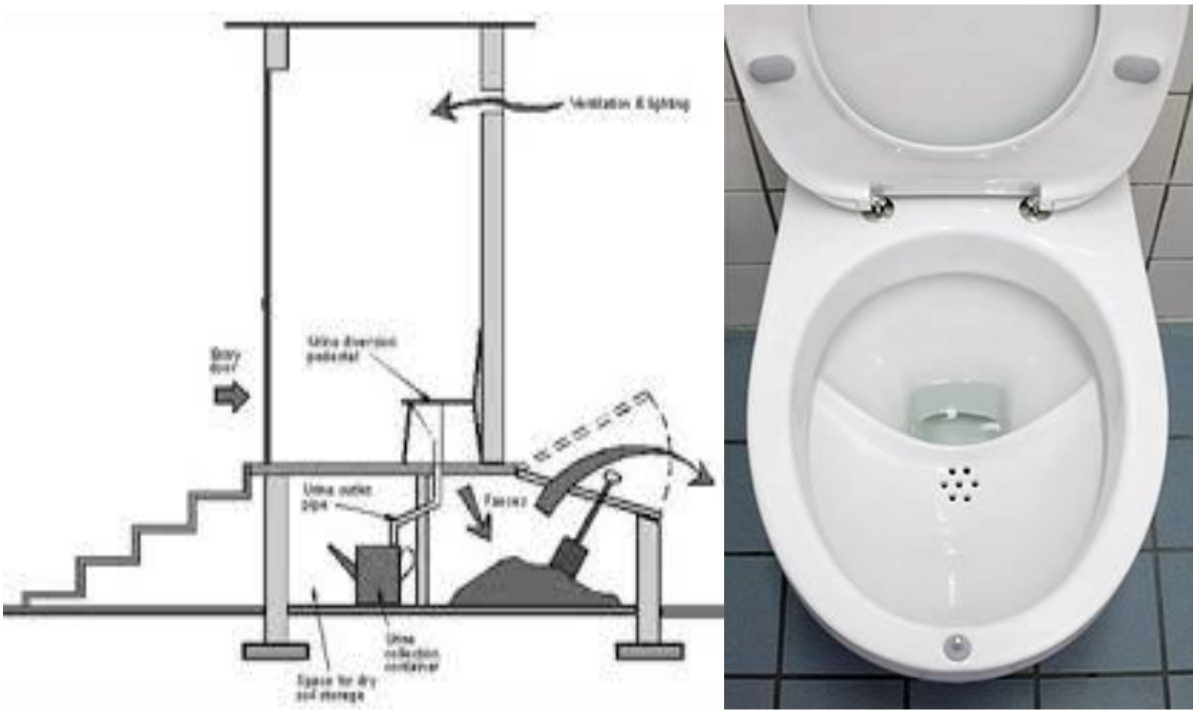


Figure 1.1. Dry toilets; the VIP latrine on the left and the UDDT on the right

Installing these units for each household reduces the costs of expansion of the existing sewer lines for the municipality and also gives the advantage of potential fertiliser production. However, after assessing the socio-economic factors regarding the use of the UDDTs, there were various issues concerning the use of these toilets as the social acceptance levels among the user households was low (Odindo et al., 2018). This has led to the conduct of hygiene and health campaigns to encourage the use of these toilets by Durban social workers.

Through sanitation provision initiatives, such as the Valorisation of Urine and Nutrients in Africa (VUNA) Project in Durban, about 82, 000 UDDT units have been constructed in peri-urban Durban by the municipality which has mobilised collection teams for empting and transporting the waste products to processing plants (Udert, 2015). The VUNA Project has seen developments in the extraction of the necessary agricultural nutrients from urine, which is normally disposed as a waste product. Urine conversion technologies were developed for easier extraction of nutrients in the urine, also at higher extraction rates. Efficient health service provision is one of the government's main focus, as health provision is part of the sustainable development goals (SDGs). Dry sanitation provides a very cost-effective way of providing health services through sanitation provision to the communities, reducing water use and also reducing the tremendous challenge of waste disposal.

This sustainable waste disposal way of converting waste into useable products and development is an advantage as nutrients that were disposed into the landfills and rivers will now be retained for useful and productive purposes. This paradigm shows development and improvements of previously proper sanitation-lacking households, which can continuously be developed to meet top urban and largely favoured sanitation standards across the nation. Human Excreta Derived Materials are potentially low cost fertilisers which may also be readily accessible to all consumers, which may boost their yields, providing a potentially new means of agricultural inputs that can be used in alleviating the food security problem.

1.1.3. Human excreta-derived materials

The lower rate of fertiliser use in SSA is mainly because of their high costs, which will lead to lower yields. A solution to this could be fertiliser subsidies from the SSA governments or making available alternative low cost fertilisers which are accessible to all farmers at all times (Crawford et al., 2006). Human excreta-derived materials, alternative plant nutrient sources, present a chance of improvement of the SSA agriculture in terms of yields and low production costs, and can replace or complement the existing commercial fertilisers (Grau et al., 2012). These plant nutrient sources can be made available as they are produced from readily available wastes. They might be always available in the needed quantities, even during the peak and off peak farming seasons with low and stable market prices, if participation in the waste material collection process increases.

On average, a human being produces about two litres of urine a day and 58 (fifty eight) million people (South Africa) will, therefore, be able to produce about a 116 (hundred and sixteen) million litres of urine a day. If about five percent of this can be recovered as dry solid fertiliser (1 litre of urine ≈ 0.05kg of struvite/NUC), hence, in a year the population will produce more than two million kilogrammes of struvite or about two million litres of NUC fertiliser which is more than enough to support South Africa's agricultural activities (East Coast Organics, 2015). This means that the social acceptance and household participation by increased use of designed toilets is essential in up-scaling these projects. If the world would adopt the dry sanitation systems, costs (environmental, water, energy) will be saved and food production could be increased even by subsistence farmers as they are potentially cheaper than chemical fertilisers.

The urine collected from the UDDTs is manufactured into two main products, namely, Nitrified Urine Concentrate (NUC), a highly concentrated nitrogen source (21%N) (Udert and Wächter, 2012) and struvite, a highly concentrated phosphorus source (12.6%P) (Rhoton et al., 2014) which are developed using different production processes as they are sources of different plant nutrients. Wastes collected from the VIP latrines can be processed into an organic fertiliser, Latrine Dehydrated and Pasteurised (LaDePa) agricultural pellets, that contain mainly nitrogen and may potentially be a good soil amelioration product (Harrison and Wilson, 2012). Nitrified Urine Concentrate is an immediate release nutrient source while struvite and LaDePa are slow release fertilisers.

Nitrified Urine Concentrate is an inorganic and liquid plant nutrient source of high nitrogen concentration, (a basic and crucial nutrient required for plant growth) which is expected to be very effective in crop production as well as being highly competent among the existing commercial fertilisers as it might have higher demand compared to the existing chemical fertilisers. It can be directly used as a nitrogen source or can be used to manufacture (blend) other fertiliser products (Udert, 2015). The manufacture of NUC starts with the collection of urine from the UDDTs to transportation and storage, before it is processed by specialised machinery to produce the final product. This involves several stages from complete nutrient recovery, nitrification, distillation and electrolysis for concentrating and purifying the initial product (Udert et al., 2014).

After the complete nutrient recovery stage, all nutrients contained in urine will be retained in the product, though it will be richer in nitrogen. The electrolysis process is, however, time and energy-consuming, though it produces a very rich plant nutrient source after the removal of unwanted impurities. However, the concentration of nitrogen in the product may differ, depending on the type and quality of urine used in its manufacture. Concentration of nutrients in urine will depend on the health and diet of the individuals, with healthy or consumers of nitrogen-rich diets producing concentrated NUC than otherwise (Udert and Wächter, 2012). The produced substance is, however, stable and can be used as a plant nutrient source, as it meets the standards of the requirements for fertiliser. For quality control, however, NUC has to be kept under the recommended conditions (dry places with temperatures under 40^{o}C) so as to avoid nitrogen losses, especially to the environment.

Struvite, on the other hand, is a highly concentrated, solid, phosphorus containing inorganic plant nutrient source. Since the world is about to face a phosphorus crisis, struvite can act as a phosphorus replacement, as it is a very rich phosphorus source. The struvite production process begins with urine collection from the households, transportation and its storage for a short period at the site in storage tanks. During this storage time, most of the infectious agents contained in the urine will be destroyed through urea hydrolysis such that it poses no health threats to end users (Grau et al., 2013). To produce struvite, a magnesium oxide dose which is proportional to the concentration of the stored urine is added to the urine to produce a phosphorus precipitate that will be dried to become struvite.

Though the struvite manufacturing process eliminates most of the pathogens, it, however, does not remove the concentrates of other nutrients contained in the urine or the pharmaceuticals (drug traces contained in urine) contained in the urine. Unlike in the production of NUC, where all nutrients are retained in the production of the plant nutrient source, struvite mainly contains phosphorus and nitrogen and also magnesium, calcium and potassium with the rest of the nutrients and pathogens being lost in the effluent.

Once filled, the VIP toilets are emptied by a professional team and the sludge will be transported to the processing facilities. To produce LaDePa, the collected and stored sludge undergoes high temperature drying that disinfects it from all pathogens, before it is developed into pellets. This process also eliminates ‘bad smells’ to produce a ‘smell-free’ product (Harrison and Wilson, 2012). The resulting pellets are rich in three major nutrients, mainly nitrogen, with phosphorus and potassium in lower concentrations. Though not thoroughly tested, LaDePa has the potential of restoring soil fertility if used as a soil amendment product due to its organic nature (East Coast Organics, 2015).

The process of making nitrogen-based fertilisers is normally complicated and requires special skills and technologies, which may be a reason for the products' higher prices. Phosphorus also needs to be extracted from the earth as phosphorus ores (e.g. phosphoric anhydride), before it is processed into fertilisers. Currently, the main challenge is the rising scarcity of the ores which may end up raising the prices of phosphorus fertilisers due to the high demand. Provided that all the issues are addressed along the value chain, HEDMs may be the ultimate solution to the problems.

Production of these plant nutrient sources also lies on the availability of waste material which is also dependent on the frequent use of the toilets by residents. Social acceptance of these types of toilets and the reinvented sanitation system is a vital issue as some residents still favour the waterborne sanitation systems compared with the waterless systems (Gounden et al., 2006); hence, societies have to be educated. Frequent use of the dry toilets implies that large quantities of waste will be collected and more fertilisers can be produced. Collection of these wastes is also a crucial step in the production process hence proper, effective and cost-effective waste collection methods have to be devised. This will eventually reduce their market price due to economies of scale and size.

1.2. RESEARCH PROBLEM

Proper sanitation is one of the basic needs for humanity as it creates a healthy and risk-free world; however, more than half of the global population does not have access to proper sanitation (Roma et al., 2010). Most developing countries, especially in SSA, have poor or no sanitation facilities for their populations and the majority of these people are rural communities. Though the urban sanitation systems are better than those in the rural areas, some of the facilities are poor and there is inefficient service delivery by the responsible authorities which puts the population at a high health risk.

The population rise in the eThekwini municipal area in Durban, South Africa, and the rising demand for sanitation amenities (both in the urban and peri-urban areas) by about 200, 000 new clients (households) since the early 2000s, has continuously increased pressure on the municipality to expand and improve services (Friedrich et al., 2009). However, the EWS has forecast high sanitation delivery costs for both the existing and new customers through maintenance and extension of the existing sewerage facilities and decided to take a new cost-effective route of service provision.

Construction of UDDTs could provide the customers with good and a possibly cheaper sanitation solution. However, waste disposal in these UDDTs has remained a challenge as these collected wastes have to be emptied and wastes treated. It has been observed that these wastes can sustainability be converted and developed into usable agricultural waste products (HEDMs) that can be used as agricultural fertiliser. However, this innovative idea of waste disposal and its benefits have not yet been fully explored to determine their agricultural and economic values.

Human excreta-derived materials have a high agricultural potential as their nutritional concentrations are comparable with those of the existing commercial fertilisers which makes them potentially competitive. The prediction is that they will fetch a lower market price, which will reduce farming production costs. Creation of the urine-based fertiliser struvite comes as a relief to the threats posed on agriculture by the depleting phosphorus reserves. Phosphorus is mined from the phosphate rocks as phosphate ores, with most phosphate used for agricultural purposes and the remaining for other industrial purposes (Smit et al., 2010). Through industrial processes, pure and compound phosphorous plant nutrient sources are produced for agricultural purposes. However, after being supplied to the plants and having been consumed by humans or animals, phosphorus is then lost in the form of excreted waste, most of it being passed out as urine. These wastes are finally disposed after treatment, thereby, the phosphorus lost in this continuing process.

From an economic viewpoint, the financial benefits of using HEDMs for agricultural production have not been fully analysed yet. They need to be evaluated so as to determine their competitiveness against the existing commercial fertilisers. These can be quantified in terms of the costs saved from using the new plant nutrient sources in place of the existing, widely used commercial fertilisers (Pimentel et al., 2005). They can also be quantified in terms of the yields produced from using these fertilisers in crop production. With the HEDMs' nutrient composition and their market prices, they might potentially be cheaper to use compared with the relatively expensive commercial fertilisers. Field experiments are also necessary to prove their ability as competitive plant nutrient sources which may be used with or to replace the existing plant nutrient sources.

Disposing wastes through the formation of HEDMs is a viable and sustainable option which should be thoroughly analysed, as this channel produces valuable inputs and also conserves the environment from the disposed contaminating effluent (Mnkeni and Austin, 2009). All costs of addressing environmental problems and waste treatment are normally met by the taxpayers and high household bill payments to the municipalities. With the development of HEDM and reduction of effluent pollution and treatment costs, the environmental costs together with the household bills will be reduced. With this view, it is necessary to analyse the viability of using HEDMs in agriculture as this will provide potentially low cost and effective inputs and also provide a cheaper sanitation option. This study analyses the usefulness of HEDMs in terms of production costs and fertiliser value in South Africa.

1.3. RESEARCH OBJECTIVES

The aim of this study is to assess the financial and agronomic viability of the HEDMs (LaDePa, struvite and NUC) in relation to the existing commercial fertilisers that are normally used in South Africa for maize production. This study focuses on two aspects: firstly, the empirical cost estimations, cost-effectiveness and income generated when using HEDMs as fertilisers and, secondly, field experiments to investigate if HEDMs are agronomically competitive in terms of crop production by analysing the crop growth parameters of plants grown using HEDMs. This will be achieved by performing a financial assessment to evaluate the cost-effectiveness of HEDMs in crop production and compare them with the common commercial fertilisers and investigate through growing crop trials of both HEDMs and commercial fertilisers as sources of crop nutrients, to assess their agronomic value. This will be done through the following specific objectives;

1. To compare the cost per hectare of using HEDMs in contrast to using commercial fertilisers for maize production and performing both, a total fertiliser costs per hectare comparison and the cost-effectiveness of using HEDMs in contrast to commercial fertilisers
2. To analyse growth parameters, including plant height, leaf number, above-ground biomass and seed yield of crops developed with HEDMs compared with commercial fertilisers in a maize pot experiment and determining the HEDMs' agronomic-effectiveness in crop production by comparing plants grown with HEDMs versus those grown with commercial fertilisers.

1.4. STUDY OVERVIEW AND EXPECTED OUTCOMES

The main focus of this project was to perform an economic and agronomic assessment of using HEDMs in agriculture which will be achieved through following the objectives listed in the previous section. This study also aims to promote the use of the reinvented toilets thereby assigning value to wastes, recovering the nutrients contained therein and developing valuable fertilisers also addressing environmental protection issues. This study consists of five chapters. Chapter one, the introductory chapter has given a clear picture to the reader and a broad overview of what the study is about, the research question and the objectives. This is followed by a literature review chapter (Chapter 2) which reviews similar previous work that has been done on this subject and how it relates to this study.

Chapter three focuses on the economic evaluation of using the different fertiliser types, including HEDMs using economic assessment tools such as partial budgeting. This financial analysis will inform of the advantages or disadvantages and profitability to farmers of using HEDMs compared to commercial fertilisers. It will also inform potential investors who can venture into the HEDM value chain business. This chapter contributes to the work on this project, as the farmer normally focuses on the financial aspect of a move before its implementation. This is then followed by a chapter which analyses the agronomic value of the HEDMs (Chapter 4). This was achieved by measuring growth parameters, including above-ground biomass and seed yield of all the assessed maize plants and making a comparison between the types of fertilisers used. Finally, chapter 5 presents the conclusions, implications for policy and future research directions.

HEDMs are expected to have lower production costs than common, commercial fertilisers that will be assessed in this study, ad are expected to be cost-effective and financially viable. In analysing the profitability and the performance of the HEDMs on the market, several factors such as production costs and yields produced have to be assessed. These include the cost competitiveness of the final product as most farmers or any end-users considers the product prices before purchasing them. The cost per unit of the final product is determined from the sum of the average collection, transportation and treatment costs. Currently, it is just presumed that these will be low cost products which will reduce total production costs.

Market demand of these products will also depend on their nutrient composition as this determines the fertiliser quantity that will have to be applied. Both NUC and struvite have high nutrient compositions, such that their demand is expected to be the same as or more than that of the existing commercial plant nutrient sources. However, LaDePa has low nutrient concentrations but is comparable to other commercial, organic fertilisers. It can, potentially prove to be a very useful and powerful plant nutrient source, if its organic benefits are considered. HEDMs are expected to produce the same or better, healthier plants with higher biomasses and yields as those that are produced by commercial fertilisers.

CHAPTER 2 : LITERATURE REVIEW

2.1. INTRODUCTION

Poor service delivery, resource or capacity constraints and population increase are among the causes of the unacceptable poor sanitation services provision in SSA. With the rising population in SSA, there are increasing calls for improvements in the level of service delivery so as to match the rising demands of the services (Ezeh et al., 2012). Through urbanisation, governments are slowly upgrading rural communities into towns, which will require sanitation service delivery. However, the rate at which these services are being supplied is slow, probably because of the high expenses related to the move. Similarly, this is being experienced in South. An increase in SSA's population is evident, as is also the case in Durban, where a rise to about 3.5 million customers require standard municipal sanitation services (Roma et al., 2010). This expanding urban and peri-urban population has placed a huge burden of sanitation provision on the eThekwini municipality which is currently servicing less than half of this population (Udert, 2015).

The eThekwini Water and Sanitation (EWS) division is providing waterborne sanitation services only to 47% of the population in its service area seemingly struggling to meet their customers' needs. These concerns drive municipalities to think of alternative, cost-effective ways of sanitation provision as the conventional ways are costly, more so in the short term. The EWS' studies on the impact of increasing the water and sanitation facilities on the environment showed that with a population increase of about 200 000 new customers from the early 2000s who require sanitation services, the municipality would have to consider various options, such as enhancing the capacity of the existing sanitation facilities, water recycling and construction of new infrastructure (Friedrich et al., 2009).

There is evidence of several low standard informal urban settlements which, in most cases, do not have power, water and sanitation facilities, making the environment unhealthy for the entire population. A survey on government-subsidised low-cost housing communities in Cape Town, South Africa, showed that most of the houses had at least one informal dwelling at the backyard which did not have any or had only poor sanitation facilities (Govender et al., 2011). Only 42% of the toilets were working, which may be a health hazard and/or pose risks of disease outbreaks (Mels et al., 2009). However, due to the bad topography in the area and long distances from the location of these informal settlements to the existing sewerage networks (main sewer lines), providing better sanitation facilities is difficult and expensive.

Though the conventional centralised sewer, waterborne sanitation systems are a good means of waste containment, transportation, treatment and final disposal, the costs, in terms of infrastructure construction and maintenance, can be expensive and unsustainable (Dominguez and Gujer, 2006). In addition, the process involves higher costs due to the high amounts of electrical energy and specialised chemicals which are required during waste treatment. This places huge costs on those the services are being provided to, which can be relatively high for some, especially low income households.

In a study by Spångberg et al. (2014) on the environmental impact of recycling nutrients in human excreta for agricultural use, it was observed that wastewater treatment plants have high demands of energy and chemicals for use to remove nitrogen and phosphorus, as these nutrients can lead to eutrophication and soil acidification. The authors also discovered that plant nutrient sources in recycled wastewater released high levels of ammonia; hence, further research needs to capture the full benefits of using wastewater as an agricultural plant nutrient source.

Another challenge faced with the waterborne sewer systems arises from the final disposal of the treated effluent, as it normally contains traces of nitrogen and phosphorus, as the treatment process as treatment cannot totally eliminate these elements. When disposed into either rivers or landfills, these elements cause groundwater contamination, algal growth and eutrophication of rivers, as nitrogen enhances crop growth (Molinos-Senante et al., 2010). Addressing the negative effects resulting from environmental pollution is costly, a burden that taxpayers have to bear. Quantifying the levels of environmental damage, however, remains a tremendous challenge though informal ways of quantifying these have been developed (NewsRx, 2014).

Decentralised sanitation facilities may be the solution to this problem, as they are less expensive to install and maintain. This solution can improve the sanitation provision services, even in areas of topographies where the centralised waterborne systems will be less efficient. This has seen the development of about 82, 000 waterless toilet units in the peri-urban areas of Durban by the EWS. These have an advantage that they can be installed at any place regardless of how uneven the topography is and it ensures proper and accessible sanitation to the population.

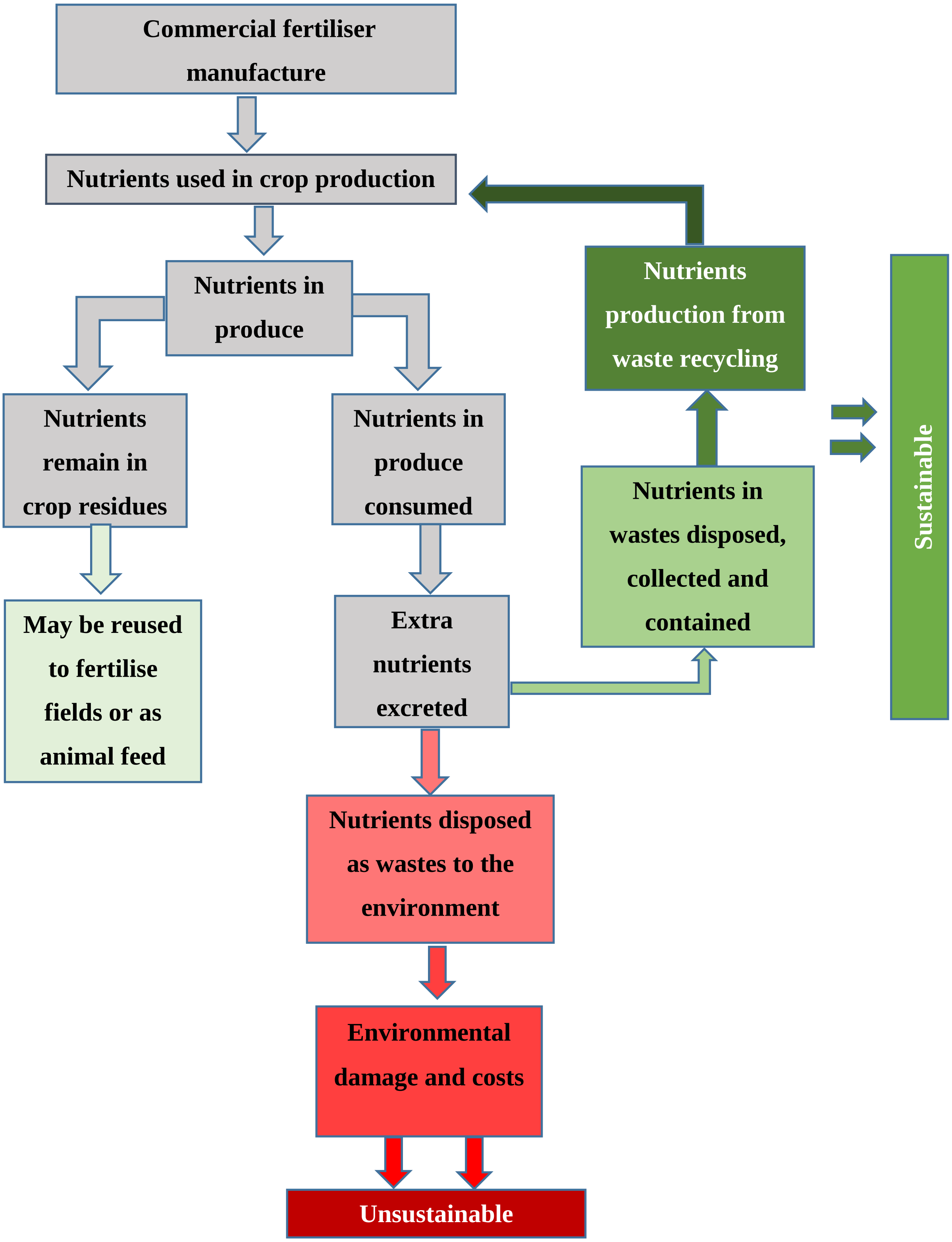
In some peri-urban and rural areas, the majority of the ablution facilities dispose wastes straight into the ground which might result in environmental problems, as all soluble materials infiltrate into the ground (Udert, 2015). The VIP latrines and the UDDTs are, however, serviceable and have the ability to effectively contain wastes and can be emptied when they are full, making their use sustainable as they can be reused and also provide useful inputs. The government of South Africa has also set the dry toilet as the minimum standard sanitation unit that any household should at least have (Harrison and Wilson, 2012). This means that the old dry toilet systems are being reinvented so as to avoid wastes contaminating the environment.

With this background, this chapter examines a potentially sustainable way of waste disposal through converting human wastes into usable agricultural products. This may also be a solution to sanitation provision challenges that many municipalities are facing, through the provision of low costs dry sanitation systems. These excreta-derived products may be used to replace or supplement the existing commercial fertilisers, if they prove to be economic and agronomically effective plant nutrient sources and may also reduce environmental contamination from disposed wastewater. This chapter will explore HEDMs' production and their potential to be cost-effective plant nutrient sources, fertiliser use in SSA, the global phosphorus challenge, the South African fertiliser market and aspects associated with climate change and food security.

2.2. HUMAN EXCRETA-DERIVED MATERIAL PRODUCTION

Conversion of waste products into fertiliser material is now a worldwide phenomenon, also increasingly accepted across Africa (IWMI, 2014). Most of the nutrients contained in the consumed food and feed around the world are lost as wastes which implies that there will be continued and unsustainable mining and extraction of these nutrients only to be lost as wastes (see Figure 2.1). This has resulted in the invention and development of technical solutions to restore these valuable nutrients, including the soon to be scarce phosphorus from the wastes that are usually disposed. This is a sustainable way of waste disposal and a potential solution to the problem of low agricultural productivity across Africa due to inaccessible fertilisers and potential phosphorus scarcity (Crawford et al., 2006; Neset and Cordell, 2012).

Human excreta-derived materials are potentially low cost plant nutrient sources produced in a sustainable and cost-effective way. This means that the products may be inexpensive on the fertiliser market which will reduce farming costs. Production of plant nutrient sources in SSA has largely been done industrially through energy-consuming processes, producing expensive materials. Even though Africa produces plant nutrient sources, the level of fertiliser production is still low as it does not meet the agricultural market requirements, which is another fact why there is fertiliser unavailability and low levels of crop production (Dawson and Hilton, 2011). The unsustainable (from fertiliser development until nutrients are lost) and sustainable (HEDMs production that recycles nutrients to keep them in the system) nutrient cycles are shown in Figure 2.1.



Source: Author's compilation

Figure 2.1. Flowchart of sustainable and unsustainable waste disposal from fertiliser manufacture up to reuse or disposal

Farmers in the SSA region, among other problems, have nutrient-poor soils (Yanggen et al., 1998). Due to this, nutrient mining is very common in the SSA region which leads to continuously falling yields, if the problem is not addressed. There is substantial loss of the topsoil from erosion as a result of lack of groundcover which is caused by, among other activities, overgrazing. Organic fertilisers can amend these soils and restore their fertility by increasing the organic matter, soil microbes and topsoil, making soils fertile and better able to retain soil moisture (Dubeux and B., 2005). There is, however, little and in some instances, no use of organic matter to ameliorate these soils.

Of all the 82, 000 units that were installed by the EWS, about 64, 350 units were properly working with the others being broken (probably from misuse or vandalism) on some parts of their infrastructure (Udert, 2015). These units also corresponded to the number of the households who were presumed to be part of the project, though their participation level varied from 20% to 80% producing from about five to twenty litres of urine a week per participating household. The local collection teams were composed of the supervisors, drivers, labourers and community liaison officers. The urine treatment reactors were processing about 120 cubic metres of urine per day.

Challenges, such as decreasing level of participation of households, were encountered in the project with a drop from producing on average about 16.7 litres to about 6.5 litres per week. There was also a challenge that the collected urine samples showed differences which may result in fertilisers of different composition. From the experience gained by the social workers and the management teams, improvements in collection times and the collection efficiency decreased the collection costs.

Despite these processes from urine collection, transportation, storage and manufacture that are gone through in the production of the HEDMs, the process could be cost-effective, if the production costs are smaller than the profits that the fertilisers will fetch on the market and, if their effectiveness as agricultural fertilisers compares to that of the common, commercial fertilisers. Furthermore, other benefits like reduction in the level of fertiliser imports relate to the costs saved through the creation and use of HEDMs. Other European countries, such as Switzerland, have managed to create and market human urine-based fertilisers successfully which has given them alternative nitrogen and phosphorus sources (Bonvin et al., 2015).

Though sewage sludge can be used to fertilise field crops or can be converted into valuable fertiliser products, it has been listed as a microbial contaminant under the Environmental

Management Act of South Africa[1]. However, LaDePa, struvite and NUC can be appropriately handled as required, which also meets the standards of the Waste Management Act of South Africa[2]. This is done to ensure that the end-product may not be harmful to either the end user (farmer) or the consumer of the foods produced using these plant nutrient sources.

From Figure 2.2, it can be deducted that the majority of the nutrients contained in wastes are found urine which gives it the capability to produce concentrated plant nutrient sources with a wide range of nutrients (Spångberg, 2014; Udert, 2015). It is mostly made up of water (about 99%) and contains all the three basic macro-nutrients and several other including calcium, magnesium and sulphur. Other nutrients present in urine include iron, manganese, boron, molybdenum, copper and zinc. It also contains bulk organics (organic materials that makeup constituents of urine) that causes its smell, sodium chloride, micro-pollutants (contaminants that are not highly toxic) and several pathogens (Etter, 2015). Sulphur, followed by nitrogen and potassium, is the dominant nutrient contained in urine, which is the reason why NUC contain high amounts of nitrogen and struvite is also a good phosphorus source.

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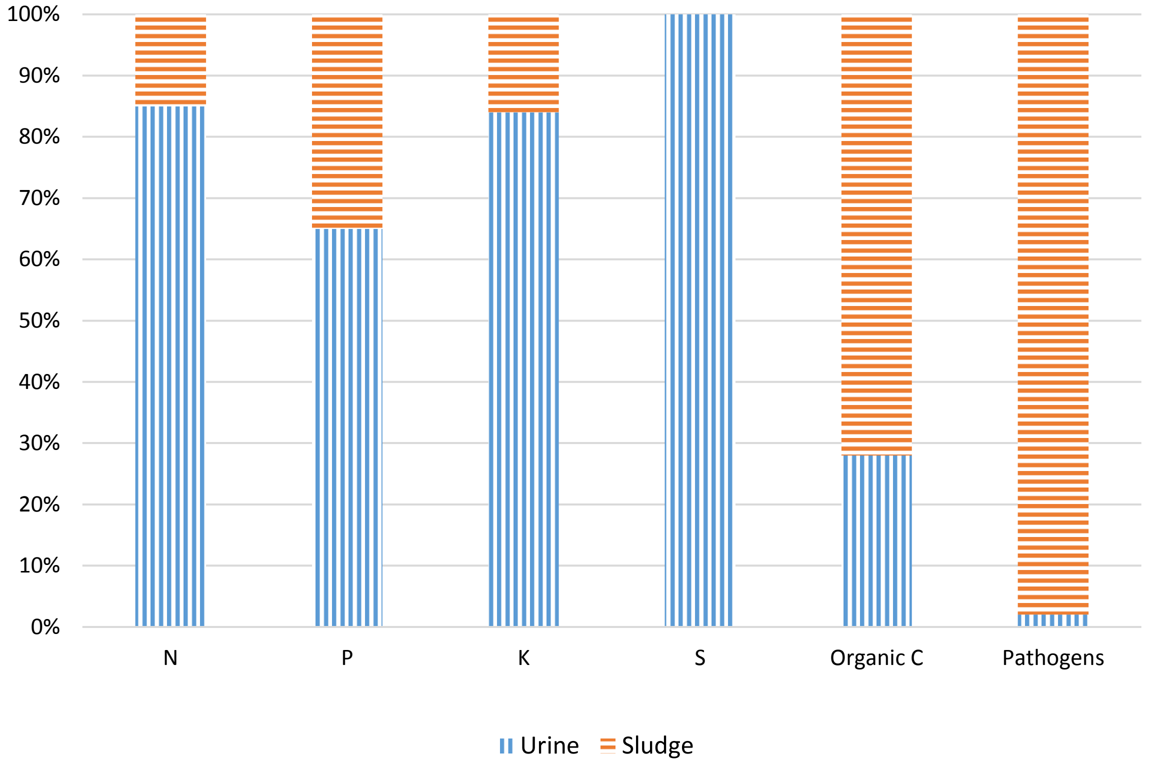
[1] https://www.environment.gov.za/sites/default/files/legislations/nema_amendment_act59.pdf

[2] https://www.environment.gov.za/sites/default/files/legislations/nemwa_actno26of2014.pdf



Source: Udert (2015)

Figure 2.2. Total nutrient amounts in excreta

Urine in many cases, however, also contains pharmaceuticals, as most of these are excreted through urine. These compounds might affect the quality of the end-products (Decrey et al., 2015). Most of the pathogens in the source-separated urine result from cross-contamination (accidental mixing of liquid and solid wastes) and have to be removed to ensure safe use of the final product. All macro and micro-nutrients are retained, but pathogens, most water, sodium chloride and micro-pollutants are removed from the solution to obtain a nutrient-concentrated solution during the nutrient recovery process of the NUC production steps. This process is takes some time and involves nitrification, distillation and electrolysis of the urine.

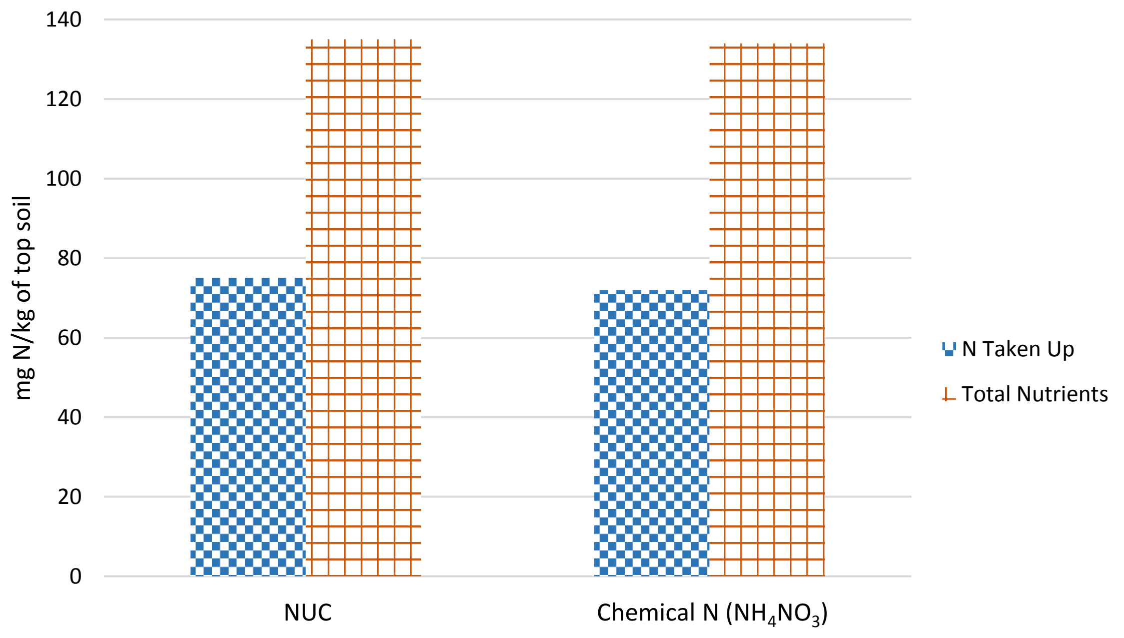
Most water is lost during the distillation process to remain with a nutrient-concentrated solution. The bacteria contained in the urine are also destroyed during the storage and distillation processes. This is followed by the nitrification process which concentrates the nitrogen by using specialised machinery and also retains all the nutrients contained in the urine. The electrolysis stage removes the remaining bulk organics, sodium chloride and the micro-pollutants but is a high energy-consuming process which might have cost-adding effect and may raise the price of the end product. An alternative way or power source, such as the use of natural/solar power, might be used for this process to reduce the energy costs. After processing, the final product will mainly (be concentrated in) contain nitrogen of about 18% - 23%.

Sludge, on the other hand, contains more organic carbon as compared with urine, which makes it a good organic substance that ameliorate soils, improving soil structure, tilth and fertility (Figure 2.2). Its levels of N, P and K are lower than those of urine, hence, it produces less-concentrated fertiliser. It, however, contains the majority of the pathogens contained in the wastes (about 98%) and there is need for effective treatment to make the fertiliser safe for use and making sure that no pathogens are passed into the product produced from the nutrient source. Sludge also contains water, though it is not in high amounts and is removed during the LaDePa making process during the preheating stage. Harrison and Wilson (2012) described this process as "easy to work with" as it could be done easily because it is not complex.

During the preheating stage, sludge is heated at about 70^{o}C for about 48 – 72 hours, which deactivates all the pathogens contained in the sludge, making the products safe to use. After this step, the final product can be moulded into pellets. If properly implemented, the LaDePa recovery process can offset the collection and treatment costs, which may also be less than the costs of waste processing at a centralised treatment facilities. This may also decrease the public service costs due to a low cost and sustainable way of waste disposal.

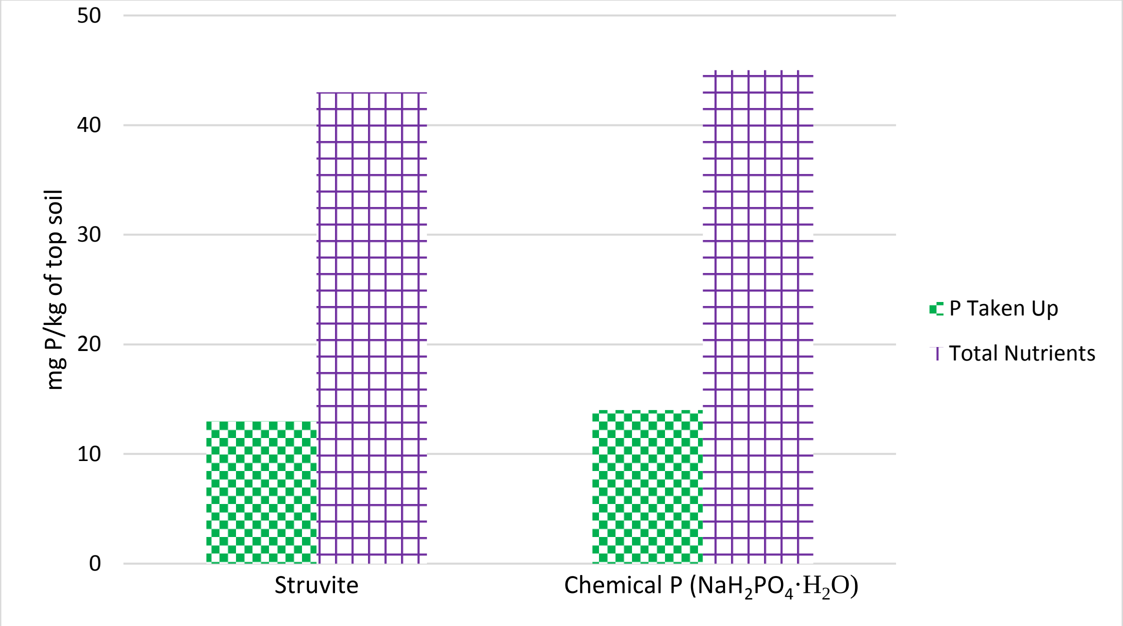
During the struvite production process, nitrogen, phosphorus, magnesium and calcium are retained, while the other urine constituents such as organic compounds, salts, hormones, metabolites etc. are lost. The storage, processing, drying and the filtration of the urine steps will deactivate infectious micro-organisms. Though drying temperatures of above 40^{o}C are effective for destroying pathogens, struvite might face partial decomposition at higher temperatures than 40^{o}C (Decrey et al., 2015). Also, the effluent from struvite should be cautiously handled as it is untreated and contains infectious organisms. These HEDMs, especially NUC, can be used directly as a fertiliser or can be mixed with other products to produce compound fertilisers. Just the same as the commercial fertilisers, proper application at the recommended rates is also required in HEDMs, as over-application may lead to volatilisation and/or leaching which may have negative environmental effects, and under-application may lead to sub-standard yields.

Effectiveness of NUC and struvite after field application in respect of nitrogen and phosphorus uptake by plants, is comparable to that of the chemical fertilisers. This has been proved in a study which showed that nitrogen from NUC is even absorbed slightly more by the plants than the nitrogen from commercial, chemical fertilisers (Figure 2.3) (Bonvin et al., 2015). This might be so because of the liquid and fast-release nature of NUC which makes it more soluble and absorbed quickly by the plants. From Figure 2.4 it can be deducted that the rate of phosphorus absorption from struvite in relation to the total available nutrients is almost similar to that of commercial fertilisers (Meyer et al., 2014; Bonvin et al., 2015). These facts alone prove necessary conditions for competitiveness of HEDMs as agricultural fertilisers and it can be presumed, that they are very effective in plant growth.



Source: Bonvin et al., 2015

Figure 2.3. Plant nitrogen uptake from Nitrified Urine Concentrate (NUC) in comparison with ammonium nitrate



Source: Bonvin et al., 2015

Figure 2.4. Plant phosphorus uptake from struvite in comparison monosodium phosphate

As these fertilisers have agronomic potential, a strategy may be devised to enhance their adoption in agriculture. Marketing strategies and technologies to decrease production costs may also be employed to effectively to enhance their adoption. The HEDMs must be able to release nutrients and make them available at critical stages of crop growth and development. Awareness campaigns have to be conducted to remove the potential stigma and negative perceptions related to the reuse of human waste in agriculture. This will also help in attracting more consumers of foods produced with HEDMs. If consumers are willing to purchase output produced with these HEDMs, their growth in the fertiliser industry will be accelerated.

2.3. AGRICULTURE AND THE PHOSPHORUS CHALLENGE

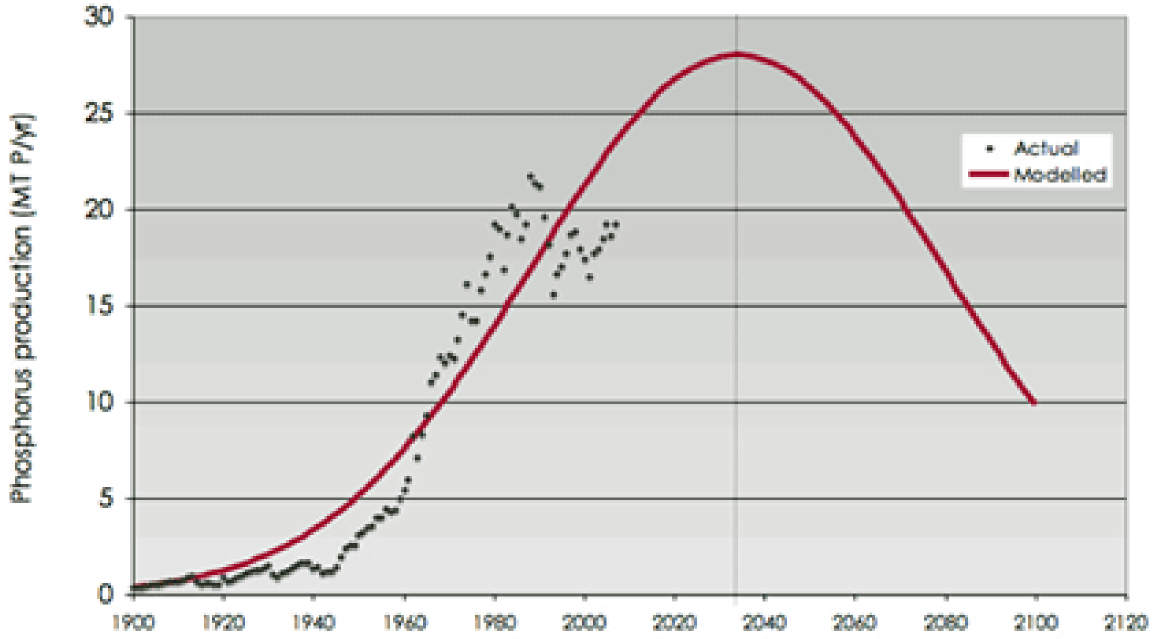
Phosphorus is a major nutrient needed by crops for growth and development. Good crop establishment is needed for healthy growth which may lead to high yields, if all crop requirements are provided. Most of the phosphorus that is used for plant growth is derived from phosphorus rock deposits as ores. These are located in certain regions of the world, with Africa mining phosphate ores in Algeria, Egypt, Morocco, Togo, Tunisia, Senegal, Angola and South Africa (Dawson and Hilton, 2011). South Africa, however, has little phosphate deposits which is also the case in some countries of the SSA region.

Production of phosphorus-containing fertilisers from phosphate rock begins with addition of sulphuric acid to the mined rocks to produce phosphoric acid. Addition of ammonia to the phosphoric acid produces the final products such as di-ammonium phosphate, mono-ammonium phosphate, single *superphosphate,* triple *superphosphate and various other phosphates (DAFF, 2015).*

The world generally has low amounts of phosphorus rock deposits which are being depleted unsustainably, i.e., the rate at which they naturally form is slower than the rate at which they are mined. Globally, about nineteen million tonnes of phosphorus are produced annually. Most of the globally extracted phosphorus (about 85%) is reserved for agronomic purposes to produce edibles, either for human or animal consumption, with the remaining being used for other industrial purposes and other needs (Neset and Cordell, 2012). All this phosphorus is, however, lost in different ways with about 18.5 million metric tonnes being lost as solid wastes in the soil and through soil erosion and about 1.32 million tonnes being discharged in the air and water (Villalba et al., 2008). Phosphorus is also lost in human and animal wastes after excreting phosphorus-rich foods or feeds (Meyer et al., 2014).

Measures of sustainability have now been called for as a result of the anticipated phosphorus scarcity that the world is about to face which will lead to a scarcity of phosphorus-based plant nutrient sources. Phosphorus depletion is a major concern, as it has no alternative sources, as compared to nitrogen, which can be directly fixed in the soil by nitrogen fixing bacteria, lightning or other means as it is abundant in the atmosphere. Phosphorus has no other means of getting into the soil except through physical human application, which makes it a limiting nutrient. Whereas the rate of recycling of nitrogen can be measured in years or centuries, the phosphorus recycling rate is very slow and can be measured per millennia (Dawson and Hilton, 2011).

It is predicted that most of the remaining world's phosphorus reserves will be depleted in the 21st century (Figure 2.5). The rate at which rock phosphates are harvested is on the rise and it is predicted to reach peak around the mid-2030s (Cordell et al., 2009). Over the second half of the 21st century, the level of phosphate rock mining, which is currently the main agricultural phosphorus source, will continue to decline until phosphorus is depleted in around 2130. The rising levels of extraction may also imply that the level of demand from agriculture and other industries is on the rise and the peak level of mining will have to be maintained so as to be able to supply phosphorus without negatively affecting the productivity of agriculture and the other industries. If the level of phosphorus supply declines after the mid-2030s, agricultural productivity may also decline, leading to food (and nutrition) insecurity. Low supply of phosphorus with a continuous high demand may also result in a rise of the phosphorus product prices (Villalba et al., 2008).



Source: Cordell et al., (2009)

Figure 2.5. Predicted global phosphorus mining and production curve over the next 80 years

This means that crop production will require alternative phosphorus sources, as it is a basic crop nutrient that plants cannot grow without. Other sources of phosphorus, besides rock phosphate include crop residues or alternatively excreted animal materials, which sometimes may be directly applied to crops or processed to retrieve necessary plant nutrients, including phosphorus (Kern et al., 2008). Human waste is a rich source of phosphorus, because most of the phosphorus in agricultural products consumed finally gets disposed of as waste. Mined phosphorus gets lost back to the environment and in certain instances, also contaminates the environment (Neset and Cordell, 2012).

Researchers have discovered human urine as an alternative phosphorus source, it is more concentrated in urine than in any other excreted wastes from humans (Meyer et al., 2014). Urine is currently being developed into potentially effective plant nutrient sources in South

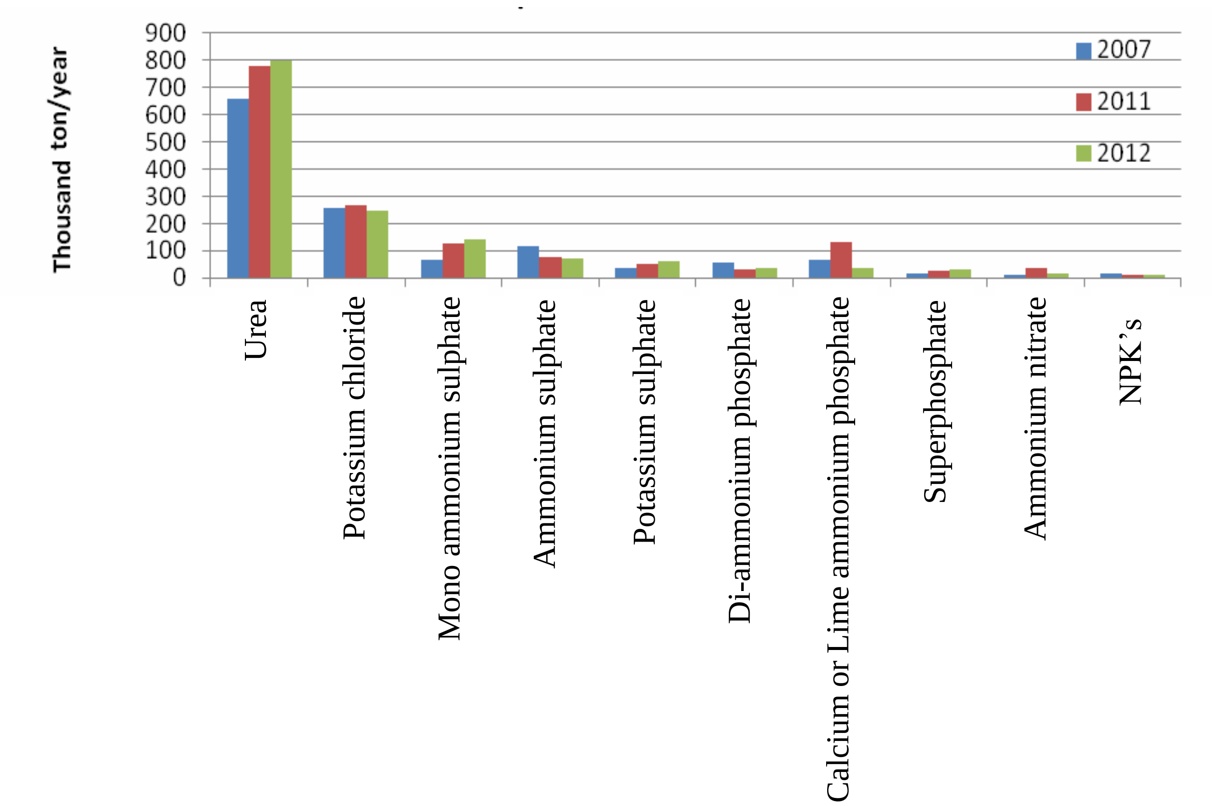
Africa to supply phosphorus and other nutrients. Struvite (a urine derivative) is a solid compound and a very good phosphorus source (12.6% P), produced by the precipitation of urine after adding to it a magnesium dose (MgO) (Grau et al., 2013). It has the potential to become a dominant agricultural phosphorus source, if there is effective urine collection, treatment and processing into this valuable product.

Nitrified Urine Concentrate (NUC) is another urine product which is a good source of nitrogen for agricultural purposes and also contains phosphorus, though in low amounts. Urine-derived plant nutrient sources can provide nutrients in high concentrations that compare to those provided by commercial fertilisers, which makes urine potentially an input of great value and importance (Dawson and Hilton, 2011). Latrine Dehydrated and Pasteurised (LaDePa) pellets are also a potentially good soil amendment product with low phosphorus concentrations (1.5% P) (Harrison and Wilson, 2012).

2.4. THE SOUTH AFRICAN FERTILISER MARKET

South Africa is one of the largest fertiliser consumers in SSA, which also produces several types of nitrogen, phosphorus and potassium fertilisers. It consumes about 0.5% of the globally produced fertilisers which makes it a price taker (DAFF, 2015). Over a ten year period (2004 to 2014), South Africa required on average about of 400 000 to 450 000 tonnes of nitrogen, about 60 000 to 100 000 tonnes of phosphorus and about 90 000 to 130 000 tonnes of potassium for agriculture annually (FERTASA, 2014). Two crops, produced commonly, are the largest fertiliser users, maize and sugar cane, accounting for 41% and 18% of the nationally used fertilisers, respectively.

Although South Africa is a fertiliser producer, most of its fertilisers are imported, making it a price taker, with the country importing all of the required potassium and most of the nitrogen. This is because the level of fertiliser production is less than the fertiliser processing for its agricultural activities. Most fertiliser processing plants in South Africa depend on unprocessed, imported fertiliser material inputs (unprocessed ores) brought in from several countries around the world (FERTASA, 2013). These are then processed into ready to use commercial fertilisers that are used locally, with the remainder being exported to several countries around the world. South Africa also imports finished/processed fertilisers and most of the imports come from other continents with nitrogenous materials being the most abundantly imported (Figure 2.6).



Source: The Fertiliser Association of Southern Africa (2013)

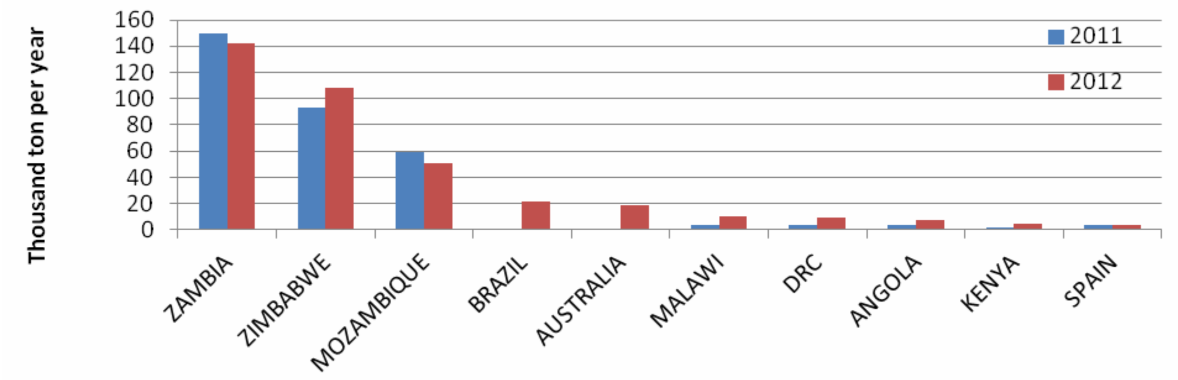
Figure 2.6. Fertiliser products imported into South Africa, top 10 for 2007, 2011 and 2012

According to a report by the Fertiliser Association of Southern Africa (FERTASA) (2013), the country imported about ten different plant nutrient sources, mainly nitrogen sources, from fifteen different countries, worth almost six billion Rands per year. Due to lack of potassium sources in South Africa, all potassium has to be imported and these are the second highest plant nutrient sources that are imported. Phosphorus compounds are the third most imported plant nutrient sources, which are low compared to the volume of nitrogenous compounds imported. This is because South Africa has deposits of phosphate rock which are mined and used in the production of synthetic phosphorus fertilisers.

A few years before 2013, however, the phosphorus producers had been facing some industrial problems in processing the phosphorus ores which has seen South Africa increasingly importing large amounts of phosphorus ores from the world for processing into phosphorus fertilisers. Almost all of the phosphorus ores processed were imported, which is expected to decrease once the local production of phosphorus increases, which may also see the prices of phosphate fertilisers drop (FERTASA, 2013).

Over the past ten years, fertiliser prices for all N, P and K sources in South Africa have increased (Grain SA, 2015) . Fertiliser prices are mostly influenced by the international fertiliser markets as most of it is imported. The South African government has deregulated the fertiliser imports such that the fertiliser prices in the country are only affected by the global markets and the exchange rates, especially the United States Dollar (USD) to the South African Rand (ZAR) exchange rate (DAFF, 2015). Farm gate fertiliser prices are only higher than the imported prices because of the shipping, handling, transportation and packaging costs. This also is the reason why the local fertiliser prices are higher than the international fertiliser prices.

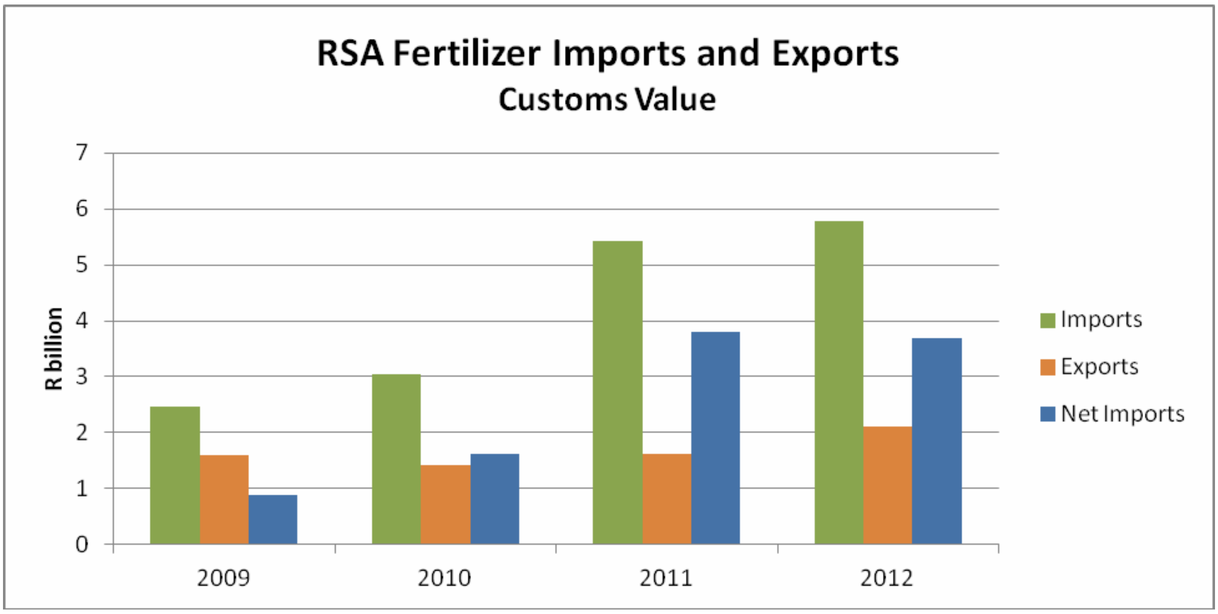
South Africa's biggest fertiliser export market is in Africa, with Zambia, Zimbabwe and Mozambique being the largest importers, respectively, and small amounts being exported out of Africa (Figure 2.7). This shows that the level of fertiliser production across Africa is very low, as most countries do not only import fertilisers from South Africa, but also from the rest of the world, normally as processed products. In 2012, South Africa exported about ten plant nutrient sources to about ten countries, all worth about two billion Rands (FERTASA, 2013). The bulk of the exported products are also nitrogenous plant nutrient sources as they are the most applied in terms of quantity, and is essential especially during vegetative growth and at the reproduction stage. This is followed by phosphorus products which are also heavily exported across the world.



Source: The Fertiliser Association of Southern Africa (2013)

Figure 2.7. South Africa's fertiliser exports for 2011 and 2012

The value of fertilisers imported and exported has generally been increasing over the period from 2009 to 2012 (Figure 2.8) (FERTASA, 2013). The value of the exported, ready to use fertiliser material is lower than the amount of the imported unprocessed fertiliser ores. There is a net trade deficit between the imported and exported material, this trend has been increasing over the 2009 – 2012 period and resulting in a trade deficit, also in terms of monetary value. This is because of the large fertiliser amounts that are reserved for local crop production, leaving small quantities that can be exported. This calls for the improvement in fertiliser production, especially through the development of HEDMs, as these can be very useful in decreasing the amount of fertiliser material imported resulting in huge forex savings. Increasing fertiliser production may also lead to an increase in fertiliser exports, thereby increasing the country's revenue.



Source: The Fertiliser Association of Southern Africa (2013)

Figure 2.8. Fertiliser imports and exports in South Africa from 2009 – 2012

Even though the level of fertiliser production is efficient for the commercial farming sector, most South African smallholder farmers do not have proper access to these chemical fertilisers due to their low incomes, hence, low their usage (Baiphethi and Jacobs, 2009). This is also the case in the wider SSA region where there is very low to non-use of commercial fertilisers in agricultural activities. This is mainly because most communal and some smallholder farmers cannot afford the highly priced fertilisers; hence, they use low amounts or no fertilisers in all in their farming processes. The rate of fertiliser adoption and use in SSA is also very low in contrast to that in Eastern Asia and North America (Yanggen et al., 1998).

Most countries with successful agricultural production are largely use fertilisers, which is directly related to the output such that they can even produce more than what the country needs (Jayne et al., 2003). This implies that these countries may be able to export their products, mainly to under-producing countries, thereby earning more income. The under-producing countries will rely on imports and/or donations to meet their food needs and will spend more money for acquiring food than they would have if they had produced enough, also exhausting their forex reserves. Since agriculture in developing countries in the SSA contributes more to the GDP in comparison with other economic sectors, manufacturing and high use of fertiliser will help in boosting the agricultural sector through improved productivity (Molinos-Senante et al., 2010). Also, for agriculture to even have a larger percentage contribution in the GDP, all agriculture related activities from the producers of agricultural inputs, the output and any agribusinesses, including retailers, should be considered to be contribution of agriculture to the economy. However, with the growth of other economic sectors, the percentage that agriculture contributes to the GDP decreases.

The value of fertilisers to farmers can be reflected by their willingness to pay (WTP) for the input and in a perfect input market, suppliers would distribute the fertilisers only, if the farmers' WTP is greater than the competitive input market price (Jayne et al., 2003). Fertiliser use in SSA is mostly influenced by two factors: (i) the profit incentives and (ii) proper access to the input (Yanggen et al., 1998). Without these incentives most SSA farmers will have no motivation for fertiliser acquisition. Adoption often differs between small scale and commercial farmers, with small scale farmers having high risk aversion when the profit incentives are poor, as they cannot afford to lose any of their hard-earned income which to most of them is not easy to obtain. Other adoption influencing factors in the SSA region include the output-nutrient (O/N) ratio and the input-output price (I/O) ratio[3], farmer's age[4], level of education[5], household size[6] and number of cattle[7] (Croppenstedt et al., 2003).

However, even in the presence of these incentives and good fertiliser access, farmers in some parts of SSA face some constraints, such as poor soil quality, low rainfall, poor infrastructure (especially roads), lack of credit facilities, poverty of human capital and other fertiliser complimentary inputs (e.g. manure and the knowhow of recommended farming systems to their specific production environments) (Yanggen et al., 1998). Also, due to certain policies and

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[3] The output-nutrient (O/N) ratio shows the extra output a farmer gets from using an extra unit of fertiliser and higher ratios favours input use. The input-output price (I/O) ratio measures the amount of output a farmer needs to purchase a unit of fertiliser and lower ratios favours fertiliser use. The value-cost (V/C) ratio compares the fertiliser attributed profits to their costs and higher values favours fertilisers use.

[4] Older ages are more experienced in farming and have quite large households which increase input adoption.

[5] More educated farmers adopt more.

[6] Larger households provide more family labour hence high fertiliser demand.

[7] Represents wealth and households with many cattle adopt more fertilisers.

management inefficiencies in SSA, markets fail to supply fertilisers even when the farmers are willing to pay for them.

This low rate of fertiliser use may be attributed to the high farm gate fertiliser prices (the final cost per unit of fertiliser that the farmer pays, after accounting for all costs incurred to get the fertiliser to the farm) which are more than those from the other parts of the world (Jayne et al., 2003). The high prices are mainly due to high costs of importation, high exchange costs among market actors, physical marketing and distribution costs, e.g. transportation on poor roads and port storage and handling. Government behaviour, such as policies and taxes, also contribute to these high prices, which reduce farmers' affordability as they have low purchasing power. Sub-Saharan African governments can introduce subsidies to reduce fertiliser prices, if this does not strain the national budget and if it does not lead to market distortions (Yanggen et al., 1998). Subsidies are useful because they ensure that farmers get enough fertilisers, leading to steady farmers' incomes and a constant supply of food (Anderson et al., 2006). However, this may result in over-supply of produce and goods to the markets, leading to lower product prices, if the excess goods are not exported to other countries.

2.5. ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPLICATIONS OF USING HUMAN EXCRETA-DERIVED MATERIALS

Extraction of plant nutrient sources from alternative sources may lead to a reduction in the high fertiliser imports into South Africa and may also result in increased fertiliser exports, thereby increasing the share contributed by agribusinesses to the gross domestic product (GDP) (FERTASA, 2013). Extraction of plant nutrient sources from human excreta is also a sustainable process as wastes will always be produced to be developed into valuable resources, such as necessary agricultural inputs, at the same time promoting good sanitation and improving the heath statuses of the public in general.

Human excreta, though not very common in agriculture, are also used as a nutrient source and in some cases raw. In certain instances people irrigate their crops using raw sewage water from blocked sewer lines or disposed untreated effluent from rivers and produce high quality produce (Kuai et al., 2000). This is evidence that human excreta contains an abundance of nutrients and, if properly developed, can be a very useful plant nutrient source. However, contact with raw sewage sludge poses health threats to the handlers, as wastes can contain various infectious agents. Thus, safety measures have to be put in place when handling human waste along the whole product cycle from storing the untreated waste up to using the processed material.

A study by Mnkeni and Austin (2009), in Ntselamanzi, Alice, South Africa, reported that human excreta, applied at rates from 100kg N per hectare, produced greater cabbage yield compared with goat manure due to high phosphorus and potassium levels. However, yields were less compared with those obtained from the use of inorganic NPK fertiliser and this was attributed to the low nitrogen content in the waste. Mnkeni and Austin (2009) also observed that human manure raised the soil's pH, thus suggesting its use could improve crop performance under acidic soils.

The use of agricultural inputs, such as fertilisers, should be controlled to avoid over-or underuse which may result in unwanted or unexpected results. Agriculture has been long known to release chemicals that can destroy the environment and contaminate groundwater (Legg and Viatte, 2001). Synthetic chemicals released from chemical fertilisers (e.g. ammonium nitrate, ammonium phosphate, superphosphate) may destroy the land and make it infertile over time. Overuse of agricultural inputs, such as fertilisers and other agro-chemicals, may result in input losses through processes such as volatilisation or damaging effects due to leaching of nutrients into the ground.

Some chemicals from inorganic fertilisers are absorbed by plants and end up in food, leading to human health hazards when such food is consumed (Wilson and Tisdell, 2001). This also happens when contaminated water is consumed. Health awareness is of much importance as many consumers suffer as a result of ignorance of these issues. Underuse of fertilisers is also undesirable as it implies that crops will not receive enough to be productive. This is common in the SSA region where the rates of fertiliser use are low, resulting in low food production levels compared with other parts of the world (Sommer et al., 2013).

Due to the delicate, low fertility and carbon content characteristics of the soils in the SSA region, chemical fertilisers are easily washed away leading to nutrient losses (Yanggen et al., 1998). Organic farming is becoming more prominent due to rising concerns on environmental conservation, soil degradation by agrochemicals and agronomy demand for healthy foods (Gil et al., 2000b); hence, farming with organic plant nutrient sources, such as LaDePa or crop residues, becomes more relevant in this respect as these compounds can restore soil structure and, potentially soil fertility. This will also be another advantage to the governments and private institutions that aim to protect the environment, avoiding various harmful effects posed by human activities, thereby avoiding costs associated with environmental damage.

Furthermore, if consumers of organic food are willing to buy products produced with use of LaDePa pellets, it will even be more valuable from a health perspective due to its organic nature. The demand for organic foods will increase, thereby, increasing the production and use of LaDePa pellets. Consumers will also pay less for food, which would have an important impact especially on low income consumers (Yahaya et al., 2015). Due to this, the government will benefit, as a result of accessibility of food products to many or possibly all people which is one of its prime targets. This means that the government is likely to support the production of HEDMs so as to make food even more accessible to the public.

Gil and others (2000) found out diet-concerned consumers and those who are familiar with the harmful consequences of agrochemicals to soils are ready to pay extra for organically produced food stuff. While most consumers were not concerned about the source of the organic fertiliser, certain individuals from the city of Durban were sceptical about consuming food produced from excreta-derived plant nutrient sources, which might be one of the drawbacks in the progress of HEDMs.

Most of the communal farmers in SSA rely on social grants and remittances for income, with most being used to acquire food since, they normally do not produce enough to sustain themselves. In the same aspect, some residents in the SSA region have low incomes and lack the financial ability to acquire food from stores or markets, however, food may be readily available and accessible. This is because of the high poverty levels in the region, such that there is a huge population that survives on less than USD 1.25 a day (Ezeh et al., 2012). Measures to fight this poverty, unemployment and gender inequality have been put in place, though they remain huge problems in SSA. These factors also influence fertiliser adoption as employment provides an income that can be used for acquiring fertilisers. Also, since most women are involved in farming in the SSA region, gender inequality undermines them, especially their ability to get farming inputs and implements.

Most vulnerable societies from this region are in rural areas where the poverty levels are higher than in towns. These rural households lack access to most of the basic needs, such as to food, clean water and sanitation (Baiphethi and Jacobs, 2009). In certain rural areas in South Africa, the government and some non-governmental organisations (NGOs) have implemented support programmes so as to uplift food production for household food security and to produce cash crops so as to improve their incomes. However, problems such as absence of markets and low farm-gate prices for their products affect most of the productive farmers such that they continue living in poverty.

Even though the development programmes from both the government and NGOs, such as economic empowerment, to alleviate poverty and problems from the vulnerable societies were in place, the impact from them was low, with most households claiming that they got little assistance or gained nothing at all (Jayne et al., 2003). This may be due to high incompetence in government or poor management skills by both parties, such that more stringent measures should be adopted in the implementation of such development programmes. Overall, the efficiency of the fertiliser market in South Africa, and SSA at large, does not guarantee food security, unless this is coupled with effective support programmes to help low income farmers to be better able to provide for themselves. Measures to increase long-term food security, such as use of fertilisers, organic inputs and conservation agriculture, have to be put in place. Increased production of easily accessible HEDMs might be another solution to this problem.

The entry of HEDMs into the market may result in a fall of the prices of commercial fertilisers due to increased supply of plant nutrient sources on the fertiliser market (Nikiema et al., 2013). Using HEDMs may also be more beneficial to the end-users due to their potentially low prices. This implies that the farmer’s production costs will be lower than those incurred, while using commercial fertilisers. This means that the SSA farmers may improve productivity on their pieces of land due to availability of inputs, also making them more food-secure. This may also open opportunities for farmers to export excess products, if there is no export-restricting legislation. Farmers’ income may be raised and they will be motivated to produce more, if the market price for the produce is high. This will be an incentive to the subsistence farmers who rely on agriculture for a living, as an increase in revenue boosts their purchasing power such that they will be able to develop themselves.

2.6. RECYCLING OF WASTE AND ITS ROLE IN COMBATTING CLIMATE CHANGE AND FOOD INSECURITY

Climate change adversely affects crop production as, it aggravates environmental constraints. South Africa, like other SSA countries faces climatic changes, as evidenced by fluctuating rainfall and increased temperatures. This has mainly been attributed to the greenhouse effect, a condition that arises when the greenhouse gases, for example carbon dioxide (CO_2), nitrous oxide (N_2O), water vapour (H_2O) and methane (CH_4), enter the atmosphere, absorb and later release heat (Dove, 1996). Human activities, including agriculture, and deforestation promote the greenhouse effect.

Climatic changes are accelerated by the emission of carbon contained in the reserves (e.g. soil) into the atmosphere which aids to increase the greenhouse effect (Dove, 1996). Overgrazing from high livestock volumes, as discussed earlier, is common in SSA and exposes the soil's carbon such that it can easily be lost into the environment. The carbon content of the soil, its humus or organic matter, have to be maintained and preserved, mainly by covering it with vegetation, as it will react with other elements, such as oxygen, in the atmosphere forming greenhouse gases.

Adding organic matter to the soil will cover the soil surface, thereby, improving soil water-holding capacity, adding more carbon into the soil and helping in the process of carbon sequestration, overall reducing carbon emissions (Dubeux and B., 2005). Organic farming manages soil nutrients from fertilisers thereby reducing nitrous oxide emissions caused by chemical fertiliser applications. LaDePa can potentially help in lessening the effects of climate change due to its organic nature (Decrey et al., 2015).

Global warming affects t agricultural productivity of different regions, depending on their climatic conditions. A temperature increase in the temperate regions will potentially increase crop yields, as warmer temperatures favour plant growth. In the SSA tropical regions, however, where temperatures are usually higher, most crop yields will be negatively impacted, as heat-intolerant plants will not be able to withstand the increased heat, thereby reducing their productivity (Lobell et al., 2008).

This may lead to a decline in the supply of crop and livestock products, especially in the tropical, regions where cereal crops, wild and cultivated fruit trees are the main food, sources which are vulnerable to damage by temperature variations. The changing climate has an adverse effect on food production, as climatic seasons shift and change and the weather becomes unpredictable (Parry et al., 2004). Climate change may also cause pest and diseases outbreaks, damaging crops, livestock or even human-beings which might lead to ill-health and food insecurity.

Another main constraint resulting from global warming might be water scarcity which may fuel conflict among individuals and societies (Barnett and Adger, 2007). Small-scale food production may decline due to scarcity or excess of water which could adversely affect plant and human nutritional statuses and the level of food utilisation. This will result in low productivity of smallholder and subsistence farmers who normally have low incomes. Crop yields may fluctuate with climate variability which destabilises the food supply. The use of organic matter to improve soils, farm diversification and the use of low-cost inputs, such as HEDMs, can improve farmers' productivity and incomes (Scialabba and Müller-Lindenlauf, 2010).

Climate change affects income-earning opportunities which in turn, affect the ability to afford food (Levy and Egan, 2003). Since low-income households tend to devote a larger share of their incomes to food, they will be affected by high food prices more than the higher-income households as it has a real income effect (impact on income as a result of price change which can either be negative or positive). The unemployment rate among farm workers may rise as a consequence of reduced productivity. Accessing food of consumers' choices may be a challenge, as it might be unavailable both, physically and economically, which may lead to food allocation through both, the market and non-market mechanisms, as it will not be enough for everyone, thereby creating black markets (Barnett and Adger, 2007). In this case, access to sufficient food through markets will be determined by affordability (the proportion of the price of food a household requires on a daily basis to the income that a household can generate in a day). However, developing plant nutrient sources from wastes creates new businesses and also creates employment opportunities for farm workers resulting from enhanced farm productivity (Semadeni-Davies et al., 2008).

Another solution to climate change may be to produce crop varieties and implement agricultural practices that are best suited to specific areas of production, so as to boost and maintain crop productivity in all areas (Lobell et al., 2008). These also need to be heat-resistant or-tolerant varieties, bred in a way that guarantees high productivity to ensure food security. Use of fertilisers will, therefore, be vital as they are essential for crop growth and make crops produce more. Use of cheaper alternative plant nutrient sources will be advised as this would reduce the production costs which would rather result from high water (irrigation) costs. Water harvesting techniques will in this case be beneficial, as this would reduce these irrigation costs (Pandey et al., 2003). Use of cheap agricultural fertilisers and inputs might also help in reducing financial stress to all farmers. Therefore, the use of HEDMs will be helpful, as they are potentially cheap and LaDePa will be potentially beneficial due to its organic nature and soil conservation and amelioration qualities.

The Food and Agriculture Organisation (FAO) has encouraged climate-smart agriculture (CSA) as a way to mitigate the effects of climatic changes on agriculture (Kaczan et al., 2013). These are ways (such as conservation agriculture) that can be implemented by farmers to ensure food security, sustainability and reduction of greenhouse gas emissions (e.g. ammonia and nitrous oxide) from farmland fertiliser application under current climatic conditions. Fertiliser application practices, such as foliar application, soluble fertiliser granules application, deep placement and fertigation (fertiliser dissolved in water that is used for irrigating crops), help in the reduction of greenhouse gas emissions (Lipper et al., 2014). Coupled with these practices, proper application HEDMs, such as struvite and LaDePa, will be effective in reducing greenhouse gas emissions since they are slow-release fertilisers, thereby avoiding global warming. Building on this background, the use of HEDMs could benefit farmers and all players within the value chain and also SSA region at large.

2.7. SUMMARY

Waste management in most African urban areas has increasingly become a problem due to increasing population and high rates of urbanisation. The most common way of waste management is through waterborne sewer systems and treatment at the wastewater treatment plants. In Durban, South Africa, the authority responsible for rendering sanitation services, eThekwini Water and Sanitation, is facing challenges in providing sanitation services to all the communities in its service areas, with about 200, 000 new customers since the early 2000s, both from urban and peri-urban areas surrounding Durban requiring their services. This has increased pressure on the municipality such that is has considered extending the existing sewerage network and constructing new wastewater treatment infrastructure.

Extending the existing sewer network has, however, been observed as highly costly due to the uneven topography of the service areas. An innovative way to address this challenge had to be put in place to ensure that all customers were fully serviced. This has led to the discovery of a new technology, reinvented toilets that can be installed even in the areas of uneven topography, namely, the Ventilated Improved Pit (VIP) latrines (for collecting solid wastes) and the Urine Diversion Dry Toilets (UDDT) (for collecting liquid wastes). These are easily serviceable, waterless toilets that provide the user with necessary comfort, safety, light and privacy. These toilets were installed mainly in the peri-urban areas surrounding the city of Durban with some installed in selected areas of the city.

Dry sanitation is a cheap alternative compared with the use of waterborne systems. It can save municipalities costs and also provide the needed sanitation to the customer. Also, waste disposal with a waterborne system can result in environmental problems due to the presence of nitrogen and phosphorus in the final effluent which is disposed in the rivers and/or landfills leading to unnecessary environmental costs. Groundwater contamination and eutrophication are the most common problems associated with disposal of wastewater, which are difficult and costly to correct. Even though waste management and containment in dry systems is effective, disposing these wastes is a challenge as they have to undergo treatment first.

A new way a waste disposal was then introduced which saw the conversion of wastes into useable agricultural inputs, HEDMs. Faecal sludge collected from the VIP latrines was developed into an organic fertiliser named Latrine Dehydrated and Pasteurised (LaDePa) pellets, an organic fertiliser and source of nitrogen (3%), phosphorus (1.5%) and potassium (1.5%), which can also be used as a soil ameliorating product. The urine collected from the UDDTs was developed into two products namely, Nitrified Urine Concentrate (NUC), a rich inorganic nitrogen source (21%) and struvite, a rich inorganic phosphorus source (12.6%) which also contains nitrogen (5.6%).

Subsistence farming practises with low rates of adoption of agricultural implements is evident across the SSA. The rate of fertiliser use across SSA is very low, which results in low yields and food insecurity, considering that most families in this region rely on farming for a living. The rate of fertiliser use, however, among the commercial farmers in this region, is high. HEDMs could be used to replace or supplement the existing commercial fertilisers. These HEDMs are potentially cheaper agricultural inputs that could reduce farming production costs, which could possibly make the smallholder farmers food-secure.

The world is about to face a phosphorus crisis due to the continuously diminishing phosphorus rock deposits. Phosphorus is a basic plant nutrient source required for crop establishment. Most of the produced phosphorus from phosphate rocks in form of ores is used for agricultural purposes, with only a low amount being used for other industrial purposes. It is predicted that the remaining phosphorus rock deposits may last only a hundred years from now. In this light, an alternative phosphorus source has to be established in order to avoid future food crisis. Struvite, a urine based phosphorus source, can be used as an agricultural fertiliser as it is highly concentrated and comparable to the existing commercial phosphorus fertilisers. This may help in alleviating the phosphorus threat that the world is currently facing.

South Africa is one of the biggest fertiliser producers in SSA. It, however, imports raw fertiliser products from different countries across the globe to process them into finished products for local use with the remainder being exported, mostly to other southern African countries. There is a net fertiliser trade deficit as the amount that is exported is less than the amount that is imported into the country. South Africa is, however, a price taker in the global fertiliser trade, as it consumes less than 1% of the total global fertilisers used. The government has removed fertiliser import barriers in an effort to reduce fertiliser prices, hence fertiliser prices are only affected by international markets, especially the Rand/USD exchange rate.

The farm gate fertiliser prices are higher than prices of imported fertiliser due to shipment, handling, packing and transportation costs. However, most subsistence farmers cannot afford the fertilisers because of low income. Creation of HEDMs does not only bring business opportunities, job creation or an effective sanitation provision, but will also lead to reduced fertiliser imports and increased fertiliser exports, thereby enlarging the stake of agribusinesses in the total GDP of South Africa.

Due to the rising concerns about global warming, climate-smart agriculture is now preferable to reduce the level of greenhouse gas emissions into the atmosphere. Chemical fertiliser application can lead to the release of nitrous oxide and ammonia from farmlands, which causes global warming. Conservation agriculture and organic farming may help in reducing these emissions. Organic farming is also gaining popularity due to environmental conservation practises it is associated with, such that certain consumers are prepared to spend an extra amount for organic foods. LaDePa, an organic HEDM can be used in organic farming and can potentially bring the same yields and quality products as those developed from commercial organic fertilisers. Building on this, HEDMs should thoroughly be tested in order to prove their competitiveness on the market and in production of crops as they show great potential as plant nutrient sources.

CHAPTER 3 : THE COST-EFFECTIVENESS OF USING HUMAN EXCRETA-DERIVED MATERIALS AS PLANT NUTRIENT SOURCES: EXPERIMENTAL EVIDENCE FROM KWAZULU-NATAL, SOUTH AFRICA

3.1. INTRODUCTION

The processing of waste into useable fertiliser products could provide viable, practical and sustainable solutions to agricultural and sanitation provision problems in sub-Saharan Africa (SSA). Wastes generated from both, dry and waterborne sanitation systems, can be processed into fertiliser products, which could provide sustainable alternatives to expensive chemical fertilisers. Farmers in the SSA region, on top of other problems, such as high temperatures and erratic rainfall, have soils with low organic matter and low water-and nutrient-holding capacities which cause chemical fertilisers to be easily washed away leading to nutrient losses (Yanggen et al., 1998).

Faecal sludge from Ventilated Improved Pit (VIP) latrines can be processed to produce LaDePa, an organic compound containing nitrogen (N), phosphorus (P) and potassium (K). Struvite, a phosphorus-rich, solid, inorganic compound, and Nitrified Urine Concentrate (NUC), a liquid, inorganic, highly concentrated nitrogen source, are processed from source-separated urine. Application of HEDMs, such as LaDePa, struvite and NUC, to these poor soils could provide cheaper, practical and sustainable options to address the problems of low soil fertility faced by smallholder farmers in SSA by improving soil physical and chemical properties.

The potential use of alternative plant nutrient sources produced from human excreta is increasingly attracting attention and could provide solutions to the problems of sustainable waste disposal and make available useful waste-based fertiliser products to farmers in SSA. In South Africa, the National Environmental Management Act (Act 107 of 1998)[8] classifies sewage sludge and related wastes as infectious for which a waste licence is required so as to work with these materials as specified in the Waste Act (Act No. 59 of 2008)[9]. However, if an organisation or waste management facility is to deal with up to 2, 000 cubic metres of sewage

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[8] Source: https://www.environment.gov.za/sites/default/files/legislations/nema_amendment_act107.pdf

[9] Source: https://www.environment.gov.za/sites/default/files/legislations/nemwa_actno26of2014.pdf

sludge a year, a licence or an Environmental Impact Assessment may not be required (Harrison and Wilson, 2012). The World Health Organisation (WHO) and the International Water Management Institute (IWMI) have developed guidelines on the use of treated wastewater and wastes in agriculture (World Health Organisation, 2006a; Nikiema et al., 2014) .

The use of processed waste products, such as LaDePa, could offer environmental benefits through organic farming by having a positive impact on minimizing the environmental problems as normally caused by chemical fertilisers such as groundwater contamination by nitrates (LaDePa is a slow release-fertiliser), acid rain formation and ozone depletion from nitrous oxide emissions caused by excessive use of agrochemicals (Gil et al., 2000a; Dove, 1996).

Production of agricultural plant nutrient sources from faecal sludge could be cost-effective (Fernández et al., 2007) because these compounds (LaDePa, struvite and NUC) could potentially have low market prices, since they are produced from readily available recycled waste. They may also not harm the environment, if they are used as per the prescribed guidelines and their use may result in reduced chemical commercial fertiliser usage and reduced imports into South Africa and the SSA region at large. Ma et al. (2014) conducted a study on the recycling of animal waste material in China and found that composting animal wastes for cropland application was cost-effective, in addition to environmental benefits.

Attempts have been made to value the level of groundwater contamination, a negative effect of excessive agrochemical usage on the environment (Legg and Viatte, 2001). Determining values to show the extent of environmental damage by agrochemicals and determining the associated monetary values, remains, however, a challenge. Spångberg et al. (2014) studied the environmental impact of recovering nutrients from human excreta for agricultural use and observed that waterborne wastewater treatment plants needed high amounts of energy and chemicals to remove nitrogen and phosphorus. These nutrients are the main sources of eutrophication and soil acidification. Using source-separated recycled nutrient-rich wastewater for agriculture proved, however, to be more efficient for conserving energy and more cost saving, than treating wastewater, which also decreases levels of global warming as a result of reduction of the use of chemical fertilisers that release the greenhouse gas nitrous oxide (Spångberg, 2014).

Studies have shown that for easy collection of mineral elements in urine, such as nitrogen and phosphorus, separating urine from solid wastes at the source using the double flash urine-diverting toilet is recommended. Solid wastes will independently be collected using the two parallel aquatron (Vinnerås and Jönsson, 2002). This can lead to very high extraction rates of nutrients with up to 91%, 83% and 59% extraction of nitrogen, phosphorus and potassium, respectively (Vinnerås and Jönsson, 2002). Urine normally contains pathogens that differ from individual to individual, with that of healthy persons being almost sterile and that of infected people containing various infectious agents (Karak and Bhattacharyya, 2011). The collected and stored urine undergoes a process of urea hydrolysis as a result of the high pH (potential of hydrogen) and ammonia concentrations creating an environment which favours inactivation of micro-organisms (Udert et al., 2003).

The struvite production process is very cost-effective, as it can be done onsite manually by an unskilled labourer, making the process relatively cheap (Rhoton et al., 2014). The collected urine is placed in a tank into which magnesium oxide is added to produce a phosphorus precipitate ($NH_4MgPO_4{\bullet}6H_2O$). The precipitate is then collected and dried to form struvite. The drying process destroys all pathogens present in the struvite precipitate (Udert et al., 2014).

Decrey et al. (2011) carried out an experiment to determine whether the produced struvite will have any negative health effects on its users as an input (farmers) and on the end-users (consumers). It was observed that human viruses and *Ascaris* eggs were still in the struvite just after precipitation and filtration, but after air-drying for some days, both organisms were destroyed. Destroying of these organisms depended on the drying condition, which is more effective at higher air temperatures (40 – 50^{o}C was favourable to preserve ammonia) and low relative humidity. Additionally, Kern et al. (2008) stated that traces of toxic heavy metals (such as arsenic, lead, mercury and cadmium) in struvite were in very small amounts and would not cause any harm.

The LaDePa process includes emptying and collection of the pit latrine material depending on the sludge characteristics. The sludge is then transferred to a storage facility where LaDePa manufacturing will start with sludge pre-treatment through heating and then processing of the sludge into LaDePa agricultural pellets. The product becomes microbe free after the sludge treatment and processing and can be used as fertiliser for agricultural purposes for all edible crops without posing any health hazards (Harrison and Wilson, 2012). According to Nikiema et al. (2013), microbial characteristics in the dry organic pellets produced were within the acceptable and safe to use standards for South African fertilisers, with no traces of *E. coli*. Also, other micro-organism levels were under the accepted WHO (2006b) standards for waste product usage.

Processing of NUC from source-separated urine follows several stages which start with complete nutrient recovery where all nutrients available in the urine are restored and recycled to be usable again (Udert and Wächter, 2012). This is followed by the nitrification process where the urine is stabilised using bacteria to prevent nutrient (especially nitrogen) losses into the environment. Distillation follows this process and it removes excess water from the solution thereby concentrating the fertiliser in the making. The last stage is electrolysis where all unwanted material is removed to produce the nitrogen fertiliser. This final stage, however, consumes a lot of energy which might end up making this whole process costly.

The levels of heavy metals (e.g. arsenic, lead, mercury and cadmium) contained in the HEDMs that were produced by EWS were below the maximum permitted levels for plant nutrient sources; hence HEDMs present no threat to the environment (Kern et al., 2008; Decrey et al., 2011; Harrison and Wilson, 2012). Also, the amount of waste that was processed to produce the HEDMs was below the minimum requirement for an operating license. Due to the low capital costs, advancement of technology and user-friendly machinery, the production of LaDePa presents a good reason to get into the Private Public Partnership (PPP), showing the government's interest and commitment in the initiative, as recommended by the South African National Treasury (Harrison and Wilson, 2012). Also, given its labour-intensive nature, creation of LaDePa, struvite and NUC on a large scale can have a positive spinoff in terms of rural job creation.

Production of this organic fertiliser generates an income that other disposal options will not provide, which might offset its waste collection and processing costs and the otherwise incurred environmental costs from landfill disposal. The energy consumed by the LaDePa manufacturing machine for a specific quantity of wastes is approximately half of that used by a conventional wastewater treatment plant. In a cost comparison study between disposing 2, 000 tonnes of sludge a year against converting it to LaDePa, Harrison and Wilson (2012) observed that there were net savings of R327, 000, though not accounting for the setup costs of a LaDePa treatment plant. There might possibly be more savings with increasing sludge quantities handled and converted to LaDePa.

Though these fertilisers may be viable, social acceptance in many societies could be problematic as a result of cultural constraints and hygiene fears (Okem et al., 2013). However, there are other societies that approve their use in agriculture as observed in a study among peri-urban communities in Durban on the use of treated wastewater in agriculture, where most of the respondents supported its use, with some saying they have used greywater for irrigation before, since water was scarce (Odindo et al., 2018). Most of the respondents in these communities also expressed high willingness to purchase and eat the food that has been irrigated with treated wastewater. This might also mean that they may be willing to use or purchase food grown using HEDMs. All players in the waste beneficiation value chain should be convinced that using HEDMs for agricultural purposes is safe, may improve yields and might potentially reduce farm production costs.

The economic benefits, cost-effectiveness and value of using LaDePa as a plant nutrient source to supply nitrogen and amend soils, those of struvite to supply phosphorus and of NUC to supply nitrogen, have not been comprehensively examined in South Africa. They have not been quantified in terms of crop (e.g. maize) yield produced, the efficiency of the potential fertilisers compared with chemical fertilisers and the costs involved in the farm production processes have also not been determined (Uggetti et al., 2011). Most of the literature focuses on bio-physical aspects of human waste and there is very little information on the economic value of HEDMs as fertiliser sources. Their value as fertiliser can be estimated using farmers' willingness to pay (WTP) (Jayne et al., 2003).

This chapter empirically explore, the cost-effectiveness of an innovative waste recycling and processing programme to produce essential plant nutrients from human waste. These new nutrient sources have the potential to supplement existing commercial nutrient sources, improve crop productivity, reduce chemical fertiliser imports and increase forex savings. This chapter also outlined the research methodology used in empirically determining the cost-effectiveness of the HEDMs. The cost per hectare, using HEDMs was compared with use of commercial fertilisers to produce maize and performing a total fertiliser costs per hectare comparison and cost-effectiveness of HEDMs versus commercial fertilisers.

3.2. RESEARCH METHODOLOGY

3.2.1. Conceptual framework and assumptions

Market prices of plant nutrient sources and their nutrient composition help to determine their economic costs and, hence, evaluate their economic benefits. The costs of using both commercial fertilisers and HEDMs were calculated and analysed to determine their economic feasibility. Partial budgets were then used to make total cost comparisons of these processed waste products with commercial fertilisers to determine their financial viability, if used in place of commercial fertilisers (Tables 3.3, 3.4 and 3.7). Partial budgets are used to evaluate farm profitability, returns or losses, resulting from a suggested change in one or more parts of the farm business (Standard Bank of South Africa Limited, 2005). Partial budgets can be used to determine the financial benefits of adopting new technologies (Alimi and Manyong, 2000). They are useful tools in determining the financial viability of farm enterprises as they identify the strengths or weaknesses of a proposed change regarding the costs and incomes and, therefore, to inform on which technologies to adopt. This helps farmers, extension officers and researchers to think ahead and make the best decisions regarding farm management.

Since LaDePa pellets, NUC and struvite had not yet been used under field conditions, their nutritional and economic-effectiveness under field conditions was determined. The experimental target yields and the fertiliser application rates for the soil used in this experiment were generalised according to the results (after sending Catref soil samples for laboratory soil analysis) obtained from Cedara, KwaZulu-Natal Department of Agriculture, Environment and Rural Development (Table 3.5). The theoretical part of the study assumed that the plant nutrient sources would be applied only once, which under normal circumstances may be adequate for phosphorus but not for nitrogen, which is generally applied in splits during critical stages of crop growth and development in a season. However, for the field trials, nitrogen applications were split into two applications, at the recommended rates and times.

Unfavourable weather conditions can cause considerable nitrogen losses through volatilisation, denitrification and leaching, especially, if nitrogen is not applied as recommended. Nitrogen is also bound in organic forms (in organic plant nutrients sources) and it is not easily leached because further mineralization must occur (Mnkeni and Austin, 2009). However, nitrogen in inorganic plant nutrient sources is readily available and would leach even under unfavourable weather conditions.

3.2.2. Data sources and collection

The observable market prices for the other commercial fertilisers that were used in this study were obtained from KwaZulu-Natal Provincial Department of Agriculture, Environment and Rural Development (Whitehead and Archer, 2011). Since the HEDMs in this study are not on the market yet, their prices were derived from the prices of the widely used N, P and K chemical fertilisers in South Africa, namely, Lime Ammonium Nitrate (LAN), Single Superphosphate (SSP) and Potassium Chloride (KCl), respectively (See Tables 3.1 and 3.2). Their nutritional compositions and prices were used to determine the prices for the HEDMs as shown in Tables 3.1 and 3.2. Thus, if the cost of production and distribution of human waste-derived fertilisers is lower than those which are the sources of NPK, LaDePa, struvite and NUC will even be more financially viable, which might be the case as they are produced locally; hence no shipment costs or forex requirements to access them.

Table 3.1. Price per unit of nutrient contained in LAN, SSP and KCl

Fertiliser	**Source of**	**Proportion**	**Price (R/kg)**	**Price per unit (R/1%)**
LAN	N	28%	4.28	0.1529
SSP	P	10.5%	4.28	0.4076
KCl	K	50%	5.27	0.1054

Source: Author’s compilation

Table 3.2. Price per kilogramme for LaDePa, struvite and NUC

Source	**Nutrient composition**	**Proportional cost**	**Nutrient cost (R/kg)**
LaDePa	3.37% N	0.1529 × 3.37	0.52
	0.96% P	0.4076 × 0.96	0.39
	0.19% K	0.1054 × 0.19	0.02
LaDePa total cost/kg			**0.93**
Struvite	5.6% N	0.1529 × 5.6	0.86
	12.6% P	0.4076 × 12.6	5.14
Struvite total cost/kg			**6.00**
NUC	21% N	0.1529 × 21	3.21
NUC total cost/kg			**3.21**

Source: Author’s compilation

3.2.3. Empirical estimation procedures

The cost-effectiveness of LaDePa, struvite and NUC was estimated through the following steps:

Based on yield performance of maize under optimal nutrient levels, drawing from agronomic knowledge (Smith, 2006), it was possible to determine the optimal quantities of major nutrients (nitrogen, phosphorus and potassium) required to achieve the optimum yield potential of maize.

The second step is to ask, “What quantities of LaDePa, struvite and NUC do we need to supply the required nutrient levels?” If the plant nutrient source could not provide any of the three basic nutrients adequately, a pure fertiliser would be added to make up for the deficit which will be costed accordingly.

Thirdly, how much do the calculated (step two) quantities of LaDePa, struvite and NUC cost? From the nutrient source's unit price and the quantity to be supplied per hectare for optimal yield, the cost per hectare was calculated [price per quantity (R/kg) × quantity required per hectare (kg/ha)], resulting in an estimate for the cost of using that nutrient source.

Fourthly, how do these costs compare, if we commercial fertilisers were used to supply the same level of nutrients? This would be done by comparing the costs estimated through the above procedures with the costs of commercial fertilisers to achieve the same yield levels.

Moreover, the following assumptions had to be made to do the subsequent cost estimations:

- The actual quantity of plant nutrient source applied to meet specific (maize) crop nutrient requirements to produce the same optimum (maize) yield was based on soil fertility recommendations and fertiliser nutrient content,
- The N, P and K crop requirements per unit area for optimal productivity (yield) were determined based on agronomic recommendations for maize for Catref soil from the test results obtained from Cedara laboratory, KwaZulu-Natal Agriculture, Environment and Rural Development,
- The yield and the price received for the maize produced using any given nutrient source (commercial fertiliser or LaDePa, struvite and NUC) are the same,
- Plant nutrient sources are applied to the soil of the same type and that these soils are similar in terms of chemical and physical properties,
- All other factors for crop growth are available at the optimum required levels for the production systems, e.g. water (irrigation) and sunlight, and
- Finally, all other factors, not accounted for, are held constant.

The experimental results reported in this study have to be taken cautiously with these assumptions in mind, as HEDMs have not been used on a large scale yet.

To undertake the evaluation in the fourth step, Tables 3.3 and 3.4 show the structures of the partial budgets that were used for financial feasibility assessment.

Table 3.3. A partial budget structure for plant nutrient sources cost comparison

Forfeited income		**Additional income**		**Expected Income Change (R/ha)**	**Comment**
Nutrient Source	Amount (R/ha)	Nutrient Source	Amount (R/ha)		
Not using the lowest cost Organic or Inorganic	**a**	Using an HEDM	**c**		
Reduced costs		**Additional costs**			
Nutrient Source	Cost (R/ha)	Nutrient Source	Cost (R/ha)		
Not using the lowest cost Organic or Inorganic	**b**	Using an HEDM	**d**		
Sacrifice	**a – b**	Gain	**c - d**	**c + b – d – a**	**Positive → Acceptable** **Negative → Unacceptable**

Source: Adapted from SBSA (2005)

$$\begin{aligned} The\ expected\ change\ in\ income &= (c - d) - (a - b) \\ &= c - d - a + b \\ &= c + b - d - a \end{aligned}$$

Following the second and third assumptions made earlier, the values of ‘a’ and ‘c’ will be zero and the expected change in income becomes $b - d$ which is as indicated in Table 3.4.

Table 3.4. A revised structure for the partial budget

Reduced costs for not using an HEDM		Additional costs of using an HEDM		Income Change (R/ha)	Comment
The lowest cost Organic or Inorganic Fertiliser	Cost (R/ha)	The plant nutrient sources LaDePa, struvite or NUC	Cost (R/ha)		
x	**b**	y	**d**	**b - d**	**Acceptable/Unacceptable**

Source: Adapted from Table 3.3

If the change in income is positive, then switching to using LaDePa, struvite or NUC is financially desirable as the reduced costs will be greater than the additional costs. However, if it is negative, the change would not be financially viable and LaDePa, struvite and NUC would not be financially feasible. Essentially, the analysis done is the application of partial budget to cost-effectiveness analysis, comparing different production systems cost-wise.

3.2.4. Nutrient sources and plant requirements

3.2.4.1. *Inorganic plant nutrient sources*

The following are the inorganic fertilisers that were used in this study. Most are commercial fertilisers that are already on the market with the exception of the HEDMs, NUC and struvite.

1. **N: P: K_2:3:2 (22) = R 4.78/kg**
   A kilogram of **N: P: K_2:3:2 (22)** contains 0.063 kg N, 0.094 kg P and 0.063kg K.
2. **N: P: K_3:2:1 (25) = R 4.78/kg**
   A kilogram of **N: P: K_3:2:1 (25)** contains 0.125kg N, 0.0833 kg P and 0.0417 kg K.
3. **Lime Ammonium Nitrate (LAN) = R 4.28/kg**
   A kilogram of **LAN** contains 0.28 kg N and is a pure nitrogen source.
4. **Potassium Chloride (KCl) = R 5.27/kg**
   A kilogram of **KCl** contains 0.50 kg K and is a pure potassium source.
5. **Mono Ammonium Phosphate (MAP) = R 6.78/kg**

A kilogram of **MAP** contains 0.11kg of N and 0.22 kg P.

6. **Single Superphosphate (SSP) = R 4.28/kg**

   A kilogram of **SSP** contains 0.105kg P and is a pure phosphorus source.

7. **Struvite = R 6.00/kg - (HEDM)**

   A kilogram of **struvite** contains 0.056 kg N and 0.126 kg P.

8. **NUC = R 3.21/kg - (HEDM)**

   A kilogram of **NUC** contains 0.21 kg N.

3.2.4.2. *Organic plant nutrient sources*

The following two are the organic fertilisers that were used in this study. Gromor Accelerator is a commercial fertilisers that is already on the market. LaDePa, the HEDM, however, is not.

9. **Gromor Accelerator = R 3.75/kg**

   A kilogram of **Gromor Accelerator** contains 0.03 kg N, 0.015 kg P and 0.015 kg K.

10. **LaDePa = R 0.93/kg - (HEDM)**

    A kilogram of **LaDePa** contains 0.0337 kg N, 0.0096kg P and 0.0019 kg K.

Table 3.5. Nutrient requirements for maize production for Catref soil

Target yield (tonnes/ha)	Nutrient requirement (kg/ha)	
12	N	200
	P	85
	K	100
	Lime	0

Source: Soil analysis results from Cedara

3.3. EMPIRICAL RESULTS AND DISCUSSION

Since LaDePa contains all the major nutrients (nitrogen, phosphorus and potassium) for crop growth, its application should be based on the limiting nutrient. Basing applications on any of the nutrients may result in either a deficit or an excess of the other major nutrients. Application was based on the nutrient that would not produce a large excess of the other nutrients, so as not to apply an excess of the other nutrients, beyond the agronomic requirement. For instance, when LaDePa applications are based on provision of the optimum nitrogen amount for maize production, the following results are obtained;

$$3.37\%\ N \ = \ 3.37kg\ N\colon 100\ kg\ fertiliser$$

$$200kg\ N\colon x$$

$$\therefore\ x = \frac{200}{3.37} \times 100kg$$

$$= 5,934.72kg/\text{ha}$$

$$Cost = 5,934.72kg/ha \times R0.93/kg$$

$$= R\ 5,519.29/ha$$

Providing phosphorus results in:

$$0.96\%\ P \ = \ 0.96kg\ P\colon 100\ kg\ fertiliser$$

$$x : 5,\ 934.72kg$$

$$\therefore\ x = \frac{5,934.72}{100} \times 0.96kg$$

$$= 56.97kg/ha$$

(Below the required 85kg/ha)

Providing potassium results in:

$$0.19\%\ K \ = \ 0.19kg\ K\colon 100\ kg\ fertiliser$$

$$x : 5,\ 934.72kg$$

$$\therefore\ x = \frac{5,934.72}{100} \times 0.19kg$$

$$= 11.27kg/ha$$

(Below the required 100kg/ha)

From the previous calculations, it can be deduced that basing LaDePa applications on full supply of nitrogen would result in deficits of the other nutrients. If the applications are based on supplying the optimum amount of phosphorus, the following results would be obtained:

$$0.96\%\ P\ = 0.96kg\ P\colon 100\ kg\ fertiliser$$

$$85kg\ P\colon x$$

$$\therefore\ x = \frac{85}{0.96} \times 100kg$$
$$=\ 8,854.17kg/\mathrm{ha}$$

$$Cost = 8,854.17kg/ha \times R0.93/kg$$
$$= R\ 8,234.37/ha$$

Providing nitrogen results in:

$$3.37\%\ N = 3.37kg\ N\colon 100\ kg\ fertiliser$$

$$x : 8,854.17kg$$
$$\therefore\ x = \frac{8,854.17}{100} \times 3.37kg$$
$$= 298.39kg/ha$$

(Above the required 200kg/ha)

Providing potassium results in:

$$0.19\%\ K\ =\ 0.19kg\ K\colon 100\ kg\ fertiliser$$

$$x : 8,854.17kg$$
$$\therefore\ x = \frac{8,854.17}{100} \times 0.19kg$$
$$= 16.82kg/ha$$

(Below the required 100kg/ha)

This would, however, result in the provision of excess nitrogen. Phosphorus-based application would also result in a per hectare cost of R8, 234.37, which is greater than the cost for nitrogen-based applications (R5, 519.29). Hence, nitrogen-based applications would be cost-effective in this case.

If the same fertiliser was to be applied basing applications on supplying the optimum amount of potassium, the following results would be obtained;

$$0.19\%\ K\ =\ 0.19kg\ K\colon 100\ kg\ fertiliser$$

$$100kg\ K\colon x$$

$$\therefore\ x = \frac{100}{0.19} \times 100kg$$
$$= 52,631.58kg/\text{ha}$$

$$Cost = 52,631.58kg/ha \times R0.93/kg$$
$$= R\ 48,947.37/ha$$

Providing nitrogen results in:

$$3.37\%\ N\ =\ 3.37kg\ N\colon 100\ kg\ fertiliser$$

$$x : 48,947.37kg$$
$$\therefore\ x = \frac{48,947.37}{100} \times 3.37kg$$
$$= 1,649.53kg/ha$$

(More than the required 200kg/ha)

Providing phosphorus results in:

$$0.96\%\ P\ =\ 0.96kg\ P\colon 100\ kg\ fertiliser$$

$$x : 48,947.37kg$$
$$\therefore\ x = \frac{48,947.37}{100} \times 0.96kg$$
$$= 469.84kg/ha$$

(More than the required 85kg/ha)

Potassium-based applications would result in a very high fertiliser cost and excess nitrogen and phosphorus. This would be a loss as the plant will take what it needs and some excess, with the rest remaining in the soil or might end up leaching and contaminating water bodies. This might even affect crop growth, as nitrogen and phosphorus would be applied at very high levels. Hence, nitrogen-based applications are the best. To address the phosphorus and potassium deficits, pure fertiliser sources, which provide either of the nutrients in short supply, should be added to reach the desired crop nutrient requirements. To address the phosphorus deficit, SSP was used to obtain the following;

$$\begin{aligned} Deficit\ P &= 85kg - 56.97kg \\ &= 28.03kg \end{aligned}$$

Which would cost;

$$10.5\%\ P = 10.5kg\ P{:}\ 100kg\ fertiliser$$

$$28.03kg\ P{:}\ x$$

$$\therefore x = \frac{28.03}{10.5} \times 100$$

$$= 266.95kg$$

$$\begin{aligned} Cost &= 266.95kg\ \times R4.28 \\ &= R\ 1,142.56 \end{aligned}$$

To address the potassium deficit, KCl was used to obtain the following results;

$$\begin{aligned} Deficit\ K &= 100kg - 11.27kg \\ &= 88.73kg \end{aligned}$$

Which would cost;

$$50\%\ K = 50kg\ K{:}\ 100kg\ fertiliser$$

$$88.73kg\ K{:}\ x$$

$$\therefore x = \frac{88.73}{50} \times 100$$

$$= 177.46kg$$

$$\begin{aligned} Cost &= 177.46kg\ \times R5.27 \\ &= \underline{R\ 935.75} \end{aligned}$$

Therefore, when using LaDePa, based on the nitrogen applications and addressing the deficits, the total cost would be;

$$\begin{aligned} Total\ Cost &= R\ 5,519.29 + R\ 1,142.56 + \ R\ 935.75 \\ &= \underline{R\ 7,597.59/ha} \end{aligned}$$

The same procedure was followed for all other plant nutrient sources for all crops to obtain the results shown in Table 3.6.

Table 3.6. Costs per hectare of different plant nutrient sources for maize based on agronomic requirements

Rank	Fertiliser	Cost per unit area (R/ha)
1	MAP	6, 081.05
2	3:2:1 (25)	6, 590.5
3	2:3:2 (22)	6, 917.97
4	Pure Fertilisers Combination (LAN, MAP and KCl)	7, 575.91
5	**NUC**	**7, 575.91**
6	**Struvite**	**7, 581.3**
7	**LaDePa**	**7, 597.59**
8	Gromor Accelerator	18, 070

Source: Author's compilation

It can be seen that LaDePa, struvite and NUC were almost as competitive as the other plant nutrient sources (Table 3.6), with using LaDePa being more expensive, by a small margin, than both, struvite and NUC (R16.29 and R21.68, respectively). The HEDMs, especially NUC have proved to be competitive plant nutrient sources as their production costs range in those of the inorganic fertilisers considered in this study. Gromor Accelerator, an organic fertiliser, however, had the highest costs per hectare and LaDePa was the least cost organic fertiliser and MAP being the least cost inorganic plant nutrient source in the maize enterprise.

The inorganic nutrient source of lowest costs assessed in this study was MAP and was then used to assess the financial feasibility of using LaDePa, struvite and NUC in a farm enterprise using partial budgets. Generally, inorganic fertilisers are less bulk and may be cheaper to use in crop production compared with organic fertilisers as they have high nutritional concentrations. Because of high nutrient concentrations, low fertiliser amounts are applied to a unit area which will result in overall low costs. On the other hand, organic fertilisers have to be applied in large amounts due to their low nutrient concentrations which will generally make them expensive to apply on a unit area. Though the HEDMs had higher costs, they remain competitive among the other plant nutrient sources considered in this study. Though the least cost organic nutrient source was LaDePa, the other commercial organic fertiliser, Gromor Accelerator, the most expensive fertiliser to use, was used for assessing the financial feasibility of the three excreta-derived fertilisers as shown in Table 3.7.

Table 3.7. Partial budgets for the maize enterprise

Reduced Costs for not using:		**Additional Costs of using:**		**Income Change (R/ha)**	**Comment**
Nutrient Source	**Cost (R/ha)**	**Nutrient Source**	**Cost (R/ha)**		
Gromor		LaDePa		**10, 472.41**	Acceptable
	18, 070		7, 597.59		
Gromor		Struvite		**10, 488.70**	Acceptable
	18, 070		7, 581.30		
Gromor		NUC		**10, 494.09**	Acceptable
	18, 070		7, 575.91		
MAP		LaDePa		**(-) 1, 516.54**	Unacceptable
	6, 081.05		7, 597.59		
MAP		Struvite		**(-)1, 500.25**	Unacceptable
	6, 081.05		7, 581.30		
MAP		NUC		**(-)1, 494.86**	Unacceptable
	6, 081.05		7, 575.91		

Source: Author's compilation

From the partial budgets of the maize enterprise, replacing Gromor Accelerator with LaDePa resulted in a decrease in production costs as shown by the high positive figure (R10, 472.41/ha). This was also the case when Gromor Accelerator was replaced with struvite or NUC. This makes the change acceptable as it decreases the costs per hectare. Replacing MAP with any of the three HEDMs was not financially viable as it increased the costs per hectare by R1, 516.54/ha, R1, 500.25/ha and R1, 494.86/ha for LaDePa, struvite and NUC, respectively. These moves are financially unacceptable, as implementing them would result in unnecessary additional costs.

Even though they could not be used in place of MAP, the HEDMs have proved to be competitive plant nutrient sources for maize production. LaDePa's cost saving may even be more, if the environmental benefits, such as reduced groundwater contamination mainly caused by chemical fertilisers and consumers' WTP for organically produced products are accounted for, provided that waste-derived agricultural products are acceptable to consumers, an area for future research.

The organic plant nutrient source, Gromor Accelerator, had the highest production costs though its market price is lower than that of all the inorganic fertilisers considered in this study because of its very low nutrient concentrations. Therefore, the large quantities of nutrients that will have to be applied to meet the crop's nutritional requirements will offset its relatively cheaper price and lead to more costs of production per hectare.

LaDePa, on the other hand, has very low nutritional composition (Table3.2; Section 3.2.4.2.) of all the three basic nutrients required by the crops but has the lowest market price (R0.93/kg). Though large quantities have to be applied to meet the nutrient requirements of the respective crops, its relatively low price would keep its costs per hectare lower. Moreover, organic fertilisers have additional environmental and social benefits (e.g. employment) not accounted for in this study. NUC and struvite, however, have proved to be competitive, cost-effective and more economical compared to the other inorganic plant nutrient sources considered, as NUC is highly concentrated in nitrogen and struvite is highly concentrated in phosphorus and nitrogen.

To further clarify the economic evaluation of HEDMs, combinations of different fertilisers assessed in this study, which included at least two inorganic nutrient sources or a combination of one inorganic source and an organic nutrient source were empirically studied for maize production. This was done because farmers commonly use different fertiliser combinations in their farm production processes (Palm et al., 1997). Some of these combinations included LaDePa, struvite or NUC, with others being combinations of HEDMs.

The combinations included of pure chemical fertilisers – LAN (for N) and SSP (for P) (LANSSP treatment), chemical and excreta-derived fertilisers – LAN and struvite (P) (LANSTR treatment), organic and chemical fertilisers – Gromor Accelerator (N) and SSP

(GROSSP treatment), excreta-derived inorganic and chemical fertilisers – NUC (N) and SSP (NCUSSP treatment), excreta-derived inorganic fertilisers – NUC and struvite (NCUSTR treatment), excreta-derived organic and chemical fertilisers – LaDePa (N) and SSP (LADSSP treatment) and excreta-derived organic and excreta-derived chemical, LaDePa and struvite (LADSTR treatment). For all potassium requirements/deficits, the chemical fertiliser potassium chloride (KCl) was used to meet the nutritional K requirements. The following example illustrates the procedures followed to estimate the fertiliser quantities:

a) For chemical N (LAN) and chemical excreta-derived P (struvite)
   Phosphorus based application (struvite):

$$1\ kg\ Struvite = 0.126kg\ P$$

$$x : 85\ kg$$

$$\therefore\ x = \frac{85}{0.126}$$

$$= 674.60\ kg\ Struvite/ha$$

$$Cost = 674.60/ha\ \times\ R\ 6.00/kg$$

$$= R\ 4,047.62/ha$$

Also adding nitrogen:

$$1\ kg\ Struvite =\ 0.056kg\ N$$

$$674.60kg\ =\ x$$

$$x = 674.60\ \times\ 0.056\ kg$$

$$= 37.78\ kg\ N$$

Therefore,

$$\text{Deficit N}\ =\ 200 - 37.78$$

$$=\ 162.22\ kg$$

Using LAN,

$$1\ kg\ LAN\ =\ 0.28\ kg\ N$$

$$x :\ 162.22\ kg$$

$$\therefore\ x\ =\ \frac{162.22}{0.28}$$

$$= 579.37\ kg\ LAN/ha$$

$$Cost = 579.37/ha \times R\ 4.28/kg$$
$$= R\ 2,479.68/ha$$

Potassium:

$$1\ kg\ KCl = 0.50\ kg\ K$$

$$x : 100kg$$
$$\therefore x = \frac{100}{0.50}$$
$$= 200\ kg\ KCl/ha$$

$$Cost = 200\ kg/ha \times R\ 5.27/kg$$
$$= R\ 1,054/ha$$

$$Total\ Cost = R\ 4,047.62 + R\ 2,479.68 + R\ 1,054$$
$$\underline{= R\ 7,581.30/ha}$$

b) Nitrogen based application (LAN)

Nitrogen

$$1\ kg\ LAN = 0.28\ kg\ N$$

$$x : 200kg$$
$$\therefore x = \frac{200}{0.28}$$
$$= 714.29\ kg\ LAN/ha$$

$$Cost = 714.29/ha \times R\ 4.28/kg$$
$$= R\ 3,057.14/ha$$

Phosphorus:

$$1\ kg\ Struvite = 0.126kg\ P$$

$$x : 85kg$$

$$\therefore\ x = \frac{85}{0.126}$$

$$= 674.60\ kg\ Struvite/ha$$

$$Total\ Cost = 674.60/ha\ \times\ R\ 6.00/kg$$

$$\underline{\qquad\qquad = R\ 4,047.62/ha}$$

Also adding nitrogen:

$$1\ kg\ Struvite =\ 0.056kg\ N$$

$$674.60\ kg\ =\ x$$

$$x = 674.60\ \times\ 0.056\ kg$$

$$= 37.78\ kg\ N$$

A combination of these nutrient sources cannot be used based on the application of nitrogen from LAN (b) as it results in an excess of nitrogen being applied (37.78kg) at extra costs. Hence, a combination of LAN and struvite was based on the supply of phosphorus from struvite. After the calculations for the different fertiliser type combinations were made, the results are shown in Table 3.8.

Table 3.8. Costs (R) per hectare from using different fertiliser combinations in maize for Catref Soil

Nutrient combination		Cost per hectare (R/ha)
1	LAN + SSP	7, 575.90
2	**NUC** + SSP	7, 575.90
3	LAN + **Struvite**	7, 581.30
4	**NUC + Struvite**	7, 581.30
5	**LaDePa** + SSP	7, 597.06
6	**LaDePa** + **Struvite**	7, 789.26
7	Gromor + SSP	21, 411.10

Source: Author's compilation

From Table 3.8, it was affirmed that using a combination of pure chemical commercial fertilisers or inorganic excreta-derived and commercial chemical fertilisers, (nutrient combination 1 and 2), had the lowest costs per hectare. This was followed by using LAN with struvite or NUC with struvite. Combining LaDePa and SSP came fifth in terms of costs which was followed by a combination of LaDePa and struvite, with these combinations showing a monetary difference of R192.20/ha. There was also a small difference in costs between combinations 1 and 2 and combinations 3 and 4, R5.40/ha. This shows that using the excreta-derived sources, NUC and struvite, would result in lower maize production costs. Combinations of excreta-derived fertilisers containing LaDePa were also among those which had lower costs per hectare for maize owing to LaDePa's low price. The combination which included Gromor Accelerator was the most costly as shown in Table 3.8 because of its low nutritional composition and higher market price.

To supplement these results with experimental evidence, a maize pot experiment was carried out in a tunnel and maize was fertilised according to nutrient combinations (treatments) shown in Table 3.8. The plants were allowed to grow to full maturity, until they produced yield and were harvested. To determine the yield per hectare, the following procedure was used:

- Recommended maize spacing in KZN is about 75cm × 30cm (Smith, 2006)
- This equates to 2, 250 cm^2 = 0.225 m^2 per plant

$$1 \text{ ha} = 10,000 \text{ m}^{2}.$$

$$\therefore \text{Plants per hectare } = \frac{10\,000}{0.225}$$

$$\approx 44,444$$

twenty litre pots that were used had a 30cm diameter and had a spacing of 75cm apart to be equivalent to 44, 444 plants per hectare. The average yield per treatment was used to predict the yield per hectare and with the maize price per hectare, the income per hectare was obtained. Table 3.9 shows the average yield produced per hectare for the treatments, the income and the net income per hectare obtained therefrom. The net income tabulated was obtained by subtracting the treatment fertiliser costs per hectare (shown in Table 3.8) from the calculated income per hectare. The maize seed yield price per unit (tonne), R3 105.25/tonne, was obtained from the KwaZulu-Natal Agriculture, Environment and Rural Development, COMBUD 2015-2016 (KZN Department of Agriculture, Environment and Rural Development, 2015) .

Table 3.9. Maize seed yield (tonnes) per hectare for different fertiliser treatments

Treatment		Average Yield (kg/ha)	Income (R) Per Hectare	Net Income (R) Per Hectare
1	**LaDePa** + **Struvite**	6, 111.11	18, 976.53	11, 187.27
2	**NUC** + **Struvite**	5, 740.74	17, 826.44	10, 245.14
3	**LaDePa** + SSP	5, 007.41	15, 549.25	7, 952.19
4	No fertilisers	2, 244.44	6, 969.56	6, 969.56
5	LAN + **Struvite**	4, 392.59	13, 640.10	6, 058.8
6	**NUC** + SSP	3, 977.78	12, 351.99	4, 776.09
7	LAN + SSP	3, 718.52	11, 546.94	3, 971.03
8	Gromor + SSP	7, 051.85	21, 897.76	486.66

Source: Author's compilation

From Table 3.9, it can be affirmed that HEDMs are very effective in terms of crop growth as the first two combinations, LaDePa + struvite and NUC + struvite had the highest net income per hectare. These combinations produced the highest yields in this study showing a great potential of HEDMs in crop production. Their relatively higher production costs will be offset by the higher incomes obtained from the higher yields. Even though the LAN + SSP combination had the lowest per hectare costs, the yield produced was relatively low, hence a lower income. The combination with Gromor Accelerator had the lowest net income even though it was the one that produced the highest yield as its fertiliser costs were very high.

In terms of yield, it can be deducted that combinations that contained organic fertilisers (Gromor and LaDePa) performed better compared with the ones with inorganic fertilisers, with the exception of the HEDM combination of NUC + struvite which also had a high yield. This may be so because nutrient mineralisation in organic sources occurs at a later stage compared with inorganic fertilisers, which might have occurred when the crops were accumulation grain yield. LaDePa performed better than most fertilisers assessed due to its low market price, hence, it is more cost-effective than Gromor Accelerator. The control had the lowest yield and income per hectare among all the treatments as no nutrient sources were applied to aid the crop growth. However, due to the fact that there were no fertiliser costs accounted for in its net income deductions, it came on the fourth position in terms of the net income generated.

None of the treatments that were experimented on reached the target 12 tonnes of maize per hectare which would have generated R37, 263/ha. This may have been caused by the growing conditions in the growing tunnel which might have been not very favourable for crop growth e.g. very high temperatures. The treatments may perform better in real field conditions. These results depict a high potential for the HEDMs compared with commercial fertilisers. Other factors of production (such as transport, harvest, fuel, maintenance and labour costs), however, should be accounted for in future studies as fertiliser costs are not the only costs incurred in farm production. If these costs had been incorporated into this study, the results would have been different.

The production costs of using LaDePa, struvite and NUC as plant nutrient sources would also decline with increasing size of the farm due to economies of scale and size as normally experienced by large scale farmers with a stable fertiliser demand. Consequently, operating in large scale and increasing production may be more beneficial in the case of using the LaDePa as its overall net incomes were higher compared with those for most of the plant nutrient sources assessed in this study.

3.4. SUMMARY

Human waste can be processed into useable, potentially effective agricultural inputs. The financial benefits of using the HEDMs, namely LaDePa, struvite and NCU in South Africa and SSA at large have not been analysed yet. This study aimed at acquiring this knowledge so as to analyse the financial and cost-effectiveness of HEDMs for crop production. These are potentially cost-effective products that may be used to replace the common chemical fertilisers that most subsistence and small scale farmers cannot access due to their high* costs among other reasons.

The costs per hectare of using HEDMs and selected, common, commercial organic and inorganic fertilisers for producing a specified maize yield were theoretically determined. Using partial budgets, a financial feasibility analysis was performed through replacing the least cost commercial organic and inorganic fertiliser with the least cost organic and inorganic HEDM.

The results showed that replacing the least cost commercial organic fertiliser studied, Gromor Accelerator with HEDMs resulted in a reduction in farm production costs and was financially feasible and preferable. However, replacing the least cost commercial inorganic fertiliser studied, MAP with HEDMs resulted in an increase in farm production costs, a move that is not preferable.

The partial budget analysis results, however, suggest that human excreta-recycled and derived fertilisers have a potential to reduce cost of crop production. LaDePa could also be environmentally beneficial by contributing to a reduction in the use of agrochemicals and consequently, reducing agricultural pollution. Building on these promising results, further strategies should be designed for the large scale production and use of these waste recycled products for better sanitation outcomes, reduction of environmental contamination by human wastes, job creation through creation of wealth via waste recycling, better environmental outcomes and soil fertility improvement. Moreover, it will have economic multiplier impacts.

To further this study, a tunnel experiment of maize crop trials was conducted. Fertiliser combinations which included commercial fertilisers and HEDMs were grown and analysed. These fertiliser combinations (treatments) included the negative control (no fertilisers applied), the positive control (LAN + SSP fertilisers), LAN + struvite, Gromor + SSP, NUC + SSP, LaDePa + SSP, NUC + struvite, and the LaDePa + struvite treatments. Production costs per hectare of using these fertiliser treatments were determined. The income from the produced yield of each treatment was also determined.

The costs per hectare of using the above-listed fertiliser combinations showed that using a combination of pure commercial fertilisers (LAN + SSP) had the lowest costs. Even though, the costs per hectare for the HEDM fertiliser combinations were not widely different from those of the commercial fertilisers, as they were in a similar range (≈ R200/ha). This showed that the HEDMs were financially competitive in crop production. The HEDM treatments, however, had higher net incomes (total income – fertiliser costs) because of their high yields and relatively low costs per hectare with the pure HEDMs combination LaDePa + struvite treatment having the highest net income. The fertiliser treatment that resulted with the lowest net income was the Gromor + SSP treatment, which was lower than HEDM treatments, as it had very high fertiliser costs per hectare. From these results, it can be affirmed that the use of HEDMs in crop production is financially desirable as they are cost-effective inputs in crop production.

CHAPTER 4 : THE FERTILISER VALUE AND AGRICULTURAL-EFFECTIVENESS OF HUMAN EXCRETA-DERIVED MATERIALS: EXPERIMENTAL EVIDENCE FROM KWAZULU-NATAL, SOUTH AFRICA

4.1. INTRODUCTION

Fertiliser use in crop production is to a greater extent associated with good crop growth and optimum yield production, provided that all other factors of crop growth including but not limited to optimum watering, optimal temperature, light conditions as well as effective disease and pest control are provided (Šturm et al., 2010). In South Africa and the sub-Saharan African region at large, the most common and widely used type of fertilisers are commercial inorganic fertilisers which normally are sources of nitrogen (such as LAN, Urea), phosphorus (SSP, Double Super Phosphate) and potassium (KCl) or compound fertilisers that supply N:P:K in ratios (2:3:2 (22), 3:2:1 (25)). This might be due to their portability as they normally are less bulky and also that nutrients will be readily available, such that nutrient mobilisation occurs as soon as the fertiliser is applied.

Organic fertilisers are also available on the market, but are not as commonly used as inorganic fertilisers (Stewart et al., 2005). Also, organic farming is not as common as inorganic farming. This may be attributed to the fact that organic fertilisers are bulky in nature, and normally contains low nutrient compositions, compared with inorganic fertilisers (e.g. Gromor Accelerator which has 3% N, 1.5% P and 1.5% K concentration compared with LAN, SSP and KCl that have up to 28%, 10.5% and 50% of N, P and K respectively) which may end up hiking the costs of production despite the health, nutritional and nourishment benefits associated with organically produced foods. Also, organic farming is often more labour-intensive as compared to inorganic farming which is a disincentive to some farmers who aim at minimising production costs (Palm et al., 1997).

The most emphasised nutrients in crop growth are the macro-nutrients N, P and K. These are the basic or primary nutrients that are required for crop growth in large amounts, without which a plant will not grow well due to reduced ability to perform basic growth functions (Havlin et al., 2005). Most fertilisers, synthetic or organic, normally supply these nutrients as pure or compound sources with some also having more nutrients other than the basic N, P and K. Crops also require other macro-nutrients (e.g. magnesium, calcium, sulphur), however, and micro-nutrients (e.g. boron, copper, manganese and iron), but not in large amounts as those of N, P and K. Compound fertilisers are normally used by farmers and have an advantage as they contain at least two or more basic nutrients which may reduce their overall fertiliser costs.

Nitrogen is a basic to crop growth as it is a vital part of amino acids and, therefore, proteins and plays a huge role in plant metabolism. In field crops, it is normally applied in splits, firstly after plant emergence which will boost plant growth, and later when the plant prepares for the reproductive stage. Chlorophyll, which is an essential pigment for photosynthesis that absorbs red and blue and reflects the green colour from the light spectrum, also contains nitrogen (Havlin et al., 2005). Nitrogen will be used for vegetative growth when it is supplied in excessive amounts but will aid to yield accumulation if supplied in adequate amounts (Wang et al., 2011).

Phosphorus, another basic plant nutrient is needed mainly in the early stages of development of plants for good seedling establishment as it enhances formation and development of roots. Normally phosphorus is applied once, at the planting stage, but may also be re-applied to the plants at later stages of development if need arises. Phosphorus plays a huge role in energy transfer and storage, as it forms part of adenosine tri-phosphate (ATP), the energy produced as a result of photosynthesis and respiration (Meyer et al., 2014). It is also a constituent of many plant enzymes. It also plays part in photosynthesis, cell division and enlargement and improves yield quality (Stewart et al., 2005).

Potassium is responsible for the metabolism of carbohydrates and the breakdown and translocation of sugars to sinks (Zhu and Chen, 2002). Potassium also plays a role in photosynthesis by regulating the opening and closing of stomata (osmoregulation) and also improves water use efficiency such that plants that have sufficient potassium are less prone to water stress. It activates various enzymes in the plant for physiological processes and also controls the reaction rates (Havlin et al., 2005). The above mentioned are some but not all of the roles performed by the basic N, P and K in plants.

In South Africa and the wider sub-Saharan African region, high fertiliser usage is witnessed among commercial farmers who also produce very high and stable yields as they also have good farming implements. Subsistence farming, practised by a larger percentage of communal and small scale farmers as a result of inaccessibility of fertilisers due to their higher market costs, has resulted in poor crop growth and low yields, with produce, in most cases consumed by those households, and sometimes the small surplus is sold to cover other living costs (Baiphethi and Jacobs, 2009). Government intervention through providing some agricultural inputs sometimes fails to work as the communities may end up consuming or selling the inputs to raise money for other uses (Yanggen et al., 1998).

Human excreta-derived materials can be effective in the agricultural industry as fertiliser and have the potential to enhance crop growth as they can effectively provide the same nutrients that commercial fertilisers provide (Sommer et al., 2013). They can also be used by households and small-scale farmers to boost crop yields. In this study, Nitrified Urine Concentrate (NUC) and struvite, inorganic, urine-based fertilisers and Latrine Dehydrated and Pasteurised (LaDePa) pellets, an organic faecal matter-derived fertiliser, were analysed to determine their fertiliser value and agricultural effectiveness on crop growth and performance with respect to biomass and yield production.

Nutrient mineralisation is dependent on soil characteristics that includes the potential of hydrogen (pH), temperature and soil microbes. It normally, however, occurs slowly in organic fertilisers because the mineral elements will be bound in dead tissue, protein or other material (Mnkeni and Austin, 2009). However, if the mineralisation conditions are optimal, mineralisation can occur fast. In this sense, organic fertilisers have to be applied at an early stage so as to match nutrient supply with plant nutrient demand at critical growth stages. Applying fertilisers that mineralise slowly at the same time as planting may result in poor crop establishment and growth, as the needed nutrients may be unavailable. Such plants may show deficiency symptoms and stunted growth and may not recover after certain critical stages have been passed. Organic fertilisers should be applied when the mineralisation conditions are optimal at recommended rates as they may end up leaching, which may be avoided by applying the fertiliser in splits (Mnkeni and Austin, 2009). Due to this nature of slow release fertilisers, knowledge of the specifications of a fertiliser such as the mineralisation period may help farmers in planning the stage of application.

LaDePa pellets, an organic, excreta-derived plant nutrient source, has great potential as an agricultural fertiliser that could compare to other market-based organic plant nutrient sources (Harrison and Wilson, 2012). LaDePa's rate of nutrient mobilisation is slow and its application should be based on proper planning and knowledge about its mineralisation behaviour to make the necessary nutrients available for crop growth at critical stages. It is an organic product suitable for organic farming and contains more N (3.37%), with low P (0.96%) and K (0.19%) levels compared with other organic plant nutrient sources [e.g. Gromor Accelerator (3% N), (1.5% P) and (1.5% K)].

Plant nutrients in most inorganic fertilisers on the other hand are readily available for uptake by the crops upon fertiliser application, as they will already be in mineral form (Palm et al., 1997). Application of these inorganic fertilisers should be based on crop nutrient requirements and should be done under optimal conditions (e.g. when there are no heavy rains expected to avoid nutrient leaching), also avoiding over-application which may result in nitrogen losses through denitrification and volatilisation (Bell et al., 2015). Over-application may also result in excessive plant vegetative growth which might result in a detrimental impact in yield (Wang et al., 2011).

Struvite, an inorganic source, is a slow release fertiliser that could be applied prior to planting. Its P levels compare to those of the commercial phosphorus fertilisers (struvite contains 12.6%, SSP contains 10.5% and MAP contains 22%); however, its slow release nature means that it also has to be applied prior to planting and under optimal conditions. Struvite's solubility can increase in acidic soils and it can help in improving acidic conditions, hence, it has a liming effect (Mnkeni and Austin, 2009). NUC's nitrogen is readily available as it is an immediate release fertiliser and may seep into the ground easily due to its liquid nature, depending on soil texture (Udert and Wächter, 2012). However, there may be nitrogen losses after application due to volatilisation; hence, applications may be followed by a light irrigation to seep it into the soil, but not to leach the fertiliser, as there might be losses, if it is left on the soil surface. It would also be wise to consult weather forecast before application to avoid nutrient losses through leaching from heavy rains.

Though it has low nutrient concentrations, LaDePa is potentially a good fertiliser as it contains three basic nutrients for crop growth (see section 3.2.4) and also has soil restoration abilities due to its organic nature (Harrison and Wilson, 2012). Struvite has two of these, nitrogen and mainly phosphorus; hence it can be applied to support the early growth stages of the crops. NUC, however, contains mainly nitrogen which is made available to the crops as soon as it is applied; hence, measures minimising nutrient losses, such as application under optimal conditions, have to be observed.

The effectiveness of a plant nutrient source can be determined by analysing the performance of crop growth focusing on various growth parameters, such as the crop height, leaf number, respiration rate, chlorophyll content, leaf area and yield produced, which can be obtained, while the crops are still growing in the field (Lim and Gilkes, 2001). Biomass, another parameter, is normally determined after the plant has been harvested. Biomass can be determined as above ground or including below ground (roots) fresh mass and/or dry mass. This helps to determine the level of nutrient mobilisation into accumulation of plant tissue during the growth period. The analysis may be more effective and complete, if different plant nutrient sources are used for growing plants over the same time period under the same environmental and conditions and, thereby, treatment plants can be compared with each other.

Yield is an important aspect of determining how productive a plant has been. Assessing yield will determine how well the plant mobilised nutrients from its sources. In the presence of adequate nutrients and optimum growing conditions, a plant is expected to produce optimum yield. However, low yields can be witnessed from stunted crops as a result of lack of either one or more factors that influence plant growth.

Fertiliser availability during crop growth, at optimum quantities in the presence of other factors such as water and sunlight, positively influence crop growth. Application of very low amounts of fertiliser normally results in stunted crops in the field. This may also result in lower leaf numbers or slow rate of leaf development or, in most cases, very small leaves. Since photosynthesis mainly occurs in the leaves, the photosynthetic capacity in plants with smaller leaf areas may be lower than in those of broad leafed plants as larger leaves intercept more radiation than smaller leaves (Lawlor, 2002). This may lead to lower yields as the rate of photosynthesis will generally be slow.

The chlorophyll level is directly related to the amount of nitrogen supplied to plants. Crops that receive adequate nitrogen levels show a more defined green colour (Bonvin et al., 2015). Since chlorophyll is also directly associated with photosynthesis, high chlorophyll levels are required so that high photosynthetic rates occur. Determining the chlorophyll content in a plant can also be used as a measure of determining the levels of nitrogen contained therein and predicting yields (Mnkeni and Austin, 2009).

Besides yield, the plant’s stalk can be another part where nutrients are stored. Accumulation of resources in the stalk equate to the plant’s biomass; the more the plant accumulates, the more resources are translocated in this part, the bigger its biomass (Dubeux and B., 2005). Crops supplied with adequate fertilisers have higher biomasses than those that do not get enough fertilisers. Roots are also another part of plants that may be considered when calculating a plant’s total biomass. Since roots obtain water and nutrients, a larger root network is preferable to transport and translocate water and minerals, respectively.

The potential of the HEDMs LaDePa, struvite and NUC as agricultural fertilisers and their competitiveness when compared with commercial fertilisers is currently not known as +they have not been used in large-scale crop production. This chapter assessed these comparisons to determine the value of these plant nutrient sources as fertilisers that could advance agriculture in sub-Saharan Africa. The basis of this study was predominantly on the usefulness and competitiveness of using combinations which include LaDePa, struvite and NUC as fertilisers in crop production, comparing them with other fertiliser combinations containing commercial fertilisers. Comparison was achieved by analysing growth parameters including plant height, leaf number, above ground biomass and seed yield of crops grown with HEDMs compared to those grown with commercial fertilisers.

4.2. RESEARCH METHODOLOGY

4.2.1. Conceptual framework

Production of HEDMs is a great innovation that could benefit both farmer types, commercial or small scale, and, therefore, the national economy (Mnkeni and Austin, 2009). The benefits could be viewed from two ends; firstly, the improvement in sanitation through waste management and, secondly, the availability of potentially affordable fertilisers which might lead to reduced farm production costs, thereby boosting the level of crop production. The second benefit however, also extends to the whole economy as agriculture contributes an important part to the country’s gross domestic product (GDP), though by a smaller percentage in developed economies and more significantly in less developed, agrarian economies.

Alternative nutrient sources have to be established so as to assure the prosperity of agriculture to ensure food security, as a limited number of farmers have access to commercial fertilisers (Dawson and Hilton, 2011). Human waste can be processed into useable waste-based fertiliser products, hence, it should be handled and manipulated so as to realise its full benefits especially in agriculture thereby also complementing the existing fertiliser production. This may produce fertilisers in excess for the local crop production.

In context, production of HEDMs may potentially be beneficial, as it provide solutions to some of the general, daily problems that societies meet. These benefits are different when considered from different perspectives. From a commercial farmer's perspective, HEDMs may be beneficial as they will lead to lower farm production costs because of their potentially cheaper prices. This will also benefit smallholder and communal farmers who struggle to raise funds to acquire fertilisers for farming activities. The use of LaDePa may be beneficial to farmers as it could provide the required nutrients and also improve soil fertility which can further boost yields in successive farming seasons. However, transportation costs may be higher for LaDePa compared with other, less bulky fertilisers.

From the community or dry toilet user's perspective, waste conversion may also be an advantage as it implies improvement to their sanitation due to efficient servicing of the structures (Gounden et al., 2006). In most cases, when pit latrines get full, villagers will discontinue using them, destroy or cover them as they will no longer be of use, forcing them to erect other new structures. UDDTs presents a good sanitation opportunity as they are serviceable, easy to maintain and sustainable structures. To improve participation in the use of these UDDTs and thereby, increasing the volume of waste to be collected, the waste collectors or involved institutions may provide incentives for proper and frequent use of the dry toilets to the households.

For established, commercial fertiliser manufacturers who have a greater market share, the introduction of cheaper nutrient sources will have a negative effect on their businesses. To solve this, these institutions should also participate in the waste beneficiation projects and use their knowledge to further develop these products. Partnership of these commercial fertiliser institutions with the small scale producers may bring a significant transformation in the fertiliser industry. From the government's perspective, production, acquisition and use of HEDMs will be an advantage, as this might make the nation more food-secure which might have a food prices reduction effect due to reduced production costs from the use low cost fertilisers. Although this might not happen, politicians and governments ought to make countries food-secure and make food accessible to everyone, especially at lower prices, hence, supporting this initiative may render them support (Jayne et al., 2003). The food manufacturers/processors will also benefit as a result of buying potentially cheaper inputs which may widen their profits.

During policy formulation, with regards to conservation of the environment, the use of the organic HEDM LaDePa, should be prioritised as this will bring positive results (Harrison and Wilson, 2012). This may lead to higher investment from governments to improve the production of LaDePa. Concerning the production of struvite and NUC, governments might invest in them so as to mitigate the sanitation provision challenges, waste treatment and production of cheaper plant nutrient sources. High costs related to the treatment of wastes can be greatly reduced, if there is a move from using waterborne waste disposal systems to the waterless systems (Spångberg et al., 2014). Normally, untreated and sometimes treated wastewater contains an amount of nutrients, which is higher in untreated wastes, which can cause environmental degradation. Creation of HEDMs from wastes will, therefore, lead to a reduction in environmental costs that would have been caused if they were treated at a wastewater treatment facility and disposed into landfills or rivers. The benefits of disposing wastes sustainably should therefore be quantified.

To a greater extent and focusing on these perspectives, producing HEDMs might be highly favourable and might improve livelihoods and economies. However, production of HEDMs will make less economic sense, if the final product will not be usable. This will mean that the final product will have to be disposed again after treatment and this might only be beneficial, if the costs of waste treatment this way are lower than the costs of conventional sewer waste treatment. In this light, the fertiliser value or any other potential use of the produced HEDMs is of utmost importance, as it will make it sellable to offset all treatment and production costs and generate income, thereby formulating a business. For HEDMs to dominate the fertiliser market, their competitiveness in crop production should be equal or greater than that of the commercial fertilisers.

4.2.2. Data sources

The nutritional composition of the soil that was used in this experiment, a Catref soil, was obtained from Cedara, KwaZulu-Natal Agriculture, Environment and Rural Development, after soil tests. Cedara also supplied the nutritional requirements for production of maize using this soil (Table 3.5). All data concerning HEDMs was obtained from the Pollution Research Group (PRG) of the University of KwaZulu-Natal (UKZN) (section 3.2.4). The PRG also supplied struvite and NUC that was used in this experiment. The LaDePa pellets used in the experiment were obtained from eThekwini Water and Sanitation (EWS). The white maize cultivar, Border King, used in the experiments was obtained from McDonald Seeds in Pietermaritzburg.

4.2.3. Experimental design, procedures and data collection

Maize trials were conducted as a pot experiment under controlled environmental conditions (planting tunnel/greenhouse). Catref soil obtained from KwaDinabakubo in KwaZulu-Natal, characterized by poor soil fertility, was used for this experiment and all fertilisers were applied based on soil nutrient requirements as obtained from the soil analysis results from Cedara. Using a Randomized Complete Block Design (RCBD), a maize pot trial was designed as a single factor analysis (fertiliser). The experiment had eight treatments which included a negative control (no fertilisers applied), the positive control (LAN + SSP fertilisers), LAN + Struvite, Gromor + SSP, NUC + SSP, LaDePa + SSP, NUC + struvite, and the LaDePa + struvite treatments. Each treatment had three replications, thereby making twenty-four experimental units (twenty litre pots). Each replicate also formed a block, hence the experiment also had twenty- four blocks.

Fertilisers from these treatments mainly focused on supplying nitrogen and phosphorus with LAN, NUC, Gromor and LaDePa being sources of nitrogen while SSP and struvite were phosphorus sources. Nitrogen top dressing was done after six weeks with either LAN, NUC or LaDePa depending on the treatment requirements. To ensure that all the fertilised treatments supplied sufficient nutrients, potassium was uniformly added from the chemical commercial fertiliser KCl to meet the plants’ nutritional K requirements. Watering was done to field capacity.

This was a quantitative study as actual field trials were conducted to establish the effectiveness of these fertilisers and was repeated twice. The first trial was conducted at the EWS experimental site in Newlands-Mashu, Durban. The slow release fertilisers (LaDePa, struvite and Gromor) were applied six weeks before planting. All immediate release fertilisers that were added to respective treatments were applied during planting. The plants were allowed to grow under close supervision with data collected on a weekly basis. The data were collected by observation of variables that included plant height and leaf number.

However, realising that the cobs were being destroyed by monkeys, the plants were moved to Pietermaritzburg and placed in a tunnel. The plants were harvested and the biomass was obtained as above ground fresh and dry mass. Where there was yield (maize seed), its mass was determined. After harvesting the plants were oven-dried at 60°C for 48 hours and plant and yield dry masses were obtained.

A second trial was conducted again in Pietermaritzburg which was also allowed to grow to the harvest stage with the same procedures as those of the first trial being followed. This trial yielded except for very few plants and its results were used to conduct the economic analysis using different types of fertilisers. All data collected were then statistically assessed to evaluate the effectiveness of HEDMs in crop production in comparison with the other commercial fertilisers used in this study. To analyse plant data, a statistical software, GenStat 18th Edition, was used to perform general analysis of variance (ANOVA) tests. Means of each variable were used in the statistical analysis.

4.3. EMPIRICAL RESULTS AND DISCUSSION

4.3.1. Plant height

There was an increase in plant height during the first three weeks after planting in the first trial (Figure 4.1). From around the fourth to the ninth week, two treatments, namely LANSSP and NUCSSP (Figure 4.1.A), had taller plants than other treatments. There was an overall increase in the rate of change of height on most of the treatments, except for LANSSP and the negative CONTROL from around the ninth week for the first trial. With regard to the second trial, there was a sharp increase in height for all treatments for the first seven weeks, which further increased up to around the 10th week, except for the negative CONTROL treatment (Figure 4.1.B). These rapid increases in plant height of certain treatments could be as a result of the response of the plants to the added nitrogen from split applications. The rate of height increase was generally very slow from around the twelfth week with the NUCSSP treatment having the tallest plants of all treatments.

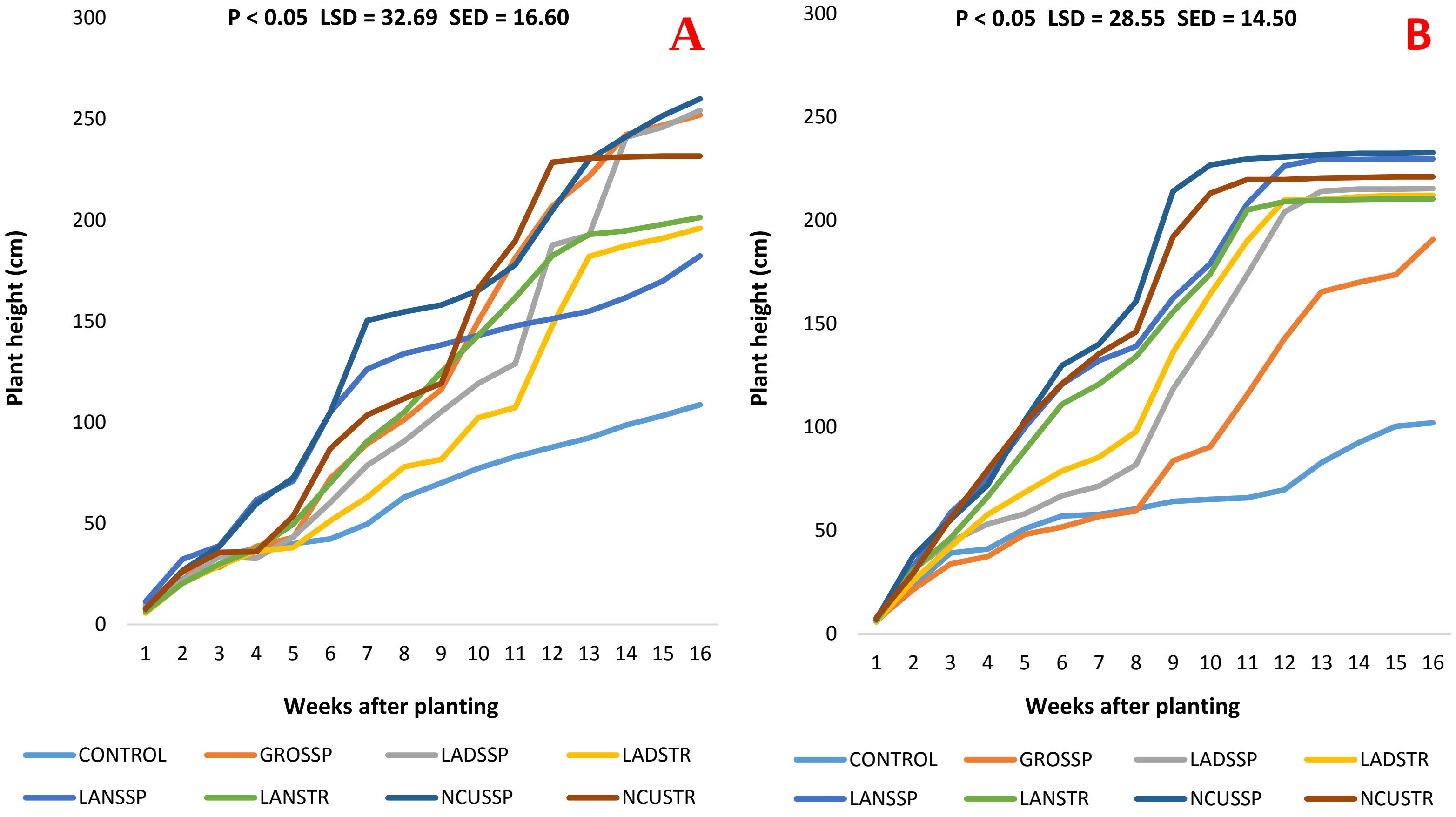

Figure 4.1. The effect of different fertiliser treatments on maize plant height for the first (A) and second (B) trials for a period of 16 weeks

There were very highly significant differences (P < 0.001) among the treatments with respect to mean plant height in the first trial. Very highly significant differences (P < 0.001) were also observed between the weeks after planting. There was a highly significant interaction effect (P < 0.001) between the treatments and the weeks with respect to the plant height. Maize plants in the negative (no fertilisers/negative CONTROL treatment) treatment (final height 108.7 cm) differed significantly from all plants in the positive control (chemical commercial fertilisers/LANSSP treatment) (final height 182.3 cm) (LSD = 32.69) (Figure 4.1.A). The plants in the negative control differed significantly from those of all other treatments. The positive control (LANSSP) did not significantly differ from LADSTR and the LANSTR treatments but differed significantly with the GROSSP, LADSSP, NUCSSP and the NUCSTR treatments which had higher heights. The NUCSSP treatment recorded the tallest final plant height (260 cm).

With respect to the second trial, there were also highly significant differences ($P < 0.001$) among treatments with respect to plant height. Very highly significant differences ($P < 0.001$) were also observed between the weeks with respect to height. There was a very highly significant ($P < 0.001$) interaction effect between weeks and treatments with regard to the plant height. The positive (229.67 cm) and the negative (102 cm) controls differed significantly (LSD = 28.55), shown in Figure 4.1.B. The negative control differed statistically from all the other treatments. The positive control only differed statistically with the negative and the GROSSP treatments. As observed in the first trial, the NUCSSP treatment in the second trial also had the tallest plant (232.67 cm).

There was no statistical difference between the positive control and all HEDMs treatments with regard to height in the second trial which suggests that HEDMs are highly competitive. There were significant differences in height for the first trial between the positive control and the GROSSP, LADSSP, NUCSSP and NUCSTR which had taller plants than the control, suggesting that these treatments performed better and that the nutrient combinations with HEDMs are as competitive as the commercial fertilisers, with NUCSSP having the tallest height. The fact that the NUC treatments had a tendency to produce the tallest plants recorded in all trials suggests that NUC is very effective for plant growth. In all trials, the negative control performed the worst, as expected with a very low plant height, which shows the importance of using fertilisers in maize production.

4.3.2. Plant leaf number

There was a constant increase in leaf number in the first trial for the first ten weeks after planting (Figure 4.2.A). The rate of increase of the leaf numbers then decreased becoming constant for most of the treatments except the LADSSP, negative CONTROL and the LADSTR treatments as shown in the figure. The NUCSTR treatment had the highest number of leaves and the LADSSP had the lowest leaf number amongst all treatments. In the second trial, there was a sharp increase in the number of leaves during the first five to six weeks. The rate of increase in leaf number then declined from around the ninth week to become almost constant from around the twelfth week in most treatments, except the negative CONTROL (Figure 4.2.B). The NUCSSP treatment had the highest leaf numbers and the negative CONTROL as expected had the lowest leaf numbers.

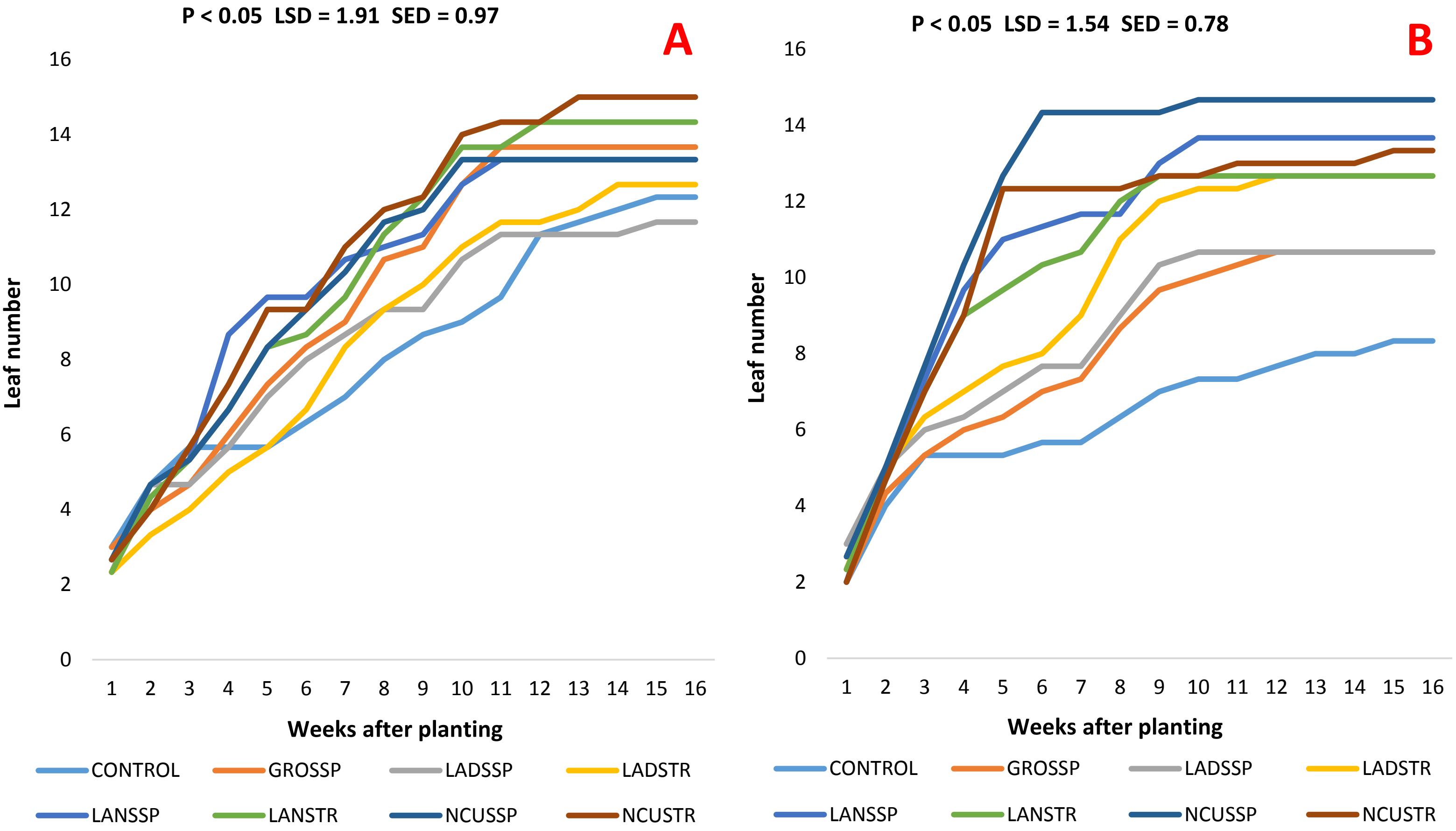

Figure 4.2. The effect of different fertiliser treatments on maize plant leaf number for the first (A) and second (B) trials over a time period of 16 weeks

The difference among the treatments with respect to mean plant leaf number was highly significant ($P < 0.001$) on the first trial. This was also the case with weeks, which were highly significantly different ($P < 0.001$) with respect to leaf number. However, there was no significant interaction effect between treatments and weeks after planting with respect to plant leaf number in the first trial. The negative CONTROL and the LADSSP treatments had the lowest leaf numbers during this trial, while the LANSTR and the NUCSTR had the highest leaf numbers.

There was a very high significant difference among the treatments ($P < 0.001$) with respect to the leaf number in the second trial (Figure 4.2.B). A very highly significant difference was also observed in the weeks after planting ($P < 0.001$). The interaction effect on leaf number between weeks and treatments was also highly significant ($P < 0.001$). The negative treatment differed significantly from all other treatments (LSD = 1.54) and had the lowest number of leaves. The positive control had high leaf numbers and did not significantly differ from any other treatment except from the LADSSP, GROSSP and the negative CONTROL treatments which had the lowest leaf number. The NUCSSP treatment had the highest leaf number in the second trial.

From Figure 4.2, it can be seen that most treatments performed well and generally had high leaf numbers except the negative CONTROL in the second trial (Figure 4.2.A), though it performed well in the first trial (figure 4.2.B). Plants which contained NUC had high leaf numbers, which may suggest the effectiveness of NUC in plant growth. This was also the case with treatments which contained struvite. Though these had fewer leaf numbers than other HEDM treated plants, the LaDePa containing treatments also performed well (figure 4.2.A and B).

4.3.3. Biomass

There was a different trend in the biomass results for the first and the second trial (Figure 4.3). Overall, the biomass produced in the second trial was greater than that produced in the first trial. A highly significant difference was observed between the treatments of the first trial with respect to the biomass ($P < 0.001$). The negative control did not differ significantly with the LADSSP, LADSTR and the LANSTR treatments (LSD = 29.79) but differed significantly with other treatments which had greater biomasses. The positive control differed with the other treatments which had lower biomasses except the NUCSSP treatment with had a higher biomass. The LADSTR treatment recorded the lowest biomass (62.3g or 2.77 tonnes/ha), while the NUCSSP treatment had the highest biomass (177.3g or 7.88 tonnes/ha).

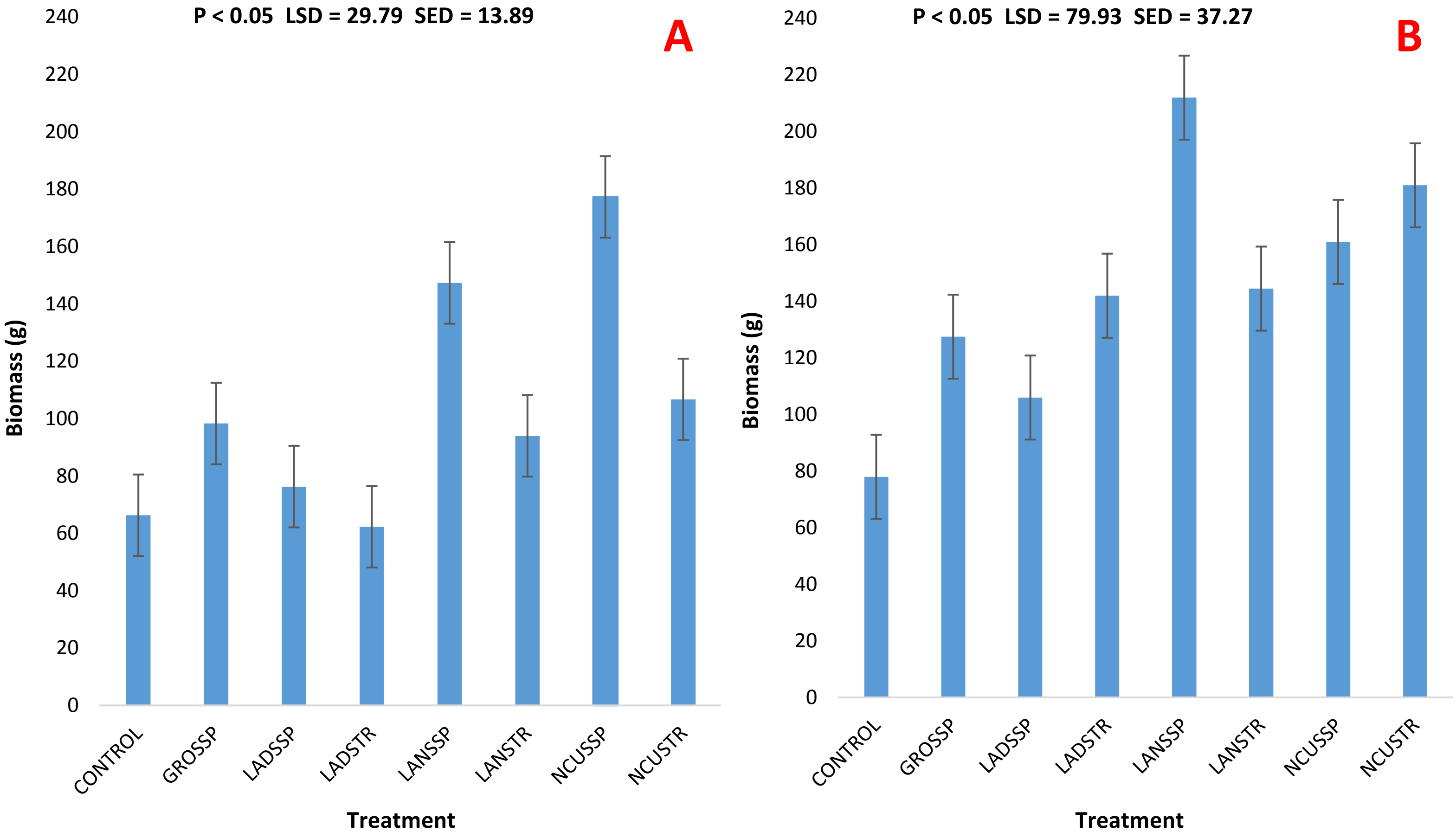

Figure 4.3. Above ground biomass of maize plants grown under different fertiliser treatments in the first (A) and second (B) trial

Though the second trial had higher biomasses compared with the first one, no significant differences were observed among the treatments ($P > 0.05$) with respect to biomass. The difference among the treatments would, however, be significant at 7% significance level (93% confidence level). In this trial (Figure 4.3.B), the negative CONTROL had the lowest biomass as expected (78g or 3.47 tonnes/ha), while the positive control had the highest biomass (212g or 9.42 tonnes/ha).

4.3.4. Yield

The first trial had very low yields compared with the second trial. The yield results for the first trial were low because some of the plants did not produce any yield (seeds/fruit), probably because were moved from their original growing site to where they finally produced.

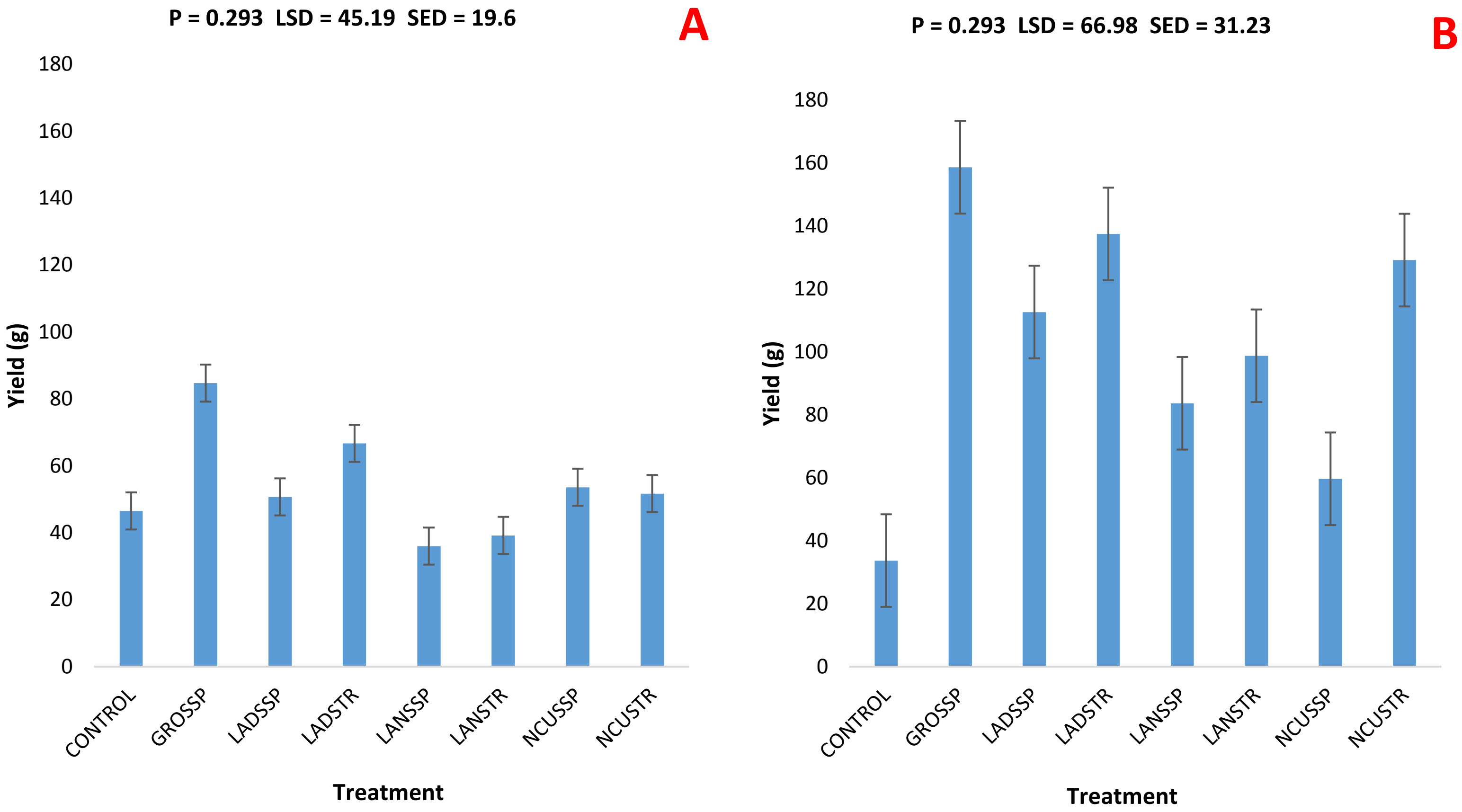

Figure 4.4. Maize yield (seed mass) for different fertiliser treatments of the first (A) and second (B) trials

There however, was no significant difference observed among the treatments ($P > 0.05$) with regard to the yield produced for the first trial. The GROSSP treatment had the highest yield (84.7g or 3.76 tonnes/ha), while the positive control recorded the lowest yield (36g or 1.60 tonnes/ha), lower than expected. There, however, was a significant difference among treatments with regard to the yield produced in the second trial ($P < 0.05$, LSD = 66.98). The GROSSP, however, recorded the highest yield (158.7g or 7.05 tonnes/ha), while the negative CONTROL had the lowest biomass recorded (33.7g or 1.50 tonnes/ha). Though all the other treatments had higher yields than the negative CONTROL (no fertiliser treatment), there was no statistical significant difference (LSD = 66.98) between the negative CONTROL and LANSTR, NUCSSP and unexpectedly the positive control (LAN + SSP treatment). This shows that the HEDM treatments performed well in yield production and some, e.g. LADSSP, LADSTR, LANSTR and the NUCSTR produced yields statistically differed from the negative control, higher than the positive control.

4.3.5. Harvest Index

Table 4.1. Harvest index for the maize plant treatments

Rank	Treatment	Average Harvest Index
1	GROSSP	**1.38**
2	LADSSP	**1.07**
3	LADSTR	**0.98**
4	LANSTR	**0.76**
5	NUCSTR	**0.71**
6	NUCSSP	**0.64**
7	CONTROL	**0.57**
8	LANSSP	**0.41**

Source: Author’s compilation

Table 4.1 shows the average harvest indices (H.I), [proportion of the yield (seed mass per treatment) to the above ground biomass] of all the treatments in the second trial. This analysis only includes results from the second trial because the first trial did not produce much yield, hence, its results may be biased. This also became one of the limitations of this study. From the results, it can be deduced that fertiliser treatments which contained the organic fertilisers had the highest H.I.’s. LaDePa treatments came second and third in the analysis and this shows that they produced large amounts of grain in relation to the maize stalk they built. This also shows that the treatments mobilised more nutrients into grain formation and not only into biomass, like both the negative and positive controls which had the lowest H.I.’s. Unexpectedly, the positive control had the lowest H.I., even though it had the highest biomass, but its yield was low in relation to its biomass. This may suggest that the vegetative growth in positive control plants was more than the reproductive growth.

4.4. SUMMARY

Production of agricultural inputs (HEDMs) from human waste is a sustainable waste disposal solution that municipalities can implement, however, for them to have a value on the agricultural market, their fertiliser value has to be known. Their agricultural effectiveness in comparison with the existing commercial fertilisers was also not known. This study aimed at acquiring this knowledge so as to determine the agronomic value of the HEDMs. Maize trials were performed twice in a tunnel using 20 litre pots to determine the effectiveness of using HEDMs for agricultural production and comparing the crop growth patterns to those produced from selected common, commercial fertilisers. Catref soil was used in a single factor (fertiliser) experiment using Randomized Complete Block Design (RCBD). The fertiliser combinations included the negative CONTROL (no fertilisers applied), the positive control (LAN + SSP), LAN + Struvite, Gromor + SSP, NUC + SSP, LaDePa + SSP, NUC + struvite, and the LaDePa + struvite treatments. Plants were allowed to grow until harvestable as dry maize and yields were recorded.

Judging the effect of HEDM containing treatments on plant height, it can be deduced that the response to these treatments does not significantly differ from that of pure chemical commercial fertiliser treatments. These HEDM treatments also performed significantly better than the negative CONTROL. The NUCSSP recorded the tallest plants, suggesting that NUC is an effective fertiliser. This trend was also observed on the leaf number analysis of the second trial, where all treatments differed significantly from the negative CONTROL and the NUCSSP treatment having the highest leaf number. Though the LADSSP differed significantly from the positive control, it had higher leaf numbers compared to that of the negative CONTROL (Figure 4.2). The NUCSSP treatment also had the highest biomass in the first trial.

With regard to seed yield, the NUCSSP treatment produced low seed yield quantities which was not significantly different from that of the negative control. This might suggest that the plants failed to mobilise resources effectively during the reproductive growth stage. There might also have been much vegetative growth which resulted in a negative effect on yield. The GROSSP treatment produced the highest yield and the other NUC treatment, NUCSTR and all HEDM treatments produced a high seed yield quantities which were significantly different from that of the negative CONTROL. The LaDePa treatment produced high yield quantities, which makes LaDePa a potentially good fertiliser for crop production. The chemical fertiliser treatments did not produce high yield quantities, which was lower than that of all HEDM containing treatments (Table 3.9).

The fact that the GROSSP treatment had the highest yields in both trials and that the LaDePa containing treatments produced high yields and harvest indices prove that organic fertilisers can produce high yields. This may be so, because of their slow nutrient release nature which makes the necessary nutrients available when they are required as they are gradually released. Organic farming may be the way forward in order to enhance productivity which will be more beneficial when also focusing on other benefits such as their positive health and environmental impacts.

In general, the HEDMs' effect on growth was satisfactory as in the rank of the chemical, commercial fertiliser treatments and sometimes even better. HEDM treatments statistically differed from the negative CONTROL and did not differ from the positive control. Sometimes HEDM treatments differed statistically from the positive control with HEDMs having higher values than the positive control. In few, certain instances, however, the HEDM treatments had no statistical difference to the negative treatment. It is advisable for a farmer to use LaDePa in their farming activities as it is cost saving and will result in higher grain yields and incomes.

LaDePa and struvite, should be applied prior to planting so that they will mineralise and make the necessary nutrients ready for uptake, which should also be done when topdressing the crops. With regards to NUC, when combined with SSP, is best for producing higher growth rates and biomass and, hence, may be used in enterprises where yield is not of primary focus, such as pastures or flowers. However, the NUCSTR combination can be used where higher yields are required (Figure 4.4.B).

CONCLUSIONS, IMPLICATIONS FOR POLICY AND FUTURE RESEARCH DIRECTIONS

RECAP OF THE PURPOSE OF THE STUDY

Due to the increasing population and high urbanisation rate, eThekwini Water and Sanitation, Durban, South Africa, is having difficulties in servicing current and new customers. The centralised, waterborne wastewater treatment facilities that are currently in use are costly due to high chemical and energy costs and servicing more customers means more costs. The municipality, therefore, constructed about 82, 000 decentralised, waterless sanitation facilities in the peri-urban areas and within the city of Durban. These are cost-effective and are easily serviceable.

Waste disposal for these waterless systems has, however, also been a challenge (Roma et al., 2010). This has led to an innovative idea of converting these wastes into agricultural inputs, human excreta-derived materials namely LaDePa, struvite and NUC. These waste-recycled plant nutrient products could potentially address the problems of diminishing phosphate reserves, overuse of agrochemicals and even increasing environmental pollution. HEDMs have been suggested as alternative sources of plant nutrients to commercial fertilisers. The value of these products as agricultural fertilisers had, however, not been assessed yet in South Africa. This study analyses the financial feasibility and agricultural effectiveness of these products.

CONCLUSIONS

Though the HEDM production costs per hectare could be more than those of some commercial fertilisers, HEDMs were cost-competitive, as their costs were in the range of commercial fertilisers. Also, the HEDMs' financial feasibility was strengthened by the affirmative outcome of reducing maize production costs, if they are used in place of the organic fertiliser studied, Gromor Accelerator. In financial terms, replacing the fertiliser MAP with any of the HEDMs increased the production costs. This cost addition effect could, however, be insignificant when replacing MAP with LaDePa which is expected to have soil amelioration effects that can be more beneficial to the environment.

Competitiveness of the HEDMs was also witnessed, when they were assessed as combinations of different nutrient sources, where the production costs of the HEDM containing treatments had costs per hectare that compared to those of the pure commercial fertilisers, even though the pure chemical fertilisers had lower costs. HEDM fertiliser treatments, however, resulted in higher proceeds than the commercial fertiliser treatments as a result of the high yields produced using HEDMs, which shows that they are effective in raising farm income. Two pure HEDMs combinations, the LaDePa + struvite and the NUC + struvite treatments had the highest net incomes, with the commercial fertiliser treatments Gromor + SSP and the LAN + SSP combinations having the lowest net incomes.

In terms of crop growth, the HEDMs proved to be highly competitive and HEDM produced plants performed as well as plants produced using chemical commercial fertilisers. In certain instances, HEDM containing treatments performed even better than the commercial fertilisers. The results from HEDM treatments did not statistically differ from the chemical commercial fertiliser treatments. HEDM containing treatments also produced high biomass, yield and had higher harvest indices compared with those of the negative and positive control.

The use of HEDMs as a fertilisers is cost-effective due to the net benefits associated with using HEDMs in crop production. HEDMs are highly competitive agricultural plant nutrient sources that can replace commercial fertilisers. LaDePa is a cost-effective, organic fertiliser which might be more attractive to farmers, if its soil structure restructuring abilities are taken into account. This implies that it could be used as a soil amendment adding organic matter and carbon to the soil and improving soil water retention, which may lead to a decrease in greenhouse gas emissions as a result of reduced chemical fertiliser use.

On the other hand, there are also potential financial benefits with regard to the use of struvite as a phosphorus source. Struvite can be a competitive plant nutrient source due to its high P and N contents. NUC is a good nitrogen source and its use is cost-effective. HEDMs can help in reducing environmental contamination from treated wastewater as they present an alternative, sustainable way of waste disposal, making available accessible plant nutrient sources and also help in alleviating poverty in farming relying South African and SSA societies as a result of access to cheaper fertiliser inputs that can also boost farmers’ yields and incomes.

IMPLICATIONS FOR POLICY

With the good performance and high net incomes associated with production using HEDMs shown in this study, increased production of HEDMs is critical. Since LaDePa was the alternative organic fertiliser studied besides Gromor Accelerator which also proved to be cost saving, organic farming using LaDePa will result in high incomes. Policy makers should realise its benefits and draft legislation that does not limit businesses in the production of this resource. There is need for government intervention and huge investments from both, the public and the private sectors, to fuel LaDePa, struvite and NUC production. The South African government will also need to review its Waste Management Act (2008) to make it easy and award entities with licenses to be able to deal with more than 2, 000 cubic metres of sewer sludge for HEDM mass production.

However, due to predicted lower production costs from HEDM use, farm production may greatly increase which might result in an influx of farm produce into market. This may reduce market prices because of product over-supply in comparison to demand. The low market prices might be a disincentive to farmers such that they will not be motivated to produce more in the following season(s), which may also result in product shortage and raise the product prices again. The government may regulate the agricultural markets by means of production quota and ensure that farmers receive good returns to their investments. However, this solution will have to be reviewed to evaluate its effect to the agricultural sector and economy. Also, alternative produce markets, such as the feed industry and the export market, where products may be able to fetch better market prices, will have to be explored. The government should, therefore, review export policies and award farmers export licences.

RECOMMENDATIONS AND SUGGESTED FUTURE RESEARCH DIRECTIONS

HEDMs may bring more revenue, if they are used as a specialised fertiliser or in niche markets, such as the flower growing industry. Municipality Park Departments may also be consumers of the final products to encourage consumption of the products. HEDM fertiliser producers should make highly effective products, with high nutrient concentration. The storage and transportation costs and application methods of the HEDMs should also be evaluated before decisions are taken to commercially produce and market these products. The organic fertiliser and marketing policy framework, the required infrastructural development, market information on demand and product branding should also be analysed.

Opportunities for scaling-up the production of HEDMs should be assessed, so that SSA at large gains from all the related benefits. If properly implemented with full participation of the households, this innovation will produce large quantities of plant nutrient sources, enough for

South Africa and possibly catering for the export market. However, scaling up will depend on household participation and to increase participation, households may be given incentives, such as free processed fertilisers or be allowed to purchase them at lower costs. They might also be given other extension services, such as farming advice, farming inputs and implements, to encourage them to keep their participation levels high at the same time encouraging others.

Dry toilets should also be structurally improved to meet urban standards such, that they may also be installed in urban areas for increased waste collection. Replication of treatment reactors, improvement in the collection networks, thereby reducing transport costs, reduction of collection and treatment costs and maximising the collection amount at any given time, will be essential for the success of these products. Since sludge and source-separated urine contain pathogens, caution during collection has to be practised by taking all preventative measures such as wearing safety protective clothing e.g. work suits, masks and gloves and sanitising all collection equipment.

With global climate change, agricultural practises in the SSA should aim at developing heat-resistant crops which produce the same or high yields as current. Due to high temperatures, nitrogen losses through volatilisation may be experienced; hence, research should also focus on the production of stable excreta-derived fertilisers that will not be affected by the temperatures raised. Produce storage technologies have to be developed to minimise produce losses especially for the smallholder farmers. Farmers will be advised to ensure harvest and minimise losses and also obtain agriculture insurance, if affordable, in the case of a bad cropping season.

There is also a need to value the environmental benefits of using HEDMs. These fertiliser sources could benefit the environment in two ways – reducing commercial chemical fertiliser use and changing human waste disposed otherwise as a pollutant into agricultural inputs. LaDePa may be more viable at national level, if the long-term environmental benefits are accounted for. The environmental costs associated with the use of chemicals in agriculture should also be valued to determine the level of damage they are causing, which would be the costs saved by using HEDMs. Other social benefits and costs on employment, poverty, food security and sanitation of these waste products will also have to be understood and accounted for.

The results of this work must be taken cautiously, mainly because HEDMs are currently experimentally tested and no large-scale crop production with HEDMs has been conducted yet. There is a need to perform the same, large-scale experiment in a field environment so as to analyse the effectiveness of these plant nutrient sources under actual field conditions.

Future research should also focus on the creation of other products from human waste, such as power cells from urine (urinetricity), purified urine as healthy drinking water or bio-oil (Uggetti et al., 2011). However, there is also a need to conduct extensive research on consumers' acceptance of these products. Faecal sludge can also undergo combustion retaining several nutrients producing incinerated ash that can be used as an agricultural plant nutrient source. There is also a need to identify the relevant variables that make the cost and benefit outcomes sensitive and undertake sensitivity analysis to assess the relative change in the outcome of certain variables, namely, benefits and costs.

The research process in this project and the findings open up opportunities for further research in various fronts. A more comprehensive study analysing the whole value chain will have to be carried out. Future research should consider the end user acceptance (farmers for the waste recycled fertilisers and consumers' acceptance and prices for the agricultural products), health and safety issues, product storage, application rates and methods, alternative market routes and the value they may add to the end users, which the existing plant nutrient sources cannot provide.

Being good as it may, the production of HEDMs may potentially face resistance, especially from the private sector's established commercial fertiliser companies because they might face reduction in the profits they make, if farmers adopt the cheaper HEDMs. This might hinder this growing advancement as these companies may be able to politically influence fertiliser markets and even policy makers. Implementation of the recommendations of the study will require public-private partnerships. Governments have to engage with private fertiliser companies to sell the idea and encourage them to invest in the new technology and incrementally replace inorganic fertiliser production by human waste-derived fertiliser products. If that happens, they can ultimately adopt the technology, make it their business and be part of sustainable development practices.

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APPENDIX

PLANT HEIGHT

The effect of different fertiliser treatments on maize plant height for the first trial for a period of 16 weeks

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	2997.2	1498.6	3.63	
Treatment	7	203264.3	29037.8	70.26	<.001
Week	15	1733507.6	115567.2	279.62	<.001
Treatment.Week	105	174182.8	1658.9	4.01	<.001
Residual	254	104976.8	413.3		
Total	383	2218928.6			

The effect of different fertiliser treatments on maize plant height for the second trial for a period of 16 weeks

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	1339.2	669.6	2.12	
Treatment	7	369779.7	52825.7	167.62	<.001
Week	15	1615947	107729.8	341.84	<.001
Treatment.Week	105	160933.5	1532.7	4.86	<.001
Residual	254	80046.8	315.1		
Total	383	2228046			

PLANT LEAF NUMBER

The effect of different fertiliser treatments on maize plant leaf number for the first trial over a time period of 16 weeks

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	50.255	25.128	17.87	
Treatment	7	352.581	50.369	35.83	<.001
Week	15	4625.435	308.362	219.35	<.001
Treatment.Week	105	160.711	1.531	1.09	0.293
Residual	254	357.078	1.406		
Total	383	5546.06			

The effect of different fertiliser treatments on maize plant leaf number for the second trial over a time period of 16 weeks

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	11.5208	5.7604	6.29	
Treatment	7	1274.1146	182.0164	198.87	<.001
Week	15	3212.5729	214.1715	234	<.001
Treatment.Week	105	296.0521	2.8195	3.08	<.001
Residual	254	232.4792	0.9153		
Total	383	5026.7396			

BIOMASS

Maize above ground biomass for different fertiliser treatments of the first trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	501.1	250.5	0.87	
Treatment	7	33941.2	4848.7	16.75	<.001
Residual	14	4051.6	289.4		
Total	23	38493.8			

Maize above ground biomass for different fertiliser treatments of the second trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	2786	1393	0.67	
Treatment	7	37076	5296	2.54	0.065
Residual	14	29168	2083		
Total	23	69030			

YIELD

Maize yield for different fertiliser treatments of the first trial

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Replication stratum	2		515.9	257.9	0.45	
Treatment	6	-1	5147.3	857.9	1.49	0.293
Residual	8	-6	4608.3	576		
Total	16	-7	9128.9			

Maize yield for different fertiliser treatments of the second trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	1114	557	0.38	
Treatment	7	36391	5199	3.55	0.021
Residual	14	20479	1463		
Total	23	57984			

ECONOMIC AND AGRONOMIC EVALUATION OF USING EXCRETA-DERIVED PLANT NUTRIENT SOURCES (LATRINE DEHYDRATED AND PASTEURISED PELLETS, STRUVITE AND NITRIFIED URINE CONCENTRATE) AS AGRICULTURAL FERTILISERS

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