INTEGRATING SUSTAINABLE AGRICULTURAL PRODUCTION IN THE DESIGN OF LOW-COST SANITATION TECHNOLOGIES BY USING PLANT NUTRIENTS AND WASTEWATER RECOVERED FROM HUMAN EXCRETA-DERIVED MATERIALS

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Volume 1: Final Report

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Volume 1: Final Report

Report to the
Water Research Commission

by

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The publication of this report emanates from a project titled: "*Integrating sustainable agricultural production in the design of low-cost sanitation technologies by using plant nutrients and wastewater recovered from human excreta-derived materials*" (WRC Project No. K5/2777). This project has been an extension of the WRC Project K5/2220, which was titled "*Integrating agriculture in designing on-site, low-cost sanitation technologies in social housing schemes*".

This report forms part of a set of two reports. The other report is *Guideline for Sustainable Agricultural Use of Human Excreta-Derived Materials* (WRC Report No. TT 870/2/21)

EXECUTIVE SUMMARY

The South African Department of Water and Sanitation, through the municipalities, aims to provide hygienic, dignified and sustainable sanitation to citizens through programmes such as "bucket toilet eradication initiatives". The target is to ensure that every citizen has access to at least basic sanitation and even flushing toilets. Connections of households to centralised sewerage systems, especially in peri-urban areas, have been hindered by uncontrolled urbanisation, which is outpacing the municipal sanitation plans and in some areas rugged terrain is a challenge. Therefore, on-site systems have been considered as potential solutions to off-grid sanitation.

Several sustainable technologies that potentially provide on-site sanitation in off-grid areas have been developed, tested and validated in different countries, including South Africa. These include the waterborne Decentralised Wastewater Treatment System (DEWATS) and dry systems such as Urine Diversion Dehydrated Toilets (UDDTs) and Ventilated Improved Pit Latrines (VIPs). However, the management of human excreta from these systems is of public health and environmental concern.

There is a paradigm shift in sanitation management where thinking is moving from conventional methods of "treatment and disposal" to "treatment and reuse". The concept of ecological sanitation thus encourages systems that ensure the safe handling of human excreta along the value chain and include a component for reuse. In South Africa, the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) considers waste as a resource that can be utilised for agriculture. Considering the linear flow of nutrients being experienced in rural areas of the sub-Saharan region, whereby nutrients are lost along the food value chain without replenishment in the soil, reuse of human excreta-derived materials (HEDMs) promotes a closed nutrient loop, thereby establishing a resilient circular economy.

Several HEDMs can be recovered from various sanitation technologies and include the water and nutrients (DEWATS), urine and faeces (UDDTs) and faeces (VIPs). Faecal sludge and urine can be further processed into various products. Faecal matter products include biochar, LaDePa pellets, Black Soldier Fly Larva (BSFL) (Hermetia illucens), BSFL residues and co-composts. Products emanating from human urine are nitrified urine concentrate (NUC), struvite and struvite effluent, and (stored) raw urine.

This report builds on previous Water Research Commission projects K5/2002 and K5/2220 and consists of two volumes. Volume 1 is this final report and Volume 2 is a Guideline document that includes the information for users of HEDMs in agriculture.

Approaches to this study involved desktop studies (literature review and sanitation safety planning), laboratory incubation studies, field and pot experiments and crop modelling (nutrient dynamics in HEDMs and irrigation water quality assessment).

The literature review revealed that studies on the use of HEDMs in agriculture are well documented. However, it showed that there are gaps in understanding some technical issues such as management of DEWATS effluent in different seasons and managing chemicals of environmental concern. Also that guidelines specific to the use of HEDMs in agriculture are not available in South Africa.

The characterisation of HEDMs was done to assess their suitability for agriculture in terms of health, environmental and agronomic impacts to add to knowledge from the preceding studies as well as to inform the practical guidelines. The assessment was based on both local and international standards for irrigation water quality and South African fertiliser certification regulations, which consider microbial and heavy metal limits, and stability of the product. The DEWATS effluent complied with all standards for irrigation water quality; the Department of Water and Forestry guideline for irrigation water quality (1996) and the Food and Agriculture Organisation guideline on wastewater treatment and use (1992). It was concluded that unrestricted agricultural use of DEWATS effluent is viable if advanced tertiary treatments are applied to the effluent.

LaDePa pellets complied with standard limits stipulated by the South African guideline for the utilisation and disposal of wastewater sludge: requirements for the agricultural use of wastewater sludge (1996), and the South African Department of Agriculture, Forestry and Fisheries (DAFF); fertilisers, farm feeds, agricultural remedies and stock remedies Act No. 36 of 1947.

The urine products complied with the DAFF standard limits for fertiliser use, except for struvite and stored urine which may contain pathogens, depending on the extent and type of treatment. The challenge with stored urine is social perceptions due to odour and this disqualifies it for fertiliser registration. Struvite dried at higher temperatures and low humidity may have fewer Ascaris eggs while urine requires a storage period of >6 months at 20ºC. The NUC is free from pathogens, pharmaceuticals, heavy metals and high in macronutrients, making it a valuable agricultural fertiliser.

The impacts of DEWATS effluent quality on crop quality, microbial contamination and environmental pollution was assessed. Three crops commonly grown in South Africa for food security; maize (Zea mays), Swiss chard (Beta vulgaris) and sorghum (Sorghum bicolor) were considered. The study was done for different soils, climatic regions and management practices using a Decision Support System (DSS). Results showed that more effluent is likely to be used for irrigation in and the more arid areas of South Africa where impacts on nutrient loading are expected. The heavy metal loading using DEWATS effluent were within acceptable limits, even in arid areas. No health risks were reported due to the use of drip irrigation and crops that cannot be consumed raw. Negative impacts of DEWATS effluent on specific ion toxicity were not reported since foliage wetting did not occur. It was concluded that agronomic challenges such as soil quality, crop quality, environmental pollution and microbial risks were low even if DEWATS effluent is used in various soils across all agro-ecological regions of South Africa. However, nitrogen (N) and phosphorus (P) should be monitored.

The use of inorganic fertilisers may be minimised by combining the benefits of various HEDMs such as using DEWATS effluent as a water and nutrient source and supplementing nutrient deficits with urine products such as struvite. Thus, incubation studies were done to assess the N and P release patterns for struvite and effluent when used in combination. Two separate incubation studies were done at 25°C for 56 days. One investigated N and P release patterns from struvite (solid HEDM) and the other used DEWATS effluent combined with struvite. The application of 469 kg ha^{-1} of struvite (12.8% P) showed similar P release patterns and magnitude to 600 kg ha^{-1} single superphosphate (SSP; 10% P) thereby proving its capability to supplement for inorganic P fertiliser. A lower N release pattern was reported in DEWATS effluent, which was attributed to the low effluent application due to limited soil water storage since it is considered as an irrigation water source, although it contains some nutrients.

Depending on the amount of DEWATS effluent used it may not provide all the nutrients required by a specific crop during its growing period. Therefore, supplementary fertilisers may be required. Studies were done to investigate the suitability of struvite as a P fertiliser supplement in maize irrigated with DEWATS effluent. All solid fertilisers were applied in combinations to meet N and P requirements. The effluent was applied to maintain 70% soil moisture content until the amount equivalent to the required N was reached. Plant growth parameters and maize yield were then measured. Effects of all HEDM fertiliser combinations (struvite and DEWATS effluent) on maize growth and yield were comparable to SSP + urea ($p>0.05$), confirming the suitability of HEDMs as potential alternative fertilisers for maize production.

The DEWATS effluent can be used as an irrigation water source through proper irrigation management practices such as scheduling giving room for rainfall. Production of effluent is expected to be in excess of crop water requirements during rainfall seasons. Two field studies were done at Newlands Mashu, Durban to determine the effects of DEWATS effluent applied at high volumes to forage sorghum (Sorghum bicolor), rice (Oryza sativa) and taro (Colacasia esculentum). The first study aimed to determine the effects of high planting density on forage sorghum yield and potential environmental pollution after irrigation with high volumes of effluent (irrigation using a fixed amount of 35 m^3 ha^{-1} day^{-1}, equivalent to the daily effluent flow rates of the DEWATS plant at Newlands Mashu). Nutrient (N and P) mass balances were determined from the difference between nutrients applied when using anaerobic filter (AF) and horizontal flow constructed wetland (HFCW) effluent, and those removed in the crop biomass. It was concluded that higher plant densities create nutrient and water demand, increase nutrient removal if less concentrated HFCW effluent is used and that a larger land area is needed when AF effluent is used. However, P accumulation was very high regardless of effluent type used. Extending the land area in summer to accommodate both effluent and rainfall might be an option in areas where land is not limited. However, other options could be investing in effluent storage facilities, hydroponics, biomass production through duckweed or forage crop production.

The second study investigated the effects of different irrigation techniques (wetting without flooding; WWF, continuous flooding; CF, and alternate flooding and drying; AWD) and intercropping on water and nutrient removal in high water-consuming crops (rice and taro). Land area requirements were calculated based on water and nutrient mass balances. The land areas required to utilise all effluent produced based on the DEWATS design capacity were approximately 250 m^2 for the CFI and WWF treatments and 400 m^2 for the AWD. If the effluent was to be used as a fertiliser source, the land area for CFI and WWF treatments would need to be quadrupled while for the AWD it would need to be doubled. The P removal per unit area was very low in all irrigation techniques but the N removal was high in AWD treatment, therefore, runoff management through conservation methods and creating a buffer area between the irrigation area and nearby rivers are recommended to prevent non-point source P pollution.

The long-term impact of DEWATS effluent on soil was assessed based on data collated from studies undertaken at Newlands Mashu between 2012 and 2018. Long term irrigation with DEWATS effluent improved soil pH and its use in poor, P deficient, acidic soils is beneficial. Accumulation of cations (calcium and potassium (K)) depends on the crop grown, irrigation volumes and effluent concentration. The K accumulated in the soil can be depleted by banana if fertilisers are not supplemented. Long term irrigation with DEWATS effluent did not significantly increase the soil inorganic N as calculated by the mass balances. However, it was lost through denitrification processes due to different irrigation techniques for different crops as well as the dynamic nature of N in the soil.

The potential for community engagement in the sustainable use of HEDMs in agriculture was assessed. A participatory rural appraisal (PRA) with Vulindlela (near Pietermaritzburg) farmers and consultations with waste management experts was done to frame the current challenges and approaches to implement a sustainable HEDM agricultural use programme in low-income communities. A simple preliminary context study was done to understand the agricultural production systems in the community and the information was used to parameterise the SWB-Sci model. Scenarios were modelled to understand the potential agricultural sustainability in terms of yields and environmental pollution using HEDMs in irrigated and dryland conditions. The PRA showed the willingness of farmers to participate in recycling activities. Human excreta-derived materials were shown to have the potential to increase yields in irrigated areas. However, to address the complex scientific and social problems in achieving a circular economy by improving waste management along the value chain by closing the nutrient loop while contributing to sustainable food systems, a transdisciplinary approach is recommended.

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LIST OF ABBREVIATIONS

ABR	Anaerobic baffled reactor
AF	Anaerobic filter
BMGF	Bill and Melinda Gates Foundation
BORDA	Bremen Overseas Research and Development Association
BSFL	Black Soldier Fly Larvae
COD	Chemical oxygen demand
DEWATS	Decentralised wastewater treatment system
DSS	Decision Support System
ESP	Exchangeable sodium percentage
EWS	eThekwini Water and Sanitation Department
FAO	Food and Agriculture Organisation
FAS	Fertiliser Advisory Services
FFU	Fitness for use
FLT	Fresh life toilet
HEDM	Human excreta-derived material
HFCW	Horizontal flow constructed wetland
IWMI	International Water Management Institute
LaDePa	Latrine Dehydration and Pasteurisation
NUC	Nitrified urine concentrate
PAC	Powdered activated charcoal
PGF	Planted gravel filter
PPCP	Pharmaceuticals and personal care products
PSS	Particle System Separation
SAR	Sodium adsorption ratio
SASRI	South African Sugar Research Institute
SAWQG	South African Water Quality Guideline
SSP	Single superphosphate
TSP	Triple superphosphate
UDDT	Urine diverting dehydrated toilet
USEPA	United States Environmental Protection Agency
VFCW	Vertical Flow Constructed Wetland
WASH R&D Centre	Water and Sanitation Hygiene Research and Development Centre
WHO	World Health Organisation

1 GENERAL INTRODUCTION

Municipalities in South Africa are facing challenges to address sanitation backlogs to improve human health in a manner that is dignified, equitable, economic and environmentally friendly as per the White Paper on Water and Sanitation (1994) (Auerbach, 2016). The eThekwini municipality (Durban) in collaboration with the University of KwaZulu-Natal (Pollution Research Group; now the Water, Sanitation and Hygiene Research and Development Centre (WASH R&D Centre) and other partners have been assessing the suitability of various technologies for the provision of on-site sanitation to peri-urban and rural settlements around the city. Some of the technologies include the Decentralised Wastewater Treatment System (DEWATS) and Ecological Sanitation Systems (Ecosan) such as Ventilated Improved Pit Latrines (VIPs) and Urine Diversion Dehydrated Toilets (UDDTs). However, the management of waste emanating from these technologies is of environmental and health concern.

Several studies have been carried out on human excreta-derived materials (HEDMs) and their potential agricultural uses. The current project is an extension of the Water Research Commission project K5/2220 to further understand the environmental, technical, social, health and agronomic impact of using various HEDMs, with the ultimate aim of producing guidelines for their use in agriculture.

PROJECT AIMS

1. To monitor the long-term effects of DEWATS effluents for irrigation on soil, crop production, storage and risks of microbial contamination at Newlands Mashu experimental site, Durban.
2. To assess the safety of HEDMs with respect to i) pathogen contamination during handling, food production and consumption, ii) their content of pharmaceutical residues and iii) the risk of environmental pollution.
3. To generate information on the fertiliser value of HEDMs and develop guidelines integrating sustainable agricultural production in the planning and design of low-cost sanitation technologies in peri-urban and rural areas.

2 LITERATURE REVIEW: INNOVATIVE SANITATION TECHNOLOGIES FOR NUTRIENT RECOVERY FROM HUMAN WASTE WITH POTENTIAL FOR AGRICULTURAL USE.

2.1 Introduction

Demographic trends show that globally 54% of the world's population resided in urban areas in 2014 (World Water Assessment Program, 2017). The World Water Assessment Program (2017) report further states that "the most urbanized regions include Northern America (82% living in urban areas in 2014), Latin America and the Caribbean (80%), and Europe (73%). In contrast, Africa and Asia remain mostly rural, with 40% and 48% of their respective populations living in urban areas". It is widely recognized that urbanization will continue, and projections are that Africa and Asia are expected to become 56% and 64% urban, respectively, by 2050. Data from the World Bank show that most of the world's fastest growing cities are in Africa and Asia (Ross et al., 2016).

In Africa, rapid and unplanned urbanization is likely to cause considerable challenges. These include increased demand for freshwater, the provision of adequate sanitation and the disposal of large amounts of waste generated in these urban settlements. The World Health Organization/United Nations Children`s Fund (WHO/UNICEF, 2017), estimates that 4.5 billion people lack safely managed sanitation, 2.1 billion people lack access to safe, readily available water at home and 892 million people worldwide still practise open defecation. More than 80% of this unserved population live in sub-Saharan Africa, and South and East Asia.

In South Africa, many households continue to have poor access to adequate sanitation (Statistics South Africa, 2016). The data show that 13.7% of households use pit toilets without ventilation pipes, 2.2% use the bucket system and 2.4% have no access to sanitation. The province of KwaZulu-Natal (KZN) has the highest number of households without access to improved sanitation (Statistics South Africa, 2016). For example, in Vulindlela (a peri-urban settlement in KZN in the Msunduzi municipality), approximately 85% of the area's population of about 16 000 inhabitants use pit latrines, with no proper disposal methods (Msunduzi Municipality, 2016). Most residents (88%) dispose of their waste by digging holes in their yards and burying it. The challenges faced by residents in Vulindlela are common and widespread across the country and in many other urban and peri-urban settlements in Africa.

In recent years, there has been a concerted effort to look for innovative sustainable sanitation technologies to reduce open defecation and disposing of human excreta into water bodies and the soil. Waterborne sewerage systems are costly, and the basic infrastructure is lacking. It is not feasible that municipal authorities would be able to provide residents with centralised waterborne sanitation systems soon. An initiative by the Bill and Melinda Gates Foundation (BMGF) is playing a major role by funding the "Reinvent the Toilet Challenge", which aims to invent a toilet that can remove pathogens from human waste and recover valuable resources such as energy, clean water, and nutrients. The toilet should be able to operate without connections to water, sewer, or electrical lines and cost less than US$0.05 per user per day. Most importantly, it promotes sustainable and financially profitable sanitation services and provides business opportunities that can operate in poor, urban settings.

Chemical engineers focusing on process technology to design toilets that could provide the means to produce human waste-based fertilisers are doing a lot of work, but there has been little emphasis on linking these sanitation technologies to agricultural production. This chapter reviews information on the use of human excreta-derived materials (HEDMs) in agriculture. The review describes innovative sanitation technologies for nutrient recovery from human waste with potential for agricultural use. Information on the technology and products processed from human waste is reviewed. The fertiliser value of HEDMs and the cost-benefit analysis for their use are analysed. The review discusses the risks to human health and the environment, social acceptance and analyses policy and regulatory frameworks governing the sustainable management of waste and concludes by highlighting the major issues affecting initiatives linking sanitation and agriculture and makes recommendations for further research.

2.2 Opportunities for nutrient recovery from sanitation systems

There are several sanitation technologies (both waterborne and waterless) that have been designed, which could provide opportunities for the recovery of mineral elements necessary for crop production (Etter et al., 2011, Foxon et al., 2005, Fumasoli et al., 2016). These include Ventilated Improved Pit latrines (VIPs), Urine Diversion Dry Toilets (UDDTs), the Decentralised Wastewater Treatment System (DEWATS) and new designs tested under the BMGF “Reinvent the Toilet Challenge”. The following section provides a brief description of these technologies.

2.2.1 Ventilated improved pit latrines

The VIP is a dry, on-site sanitation technology which consists of a pit latrine, superstructure and a mechanism to control vectors (Konradsen et al., 2019). The VIP is recognised as the minimum form of basic sanitation and they have been constructed in many rural areas of South Africa. However, there were no plans put in place for pit emptying and therefore the superstructure is abandoned after its life span (Bakare et al., 2015, Salisbury et al., 2018) and this is not sustainable. Since the VIP is not closed at the base, contained material is in contact with the soil, so that people are at risk of contracting water-borne diseases as the leachates move down the profile. Some South African municipalities have been trying to enact pit emptying programmes. For example, in eThekwini, the municipality has implemented a programme to empty pit latrines every 5 years (Septien et al., 2018, Zuma et al., 2015). The costs associated with pit emptying are generally high in most countries due to the need to transport the faecal sludge from households to the nearest wastewater treatment plant, and in some areas roads are poorly maintained and the terrain may prevent movement of heavy vehicles (Manga et al., 2021, Sagoe et al., 2019). To minimise transport costs the burying of faecal sludge on-site using deep row entrenchment followed by covering with soil and planting trees has been investigated by Still et al. (2012).

2.2.2 Urine diversion dry toilets

The concept of the UDDT is based on the principle of urine separation from faeces and is a low-cost effective technology designed in such a way that urine is collected and drained from the front area of the toilet, while faeces drop through a large hole in the back. These toilets are designed according to anal cleansing processes to ensure that faecal matter does not block the urine area and urine does not spray into the faecal matter compartment. Drying material such as sawdust, lime, soil and ash are added to the faecal compartment after defecation to promote drying, pathogen die-off and to raise the pH (Niwagaba et al., 2009).

There are three types of UDDTs, namely, single vault, double vault and tecpan. The single vault is characterised by a single compartment for faecal collection along with storage; secondary treatment of the faecal matter is required for this type of UDDT. The double vault has twin-pit compartments, used alternately. When one vault is full with faecal matter, the compartment is sealed and the other compartment is used. The tecpan has metal sheets as vault chamber doors, exposed to the sun, to absorb and transfer heat into the vaults and speed up the drying process. This is a popular model in Africa distributed by Centre Régional de l’Eau Potable et l’Assainissement à faible couts (CREPA), an organisation working in 16 African countries (Benin, Burkina Faso, Burundi, Cameroon, Central African Republic, Congo, Côte d'Ivoire, Gabon, Guinea Bissau, Guinea, Mali, Mauritania, Niger, Rwanda, Senegal, and Togo) to improve water, sanitation and hygiene in poor communities.

Sanergy, a Nairobi based initiative, is promoting the use of UDDTs under the name Fresh Life Toilets (FLT) (Figure 2.1). The facilities allow excreta to be stored in sealed cartridges, ensuring that foul odours and flies are not a problem, and making it hygienic for the surrounding community. Sanergy franchises FLTs to local informal settlement residents who run them as businesses. The enterprise supports FLT owners by providing business training and guaranteed waste collection while the owners are committed to cleaning the toilets and keeping them open. Properly equipped Sanergy staff (Figure 2.1) collect excreta daily. Full cartridges are gathered using wheelbarrows, handcarts and/or trucks, from facilities located in inaccessible areas. Approximately 1 134 FLTs are in the informal settlements of Nairobi (Auerbach, 2016). This initiative has provided decent sanitation to over 50 000 people and about 500 metric tons of waste were safely removed from Nairobi informal settlements in 2017. It has also reduced the use of ‘flying toilets’, where a plastic bag used to collect human faeces is tied and discarded on the roadsides or thrown as far away as possible.

Figure 2.1: A person cleaning a Fresh Life Toilet (left) and a worker collecting excreta from the toilet (right). Adapted from Auerbach (2016).

The eThekwini municipality, a coastal urban settlement in KZN, has installed approximately 85 000 UDDTs. These toilets serve about 500 000 residents in the peri-urban areas of Durban (Roma et al., 2010). The Valorisation of Nutrients in Africa (VUNA) Project, based at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, in collaboration with eThekwini Water and Sanitation (EWS) and the Pollution Research Group (now renamed WASH R&D Centre), University of KwaZulu-Natal (PRG-UKZN) used urine collected from approximately 700 UDDTs in Ntshongweni, Ntabankulu and Cliffdale for research on resource recovery between 2010 and 2015.

The UDDT technology is a sustainable approach to sanitation challenges because it can function without water and provides opportunities for nutrient recovery thus playing a major role in closing the nutrient loop. However, the use of UDDTs depends on the willingness and acceptance of the residents. Institutions responsible for installation of UDDTs should involve the communities in awareness programmes on the proper use and maintenance of UDDTs and waste disposal before installation. In addition, the technology is viewed by UDDT users as inferior as it is mainly installed in low income and informal settlements. Duncker et al. (2006) suggested targeting middle and high income earners to promote the technology through the eco-village concept to create some “status” for the technology.

2.2.3 Decentralised wastewater treatment systems

Decentralised systems are waterborne, low-cost sanitation technologies designed to collect, treat, reuse or dispose of wastewater at or near the generation point. In this context wastewater refers to effluent generated from domestic waste treatment systems. These systems include septic tank systems and innovative designs of on-site systems. The Bremen Overseas Research Development Association (BORDA) has been working with local universities, research institutes and municipalities in developing countries to foster the supply of sanitation, water and energy and is involved in the development of DEWATS technology. The organisation has implemented various projects in Mali, Lesotho, Zambia, South Africa, Tanzania, Afghanistan, Iraq, Indonesia, Philippines, Laos, Vietnam, Cuba, Ecuador, Haiti, Mexico and Nicaragua. In South Africa, BORDA is currently collaborating with eThekwini municipality and the PRG in experiments on the implementation of a DEWATS system connected to 83 households in a residential area at Newlands Mashu, Durban. There are plans to construct several DEWATS plants in informal settlements.

The DEWATS at Newlands Mashu consists of two settling chamber, three parallel anaerobic baffled reactor (ABR) trains and three anaerobic filter (AF) modules, a vertical flow constructed wetland (VFCW) and a horizontal flow constructed wetland (HFCW) (Figure 2.2).

The ABR is a high-rate digester, consisting of alternate hanging and standing baffles designed to treat wastewater. It has undergone improvement in design over the years to make it suitable for treating a wide variety of wastewaters (Barber and Stuckey, 1999). Studies by Foxon et al. (2005) have shown that an ABR treating domestic wastewater will convert a large amount of wastewater chemical oxygen demand (COD) to methane gas, and will reduce pathogen loads in the treated effluent.

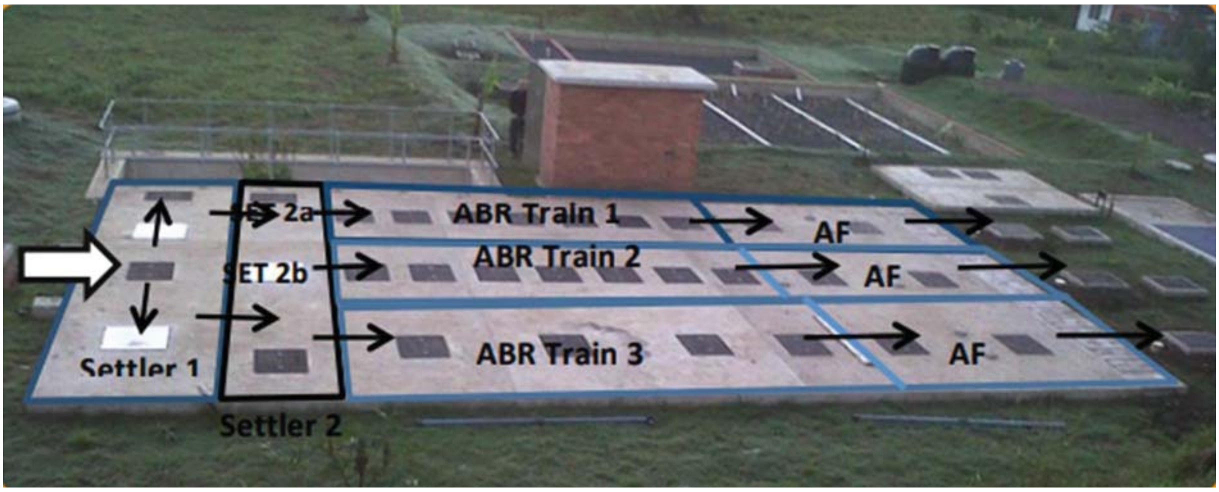


Figure 2.2: The Decentralised Wastewater Treatment System (DEWATS) constructed at Newlands Mashu, Durban, South Africa (ABR: anaerobic baffled reactor; AF: anaerobic filter; SET: settler).

Despite considerable reduction of pathogen load, secondary treatment is required before the treated effluent can be safely used in conventional irrigation. The process does not remove nutrients and the pathogen load is not low enough to render the effluent safe for human contact. The presence of significant amounts of nitrogen (N) as ammonium (NH4) and phosphorus (P) in the effluent means that it cannot be discharged into surface water or groundwater bodies. However, the NH4-N and P are mineral elements important for crop growth and this means that the effluent can be used to irrigate crops or disposed of in a soak-away (Foxon et al., 2005).

Except in the case where enough area and infrastructure are available to build a sub-surface soak-away system, some post-treatment of the effluent is required before it can be reused. It has been recommended that the use of membrane bio-filters in conjunction with the ABR be considered since a bio-filter would remove virtually all COD and pathogens, while allowing nutrients, which have a real economic value as a fertiliser, to be retained for use in agriculture (Foxon et al., 2005). Embarking on membranes is very costly and would not be economically viable. Other post-treatment options are constructed wetlands as used at Newlands Mashu.

2.2.4 The Reinvent the Toilet Challenge

The BMGF initiative on a reinvented toilet has led to new ideas on the design of future toilets that use little or no water and could allow the recovery of resources. The Challenge produced several winners. California Institute of Technology won the first prize for designing a solar-powered toilet that generates hydrogen and electricity. Loughborough University won the second prize for a toilet that produces biological charcoal, minerals and clean water. The University of Toronto designed a toilet that sanitises faeces and urine and recovers resources and clean water.

These technologies offer opportunities for the recovery of resources needed for crop production. This is particularly important in sub-Saharan Africa, where smallholder farmers are responsible for 80% of the agricultural production and use about 8 kg of fertiliser per head compared to 150 kg in South-East Asia. In the following section, information on the use of HEDMs in agriculture is reviewed.

2.3 Human excreta-derived materials with potential for agricultural use

Most practice and experience with the use of human excreta in agricultural systems is found in India, China, Japan, Korea, Nepal, Vietnam and Thailand (Blum and Feachem, 1985). Wolgast (1993) calculated that one person produces approximately 5.7 kg of N, 0.6 kg of P and 1.2 kg of potassium (K) per year in the form of excreta. The total amount of nutrients produced by human excreta annually in sub-Sahara Africa is estimated to be 2.2 million tons of N, 0.5 million tons of P_2O_5, and 0.4 million tons of K_2O (Magdoff et al., 1997).

Urine has potential for use as a form of fertiliser because it contains 90% of the N, 50-65% of the P and 50-80% of the K, while most of the organic matter is contained in the faeces. Urine can be treated to eliminate pathogens and pharmaceuticals that may be contained in the collected urine and to prevent N losses through volatilization. The VUNA project has developed treatment processes to produce urine-based fertilisers, such as struvite and nitrified urine concentrate (NUC).

2.3.1 Struvite

Struvite is a magnesium ammonium phosphate ($MgNH_4PO_4.6H_2O$) produced through urine precipitation, filtration and drying (Figure 2.3). Struvite crystals form after the addition of a magnesium (Mg) source, followed by filtration to separate the crystals from the liquid and finally drying of the crystals removes all the liquid. About 91% of the P but less than 4% of the N is precipitated from the urine, which makes struvite a phosphorus source (Etter et al., 2011).

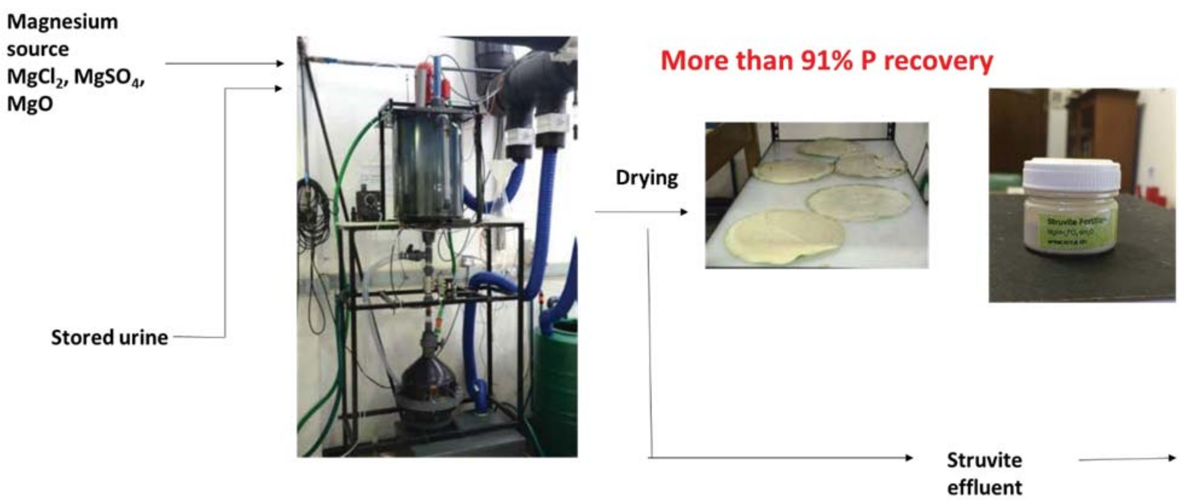


Figure 2.3: The struvite production process. The reaction takes place in the automated reactor shown on the left.

2.3.2 Nitrified urine concentrate

Nitrified urine concentrate is processed through biological nitrification and distillation. The nitrification process stabilises the collected urine. Half of the urine being processed, which in most cases is a foul-smelling liquid because of bacteria contained in the urine and with a high concentration of volatile ammonia (NH_3), is oxidised into non-volatile nitrate (NO_3^-); the other half is stabilised as non-volatile NH_4^+. The NH_3-oxidising bacteria produce nitrite, which is converted to nitrate by the nitrite-oxidising bacteria. Heterotrophic bacterial groups remove organic substances that are responsible for the foul smell. After the nitrification process, water is removed from nitrified urine by distillation and this results in a concentrated nutrient source. Distillation removes 97% of the water but all the salts remain in a solution including sodium chloride, which might pose problems for the final product's use as a fertiliser.

The Swiss Federal Office of Agriculture issued a provisional permit in 2015 to allow distribution of NUC as a flower, lawn and ornamental plant fertiliser. It is being packaged and sold under the name Aurin (Figure 2.4 and Figure 2.5) by Vuna GmbH, a company established in 2016 from the BMGF funded VUNA project. Aurin's instruction label informs customers to use the fertiliser once a month in well-ventilated areas and on moisture-absorbing soils. The dilution ratio is 10 mL of fertiliser to 1 L of water m^{-2}.

Figure 2.4: Commercialised nitrified urine concentrate with the trade name Aurin.

Figure 2.5: Instruction label of Aurin indicating application rates and methods along with disposal procedures and storage in French and English.

2.3.3 *Waste-based products*

Sanergy in Nairobi processes waste generated from the FLTs to form a nutrient-rich organic fertiliser known as Evergrow. Faecal matter is mixed with organic matter and composted to form the product. The production of this fertiliser started in 2013.

In Ghana, a treatment system involving the composting of dried faecal sludge, with or without the addition of organic matter (e.g. market or domestic waste) and enrichment with inorganic fertiliser, was developed. Nikiema et al. (2013) confirmed that the resulting products are safe, and their use represents a sustainable approach to improving soil fertility and crop production.

Biosolids which are a by-product sludge of wastewater treatment processes primarily derived from publicly owned treatment systems can be applied directly to the soil. They can be applied either as a liquid or semi-solid following dewatering (Epstein, 2002). According to Coote (2017), in Australia, approximately 180 000 tonnes of biosolids are collected and trucked to 20 farms and several mine rehabilitation sites around Sydney. Biosolids production in Europe is approximately 4.7 million tons of dry material per year, and about 50% is applied as an organic amendment to agricultural lands (EUROSTAT, 2017). Biosolids application to soils increases their organic matter content, water-holding capacity, porosity and nutrient levels, which, in turn, contribute to plant growth and yield (Singh and Agrawal, 2008).

2.3.4 *The use of Black Soldier Fly (Hermetia illucens) to process human waste into useable products*

Sanergy has also been testing the development of insect-based animal feed derived from Black Soldier Fly Larvae (BSFL). The BSFL consume large quantities of organic matter in a short period, and once the larvae stop feeding, they are boiled and dried, resulting in a high-protein animal feed, suitable for a variety of livestock. According to Auerbach (2016), Sanergy's trials have gone well thus far, and the BSFL operations are expanding rapidly.

Biocycle, a South African based organisation, currently operating with Agriprotein, a livestock feed company, has been leading the BSFL technology to process food and faecal waste to produce marketable products. The EWS engaged with Biocycle to develop a model to use the BSFL technology to process faecal waste from UDDTs. The process involves the breeding of the BSFs and the use of their larvae to process the faecal waste mixed with food waste (Figure 2.6). Food waste is added to the faecal waste to ensure a balanced food source for the larvae. The by-products are the mature larvae, larvae oil and residual organic matter. The larvae can be used as a protein source in the livestock industry.

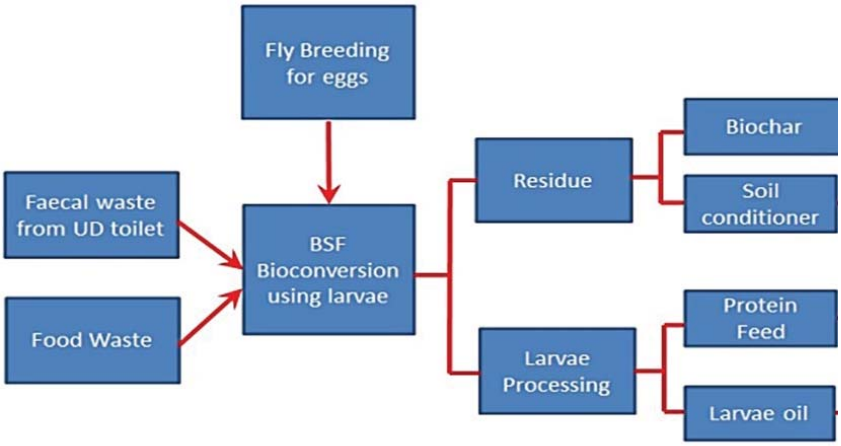


Figure 2.6: Black Soldier Fly Larvae (BSFL) technology processing faecal waste from urine diversion (UD) toilets and food waste to produce marketable products (Mutsakatira et al., 2018).

2.3.5 Biochar production

The residual organic matter from the BSFL technology can be used as a plant nutrient source, soil conditioner or processed to make biochar. Biochar is processed through pyrolysis which involves the thermal transformation of biomass under limited or no oxygen supply. Biochar is receiving attention due to its perceived potential to improve soil productivity. Incorporation of biochar can improve soil physical, chemical and biological properties (Lehmann and Joseph, 2015). Biochar application to the soil increases soil aeration, porosity and specific surface area (Laird et al., 2010), water-holding capacity and drainage condition (Burrell et al., 2016, Devereux et al., 2012, Jien and Wang, 2013).

2.3.6 Latrine Dehydration and Pasteurisation

The Latrine Dehydration and Pasteurisation (LaDePa) technology was designed to process faecal sludge, especially from pit latrines, by eThekwini municipality in conjunction with Particle Separation Systems Technologies (Pty) Ltd. Faecal sludge is treated over several successive thermal and mechanical treatment processes. The LaDePa machine separates detritus from dewatered sludge through screws, which deposit pellets on a moving belt (Figure 2.7). The pellets are dried at 100°C and pathogen reduction is achieved through infrared radiation. The machine has been modified to treat any sludge with between 20 and 35% solids to pasteurise it to an 80-90% solid product.

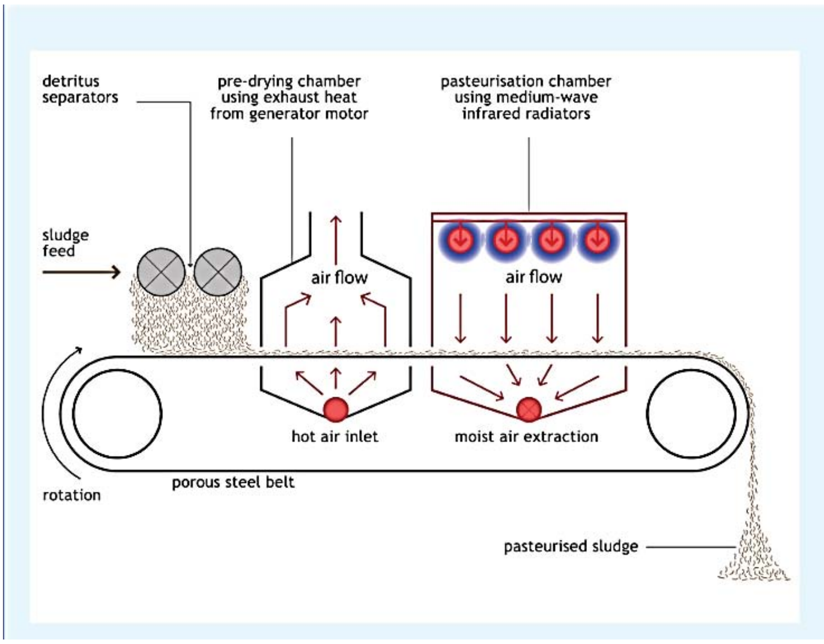


Figure 2.7: Schematic representation of the LaDePa machine designed to process faecal sludge into pasteurised sludge. Adapted from Kengne et al. (2014).

2.4 The fertiliser value of human excreta-derived materials

Several studies on the use of urine as a nutrient source for crop production have been conducted. (AdeOluwa and Cofie, 2012) investigated the response of green amaranths (Amaratha caudatus) to urine and municipal waste composts and their mixtures as fertiliser and observed that 100% urine performed better as a fertiliser at both main and residual plantings. Financial returns using urine as fertiliser also doubled those of the commonly used commercial NPK fertiliser (AdeOluwa and Cofie, 2012). Akpan-Idiok et al. (2012) investigated the use of human urine as an organic fertiliser to produce okra (Abelmoschus esculentus) in Nigeria and reported that the concentration of leaf N and P in 15 000 L urine ha^{-1} plots were comparable to the NPK treated plots. The okra leaf concentrations of calcium (Ca) and Mg were significantly ($p < 0.05$) increased with an increase in the application rate of urine compared to the control or NPK fertiliser treated plots. Similar studies were done by Pradhan et al. (2009) using tomato (Solanum lycopersicum) in a greenhouse experiment to evaluate the effectiveness of mineral fertiliser (NPK), mixture of urine and wood ash, urine only and control (no fertilisation) showed that the urine fertilised tomato plants produced equal amounts of fruit as mineral fertilised plants and more fruits than non-fertilised plants. Not much work has been reported in recent years on the direct use of urine to grow crops. This is mainly due to advances in urine processing technologies described in the preceding sections. Recent studies have focused on the effectiveness of urine-derived products as fertilisers for crop production rather than urine.

The fertiliser value of struvite is well documented in the literature. Nongqwenga et al. (2017) investigated the potential use of struvite as a P source for maize production. The maize was planted in three contrasting soils and the pattern of P released by struvite quantified. The results showed that the P released from struvite in all three soils was at a maximum within 10 days of incubation and could be considered plant available. The study concluded that struvite would be most effective in soils with low initial P, Mg, and P-sorption maxima. These results agree with the work done by Antonini et al. (2012) which compared struvite with triple superphosphate (TSP) and concluded that struvite was more effective on a long-term basis than conventional fertiliser. The explanation for the conclusion by Antonini et al. (2012) can be related to Neumann and Römheld (1999) findings that in the case of sparingly soluble P sources, P deficiency triggers roots to produce phosphatase acid which enhances P solubility of the source thus improving P availability. Acidic soils could improve the solubility of struvite and may make P readily available for plant uptake. This is evident from the work done by Cabeza et al. (2011) who concluded that struvite can be as effective as TSP, even in soils of contrasting properties. Similarly, Ryu et al. (2012) reported that there was a growth improvement of Chinese cabbage (Brassica rapa) with an increase in struvite application rates. Gell et al. (2011) noted that struvite contains a significant number of micronutrients and essential nutrients (K, sodium (Na), sulfur (S), iron (Fe) and Ca) at levels near 1% (w/w) and this composition imparts a further positive quality to struvite, which extends beyond just recovering P and N, compared to conventional P fertilisers. Studies done on the effectiveness of struvite for crop production have focused on nutrient availability, especially of P. However, there is need to consider other factors that might affect crop production and the food quality such as the chemicals of environmental concern. These include pharmaceutical residues and metabolites from the breakdown of antibiotics. These chemicals in ionic form could probably pass through the root cell membranes and accumulate in plants. The effects this could have on soils, crop quality and human health are largely unknown.

Bonvin et al. (2015) investigated the uptake of N from 15N-labeled NUC produced from synthetic urine as a model for source-separated human urine. The study reported that the effectiveness of NUC was comparable to commercial chemical fertilisers. Plants grown using this synthetic NUC took up 72% of the N applied as compared to 77% taken up by plants grown using commercial chemical fertiliser.

A few studies have been conducted on the use of treated effluent from wastewater treatment systems on crop production. Bame et al. (2014) demonstrated that NH_4^+-N in ABR effluent undergoes nitrification in soils to form nitrate, which is subsequently taken up by plants. In a study on the effect of irrigation with ABR effluent on Swiss chard yield, nutrient uptake and leaching, Musazura et al. (2015) concluded that using ABR effluent as a source of nutrients and water was comparable to the use of commercial fertilisers and water. Use of wastewater as a nutrient source in hydroponic systems could be a viable option, especially during the wet season when soils may be saturated and field crops do not require supplemental irrigation. Mavrogianopoulos et al. (2002) conducted a study on the use of wastewater as a nutrient solution in a closed gravel hydroponic culture of giant reed (Arundo donax) and the results showed that stem biomass production was more than ordinary production in soil.

The use of aquatic vegetation to absorb large amounts of nutrients has been investigated. This might constitute an effective means of removing nutrients from effluents and the harvested plants can then be used directly as fertiliser or added to compost. A study conducted by Sutton and Ornes (1975) concluded that duckweed (Lemna minor) has the potential for removing large quantities of N, P, and K from wastewater.

2.5 Agricultural management practices when using human excreta-derived materials

The effectiveness and use-efficiency of HEDMs depend on good management practices including methods, rates and timing of application. The liquid nature of NUC requires proper application methods. Foliar application is often used for liquid fertilisers. A foliar-applied nutrient passes through the cuticular wax, the cuticle, the cell wall, and the membrane in that order (Middleton and Sanderson, 1965; Franke, 1967). However, foliar fertilisation is a technique often used when soil application is ineffective. This could be due to immobilization of soil-applied nutrients or when such methods of application are too expensive. Foliar sprays are used also because they are often more immediately effective than soil-applied chemicals or when the soil is not accessible due to complete crop cover, for instance.

Foliage burning is a major risk encountered in foliar application. It is more likely when the N source is ammonium nitrate or ammonium sulfate rather than urea (Alkier et al., 1972). The reason for this is that urea has a low salt index and therefore desiccation of leaf cells through osmosis is reduced (Gooding and Davies, 1992). Foliar application may not be a good application method for NUC because the ammonium and nitrate content may cause foliage burning. The use of NUC as a source of nutrients in hydroponics may be another option in crop production.

Struvite, being a solid fertiliser, is best soil-applied. However, struvite is in powder form which makes it difficult to apply on a large scale or in windy conditions. Further processing may be required to produce struvite as pellets or in granular form to ameliorate this problem.

There is evidence in the literature on the potential use of struvite and NUC as plant nutrient sources, but most of these studies were laboratory-based, used synthetic urine and focused on macronutrients. Not much work has been done on the interaction between these plant nutrient sources processed from actual urine and on different soils to determine their effect on crop growth and crop nutritional value. The effect of substances such as pharmaceuticals and Na contained in these urine-derived plant nutrient sources on soil properties, crop growth and food quality is largely unknown.

2.6 Cost-benefit analysis for the use of human excreta-derived materials

A major challenge about the use of HEDMs is whether it would be cost-effective in terms of farmers being able to use them and realise profits. The PRG conducted an economic evaluation of replacing inorganic fertilisers with LaDePa pellets in 2013. The results indicated that there is no economic benefit if LaDePa pellets are used to substitute for inorganic fertilisers. Also, the analysis did not account for transportation, storage equipment and labour. These costs would probably increase if LaDePa pellets were used, due to the increased mass of LaDePa pellets needed to achieve the same benefit as conventional fertiliser (Table 2.1).

Table 2.1: Comparison of the quantities of different nutrients required to meet the nutrient requirements of dry beans.

Nutrient	Required nutrient for dry beans (kg required to produce 1 ha crop)	Mass of fertiliser required to achieve required nutrients (kg fertiliser ha^{-1})	
		Commercial (3:2:1)	LaDePa pellets
Nitrogen	37.5	300	2 049
Phosphorus	24.5	300	2 677
Potassium	12.5	300	7 357

Currently, there is no information on the financial costs and benefits of struvite and NUC use in agriculture. According to Jiménez et al. (2010) in Mexico, the estimated saving arising from using wastewater to supply the required N and P for crops was US$135.00 ha^{-1}. A study comparing vegetable production using freshwater and untreated wastewater in Haroonabad, Pakistan, concluded that the gross margins were significantly higher for wastewater (US$150.00 ha^{-1}) because farmers spent less on chemical fertiliser and achieved higher yields (Van der Hoek et al., 2002).

2.7 Risks to human health, the environment and social acceptance

Urine does not contain any pathogens except Salmonella typhi and Schistosoma haematobium, found in the urinary tract and which are excreted in the urine of infected persons. Therefore, other pathogens detected in urine are a result of contamination from faecal matter or menstrual blood. A study conducted by Bischel et al. (2015) on pathogen and pharmaceuticals in source-separated urine in eThekwini revealed that the most frequently detected viral pathogens were JC polyomavirus, rotavirus, and human adenovirus in 100%, 34% and 31% of samples, respectively. Aeromonas spp. and Shigella spp. were frequently detected gram-negative bacteria, in 94% and 61% of samples, respectively, and the gram-positive bacterium, Clostridium perfringens was found in 72% of samples. The antibiotics sulfamethoxazole and trimethoprim, which are frequently prescribed as prophylaxes for HIV-positive patients, were detected in 95% and 85% of samples, respectively.

Struvite production allows for pathogen die-off and reduction of pharmaceutical residue. According to Bischel et al. (2015), the main cause of pathogen die-off is the decreasing moisture content that occurs during struvite drying. Inactivation of the helminth Ascaris suum is significantly lower but the virus X174 is strongly affected by a decrease in moisture content. Washing of struvite with water before drying also lowers the concentration of pharmaceuticals in the end-product but does not completely remove all pharmaceuticals.

Treating for pathogens occurs during urine storage, biological nitrification and distillation of NUC production. However, urine storage and the nitrification process are too short to ensure that pathogens are completely inactivated. The bacteria Enterococcus spp. and Salmonella typhimurium are partially inactivated during nitrification but there is a possibility of complete inactivation if the nitrification process is extended. However, the viruses MS2, X174 and Qbeta were not inactivated by the nitrification process (Decrey et al., 2011). Distillation is an effective process in treating pathogens, as during this process nitrified urine is heated for several hours at a temperature of 80°C (Fumasoli et al., 2016).

Most pharmaceuticals are degraded during the nitrification process. Experiments conducted on the fate of pharmaceuticals during urine treatment revealed that atazanavir, clarithromycin, darunavir and ritonavir were completely inactivated in the nitrification plant after 10 to 24 hours (Bischel et al. (2015). The remaining pharmaceuticals are removed through the addition of powdered activated charcoal (PAC). According to Etter et al. (2015), the addition of 200 mg PAC L^{-1} removed about 90% of pharmaceuticals that remained after nitrification and no beneficial nutrients were removed (Table 2.2).

Table 2.2: Pharmaceutical removal by powdered activated carbon (PAC). Adapted from the VUNA final report of Etter et al. (2015).

Pharmaceuticals analysed	Type of pharmaceutical	Elimination using 200 mg PAC L^{-1}
Atazanavir	Antiretroviral	> 99%
Atenolol	Beta blocker	98%
Clarithromycin	Antibiotic	> 99%
Darunavir	Antiretroviral	> 99%
Diclofenac	Analgesic	> 99%
Emtricitabine	Antiretroviral	90%
Hydrochlorothiazide	Diuretic	97%
Ritonavir	Antiretroviral	> 99%
Sulfamethoxazole	Antibiotic	96%
Trimethoprim	Antibiotic	> 99%

Wastewater irrigation and biosolids application introduce pharmaceuticals and personal care products (PPCPs) into the soil environment. Irrigation with wastewater continuously introduces PPCPs to the soil solution, however, biosolids application allows the addition of PPCPs periodically every few growing seasons. Wastewater acts as a source of PPCPs while biosolids can act both as a source and a sink due to their adsorptive capacity (Fu et al., 2016). Decomposition of the biosolids in the soil after amendment enhances their adsorptive properties, which, in turn, reduces the bioavailability of PPCPs in the soil environment (Wu et al., 2016). A study conducted by Mordechay et al. (2018) on composted biosolids and treated wastewater as sources of PPCPs for plant uptake concluded that plant metabolism of the pharmaceutical, carbamazepine, is independent of soil type, carrier medium, and the absolute amount added to the soil, but was controlled by the total amount taken up by the plant.

The feasibility of using HEDMs for agriculture mainly depends on farmers' perceptions on the use of these products and consumers' willingness to buy food produced through their use. Duncker et al. (2006) investigated the social/cultural acceptability of using human excreta (faeces and urine) for food production in rural settlements of South Africa. The study revealed that most (76%) of the respondents in KZN were not willing to eat food that was grown with human urine, some (10%) believed it was unhealthy and culturally unacceptable. Roma et al. (2013) provided an overview of current perceptions of UDDT users in eThekwini municipality on the re-use of urine for agricultural purposes. Respondents were asked whether they would use fertiliser based on the urine of their family members or urine obtained from other people. More than half of respondents (53.3%, n = 252) reported they would use fertiliser from the urine of family members. On the contrary, only 20.5% (n = 97) would use urine-based fertiliser from urine of their neighbours. Promoting HEDMs for crop production requires a paradigm shift towards human excreta where it is viewed as a resource rather than a malodorous waste.

2.8 Policy and regulatory frameworks governing the sustainable management of human excreta-derived materials

Wastewater use guidelines have been developed to ensure that wastewater is handled in a safe manner that will protect the public, consumers and the workers exposed (Food and Agriculture Organisation, 1992, Scott et al., 2004, World Health Organisation, 2006). International wastewater health guidelines were produced by the World Health Organization (World Health Organisation, 2006) that included epidemiological data, risk assessments and other relevant information. These guidelines, although not applicable internationally due to differences in social, economic and political practices do, however, act as international standards. The guidelines consider factors such as crop restriction (eaten raw vs cooked), method of irrigation (sprinkler vs drip), worker safety (vaccination and sanitation education) and the quality of wastewater used (thresholds of pathogens) (Food and Agriculture Organisation, 1992). The WHO guidelines for the safe use of wastewater, excreta and greywater highlight maximum soil concentrations of certain elements and organic compounds as health protection measures.

The International Standards Organisation (ISO) is currently working in 162 countries to develop and publish international standards. The ISO 16075-1:2015 contains guidelines for the development and the execution of projects intending to use treated wastewater for irrigation and considers the parameters of climate and soil. These guidelines are intended to assist users of treated wastewater for irrigation of crops, public and private gardens, and landscape areas including parks, sports fields, golf courses and cemeteries.

In South Africa, existing guidelines for wastewater use have focused mainly on the potentially harmful effects of heavy metals and have not considered the potential benefits of using nutrient-rich effluent from low-cost sanitation technologies for irrigation purposes. The Department of Water Affairs in terms of Section 39 of the National Water Act (1998) requires that a person who irrigates with wastewater must submit to the responsible authority a completed registration form or any other information requested in writing by the responsible authority for the registration of the water use.

Previously, (1991-2002), several guidelines for sludge management were in place. These included the following: (1) Water Research Commission (1997) Permissible Utilisation and Disposal of Sewage Sludge, (2) Water Research Commission (2002). Guide: Permissible Utilisation and Disposal of Sewage Sludge and (3) South African Sludge Guidelines published by the Department of Health (1991). These sludge guidelines were mainly based on international research results and guidelines. However, the guidelines have been revised based on a series of studies on waste management undertaken by the Water Research Commission. Reports were produced on quality of South African sludge, agricultural use of sewage sludge, dedicated land disposal and sludge treatment technologies. The revised guidelines for the utilisation and disposal of wastewater sludge in South Africa were prepared by Snyman et al. (2006). These authors describe wastewater sludge as material removed from wastewater treatment plants designed to treat domestic wastewater which includes the following products, raw or primary sludge from a primary clarifier, primary sludge from an elutriation process, anaerobically digested sludge both heated and cold, digestion oxidation pond sludge, septic tank sludge, humus sludge, pasteurised sludge, heat-treated sludge, lime-stabilised sludge, and composted sludge. The guidelines comprise of 5 volumes, covering issues concerning selection of management options, requirements for the agricultural use of sludge, requirements for the on-site and off-site disposal of sludge, requirements for the beneficial use of sludge and requirements for thermal sludge management practises and for commercial products containing sludge.

2.9 Summary and conclusion

This Chapter has reviewed the potential use of HEDMs in agriculture. In summary, there is a need for reliable data generated through research to produce information for initiatives aimed at upscaling sanitation technologies linked to agriculture. In the case of the use of DEWATS effluent for irrigation of crops, there is need to consider management of the effluent in different seasons including storage especially during the wet season when soils may be saturated, and crops do not need additional water. The DEWATS could be used to grow aquatic plants to take up nutrients from wastewater and the harvested biomass used to make compost or used directly as green manure.

The presence of chemicals of environmental concern in HEDMs may pose a major threat to the health of people using them and consuming food produced from these products. There is little information on the uptake of pharmaceuticals by plants through added human excreta, especially urine. Research is needed to look at more crops and a range of different soils over a longer time to assess the full potential for using HEDMs to monitor both positive and negative impacts. Data generated through research should be used to inform policy and the development of guidelines for the safe use of HEDMS in agriculture.

The successful commercialisation of HEDMs requires understanding the dynamics of the market the products will be sold in. More importantly, demand for the products and the price end-users are willing to pay for the products need to be examined. Currently, there is no information on the financial cost of struvite, NUC and DEWATS effluent use in crop production. Future studies should also consider the environmental and social benefits of using HEDMs in agriculture along with economic benefits. In performing a cost-benefit analysis, governments and policy planners should take into consideration the savings in terms of waste disposal and the contributions such initiatives would make concerning job creation, improved food security particularly for rapidly increasing urban populations and better environmental protection.

3 CHARACTERISATION OF HUMAN EXCTRETA-DERIVED MATERIALS FOR AGRICULTURAL USE.

3.1 Introduction

The VIP is legally recognised as the minimum basic sanitation technology that is widely used in various rural areas of South Africa (CSIR, 2005, Masindi and Duncker, 2016). In response to the urgent sanitation needs of the residents as eThekwini expanded its city boundary in 2002 from 1 366 to 2 297 km^2 thereby serving a larger population of about 3.5 million, UDDTs were commissioned (Gounden et al., 2006). The major advantage of a UDDT is the separation of faeces and urine. However, the separated human excreta are not being valorised; urine is allowed to drain into a soakaway and the faecal matter is buried on-site (Gounden et al., 2006), which is not environmentally sustainable in the long term.

There is a paradigm shift regarding human excreta where the focus is on reuse rather than only disposal. Some limitations to the agricultural use of HEDMs are their high pathogen loads, which are relatively higher in faeces than urine (Bischel et al., 2015), hence they need treatment before being used safely in agriculture. The other aspect is social perceptions toward handling and using human excreta. For example, according to Wilde et al. (2019), most farmers prefer to use nitrified urine concentrate (NUC) than raw urine since it does not smell. Therefore, to improve consumer acceptance of HEDMs, collection methods, handling, and containment that eliminate malodours are recommended (Andersson et al., 2016, Kengne et al., 2014, Snyman et al., 2006). There are various technologies available that allow the valorisation of human excreta in a way that increases consumer acceptance. These include DEWATS treatment for irrigation water, faecal matter processing (pyrolysis, pelletisation and co-composting) and urine processing (precipitation, nitrification and distillation). Products produced by urine processing include struvite and NUC or it can directly be used after storage. Faecal matter processed products are biochar, LaDePa pellets and composts.

From previous WRC projects (K5/2002 and K5/2220) the DEWATS effluent and other HEDMs have been monitored for physicochemical and biological properties, and this continued in the current project (K5/2777). This chapter aims to characterise the various HEDMs as fertilisers that can be safely used in a social, environmental, economic and agronomically acceptable manner. The information generated has been used to partly inform the practical guidelines (Volume 2) on agricultural use of HEDMs.

3.2 Materials and methods

3.2.1 Human excreta-derived materials sources

The scope of the study was based on HEDMs emanating from on-site sanitation systems. These include the DEWATS, faecal sludge from VIPs and UDDTs, and source separated urine. Most of these studies were done at Newlands Mashu in Durban, South Africa.

3.2.1.1 Irrigation water: DEWATS effluent

The pilot DEWATS plant was commissioned by eThekwini Water and Sanitation (EWS) at Newlands Mashu where BORDA, in collaboration with the University of KwaZulu-Natal (PRG) undertook research to assess its suitability for on-site sanitation in peri-urban communities. The DEWATS is a modular system comprised of the Settler, Anaerobic Baffled Reactor (ABR), Anaerobic Filter (AF) and the Planted Gravel Filters (PGFs) (Gutterer et al., 2009). The domestic wastewater from 83 households is treated in the ABR and then AF through anaerobic degradation of organic compounds and the effluent produced contains mineral nutrients such as nitrogen (N) and phosphorus (P), which are above the discharge limits into water bodies (Foxon et al., 2005). The hybridised system allows further treatment of the AF effluent in the PGFs (Vertical Flow Constructed Wetland; VFCW and then the Horizontal Flow Constructed Wetland, HFCW), where some pathogens are removed and inactivated and aerobic conditions promote nitrification of ammonium-N (Gutterer et al., 2009). In this study effluents from the AF and the HFCW are used.

3.2.1.2 Faecal sludge-derived products

In 2002, over 35 000 VIPs constructed in eThekwini were full of sludge dating back 10-20 years. eThekwini Water and Sanitation (EWS) commenced a programme to empty VIPs through a single free emptying every 5 years (Zuma et al., 2015). The challenge of the safe disposal of the sludge remained. Several faecal matter processing options have been considered. The EWS and Particle Separation Systems Technologies (Pty) Ltd (PSS) developed the Latrine Dehydration and Pasteurisation (LaDePa) machine which dries and pelletises faecal sludge making it easy to handle, sterile and odour free (Harrison and Wilson, 2012). Another way faecal sludge is being valorised, is by the use of black soldier fly larvae (BSFL) production being piloted by Biocycle ® at Isipingo Wastewater Treatment plant (Mutsakatira et al., 2018). The process produces 0.66 tonnes of residue per 1.08 tonnes of feedstock. Biocycle ® has been considering alternative options to deal with the process residue and exploring towards testing its agricultural potential by pyrolysis and co-composting. In this study only LaDePa pellets have been investigated for their agricultural use.

3.2.1.3 Urine-derived products

The UDDTs allow separation of faecal matter from urine, which is advantageous in the sense that malodours are reduced, faecal matter dries faster and is less attractive to vectors, but these waste streams were not valorised. The Valorisation of Urine Nutrients in Africa (VUNA) project (Etter et al., 2015) led by EAWAG (Swiss Federal Institute of Aquatic Science and Technology) and co-partnered with the PRG and EWS was thus established. The project assessed different technologies for valorising urine from 82 000 UDDTs in eThekwini and its processing into various products such as struvite and NUC, and how these together with P-depleted urine (struvite effluent) can be used for agriculture.

3.2.2 Methodology

Human excreta-derived materials were characterised for their biological, physical and chemical properties. The data were either collated from published sources or collected during the current project.

3.2.2.1 DEWATS effluents

The effluents from two sections of the DEWATS (AF and HFCW) were monitored for their biological and physicochemical properties from January 2012 to February 2020. The effluents were characterised for nutrients, pH, chemical oxygen demand (COD), sodium adsorption ratio (SAR), electrical conductivity (EC), dissolved and suspended solids, specific ions, faecal coliforms, and heavy metals following standard methods for wastewater analysis (Rice et al., 2017). The average values were then compared to the quality guidelines for irrigation water at national (Department of Water and Sanitation, 1996) and international (Food and Agriculture Organisation, 1992) level.

3.2.2.2 LaDePa pellets

The LaDePa pellets characterisation data for microbiological, chemical and physical properties were obtained from an article by Septien et al. (2018) and PRG literature (Buckley, 2013).

3.2.2.3 Urine-derived products

Urine is the major carrier of N, P, K and micronutrients (Rose et al., 2015), pathogens (Schönning and Stenström, 2004), pharmaceuticals (Etter et al., 2015) and volatile organic compounds (Fumasoli et al., 2016) (Table 3.1). The urine-derived products used in this study were characterised for biological, chemical and physical properties using data from various sources.

Table 3.1: Sources of data used for characterising urine-derived products collected from on-site sanitation systems.

Property	Unit	Stored urine	Nitrified urine concentrate	Struvite
Chemical oxygen demand	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013), Udert and Wächter (2012), Randall et al. (2016)	Fumasoli et al. (2016)	
pH (H2O)		Etter et al. (2011), Decrey et al. (2011), Mchunu et al. (2018), Randall et al. (2016), Udert and Wächter (2012)	Fumasoli et al. (2016), Magwaza et al. (2020b),	
Electrical conductivity	ds m^{-1}	Mchunu et al. (2018), Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016), Udert and Wächter (2012)	Magwaza et al. (2020)	
Total N	mg L^{-1}	Mchunu et al. (2018), Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016), Udert and Wächter (2012)	VUNA (2020), Mchunu et al. (2018), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	Etter (2009), Etter et al. (2015), Tilley et al. (2009)
Nitrate-N	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016)	VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Ammonium-N	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016), Udert and Wachter (2012)	VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Total P	mg L^{-1}	Mchunu et al. (2018), Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016), Udert and Wachter (2012)	VUNA (2020), Mchunu et al. (2018), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	Etter (2009), Etter et al. (2015), Tilley et al. (2009)
Chlorides	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013), Randall et al. (2016), Udert and Wachter (2012)	VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b).	
K	mg L^{-1}	Mchunu et al. (2018), Decrey et al. (2011), Etter et al. (2013), Udert and Wachter (2012)	VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Ca	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013), Udert and Wachter (2012)	Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Mg	mg L^{-1}	Decrey et al. (2011), Etter et al. (2013)	Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	Etter (2009), Etter et al. (2015), Tilley et al. (2009)
Mn	mg L^{-1}		Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Na	mg L^{-1}	Mchunu et al. (2018), Decrey et al. (2011), Etter et al. (2013), Udert and Wachter (2012)	VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
B	mg L^{-1}		VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016).	
Co	mg L^{-1}		Fumasoli et al. (2016)	
Cu	mg L^{-1}		Fumasoli et al. (2016), Magwaza et al. (2020b), Measured.	
Cd	mg L^{-1}		Fumasoli et al. (2016), Measured	
Cr	mg L^{-1}		Fumasoli et al. (2016), Measured	
Fe	mg L^{-1}		VUNA (2020), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured	
Ni	mg L^{-1}		Fumasoli et al. (2016), Measured	
Pb	mg L^{-1}		Fumasoli et al. (2016), Measured	
Zn	mg L^{-1}		VUNA (2020), Etter et al. (2015), Fumasoli et al. (2016), Magwaza et al. (2020b), Measured	
Total coliforms	(cfu per 100 ml)	Etter et al. (2015)	Etter et al. (2015)	Etter et al. (2015)
Total viable helminth ova		Etter et al. (2015)	Etter et al. (2015)	Etter et al. (2015)

3.2.3 Data analysis

All the data were collated, and the means and standard errors calculated using the GenStat 20th Edition (VSN International, 2017). In instances where less than one set of data was found the mean and standard error determined by specific authors was chosen.

3.3 Results and discussion

3.3.1 DEWATS effluent

The biological and physicochemical properties of DEWATS effluent after two treatments stages (AF and HFCW) are reported in Table 3.2.The nitrate N concentrations were relatively higher in HFCW than AF effluent due to aerobic conditions in HFCW which promote nitrification. The nitrate values of the AF effluent were below the minimum threshold for unrestricted use (5 mg L^{-1}) (Food and Agriculture Organisation, 1992). The concentrations in the HFCW effluent allow slight to moderate restriction on use. Nitrates have implications for groundwater pollution, algal growth around the field as well as crop quality when applied in excess to sensitive crops (Ayers and Westcot, 1985).

The total N is higher in AF than HFCW and is predominantly in the form of ammonium-N. This is because of anaerobic digestion in the ABR and AF. Low total N in the HFCW effluent results from plant uptake in the PGFs and N volatilisation (Brix, 1994). This implies that management of N is important to avoid undesirable effects on crop growth and quality when AF effluent is used instead of the more dilute HFCW effluent.

Some other quality parameters such as organic matter, COD, pH, EC, total dissolved solids and alkalinity have impacts on irrigation infrastructure (Food and Agriculture Organisation, 1992). These promote accumulation of microorganisms which block irrigation pipes. The COD loading may increase soil C content, which improves soil structure, and water and nutrient retention capacity. However, excess organic C increases microbial activity which depletes soil oxygen and the resulting anoxic conditions may kill plant roots if not adapted to such an environment. Additional application of organic C may immobilise dissolved soil solution N. However, the above-listed parameters were below the levels recommended by both FAO and DWAF except for alkalinity in the AF effluent, which was within the slight to moderate range for restriction on use.

The World Health Organisation (WHO) guideline has a restriction on crop irrigation water quality with regards to pathogen loads. The target quality for unrestricted irrigation, for example on crops eaten raw, is ≤ 1 000 cfu (colony forming units) per 100 mL. Exceeding that concentration means special measures such as choice of irrigation methods (drip vs sprinkler) and crop type selection (e.g. eaten raw vs cooked or which bear fruits far away from the ground) must be considered (Ayers and Westcot, 1985, Food and Agriculture Organisation, 1992, World Health Organisation, 1989). The 50 000 cfu per 100 mL limit stated in both South African and FAO guidelines takes into consideration the extent to which microbial loads affect irrigation pipe clogging. The DEWATS treatment (even after the HFCW) does not treat all pathogens to allow unrestricted use (Odindo et al., 2016) but falls within the limits of irrigation water microbial quality suitable for the irrigation infrastructure. Although not reported in Table 3.2, studies by

Amoah et al. (2018) have shown the DEWATS system significantly removes Ascaris eggs compared to conventional wastewater treatment methods.

All the trace elements in AF effluent complied with the Department of Water and Sanitation (1996) standards for irrigation water. Low concentrations were due to the source of effluent, which originated from households where there is no contamination with industrial waste. The heavy metal values for HFCW were not analysed and an assumption was made that these were not present after not being detected in the AF treatment.

Table 3.2: Chemical, biological and physical properties of the anaerobic filter (AF) and horizontal flow constructed wetland (HFCW) effluent from the Newlands Mashu pilot plant (2013-2019) in comparison to the irrigation quality guidelines for the most severe restriction of crop use stipulated by the Department of Water and Sanitation (DWS) and Food and Agriculture Organisation (FAO).

Property	Unit	AF effluent			HFCW effluent			DWS limits	FAO limit
		Mean	Range	n	Mean	Range	n		
Total-N	mg L^{-1}	57.3±1.4	5-63	10	19±3	0.15-56	20	-	-
Nitrate-N	mg L^{-1}	2.1±0.5	0-4	9	5.6±4.2	1-26.8	6	< 30	5-30
Ammonium-N	mg L^{-1}	54.8±1.4	48-60	9	16.9±3.9	0.15-56	20	-	-
Orthophosphate-P		9.3±1.3	5-20	12	17.3±4.7	7.4-37.9	6	-	-
Total K	mg L^{-1}	14.2±2.3	8-19	4	*	*	*	-	-
Chemical oxygen demand	mg O_2 L^{-1}	465±288	81.2-2 500	6	64.7 ± 7.8	3.1-159	20	< 5000	-
pH(H2O)		7.6±0.1	7.3-8	9	6.7 ± 0.1	6.2-7.3	19	6-9	6.5-8.5
Electrical conductivity	mS m^{-1}	8.5±7.2	0.9-95	11	73.7±2.7	54-99	20	< 540	70-300
Total suspended solids	mg L^{-1}	91±17		3	4.8±6.7	1-26	20	-	450-2000
Alkalinity	mg $CaCO_3$ L^{-1}	199±38.7	7-319	5	nd	nd		-	92-519
S	mg SO_4^{2-} L^{-1}	61.3±10.8	48-74.4	3	nd	nd		-	
Al	mg L^{-1}	0.1	0-0.4	4	nd	nd		5-20	< 5
B	mg L^{-1}	0.02	0-0.06	4	nd	nd		0.5-15	
Cd	mg L^{-1}	nd*	nd	4	nd	nd		0.01-0.05	< 0.01
Cr	mg L^{-1}	nd	nd	4	nd	nd		0.1-1	< 0.1
Fe	mg L^{-1}	0.1	0.08-0.12	4	nd	nd		5.-20	< 5
Mg	mg L^{-1}	14.7±9.5	4.2-27.1	4	nd	nd		-	-
Na	mg L^{-1}	35.3	1.8	3	nd	nd		70-460	-
Mo	mg L^{-1}	0.1	0.04-0.11	4	nd	nd		0.01-0.05	< 0.01
Pb	mg L^{-1}	0.1	0-0.12	4	nd	nd		0.2-2.0	< 5
Zn	mg L^{-1}	nd	nd	4	nd	nd		1.0-5.0	< 2
Escherichia coli	cfu per 100 mL	24 900±11 370	2 600-40 000		5 200 ± 6 800	70-24 200	19	1 000-50 000	< 50 000
****Salmonella**	cfu per 100 mL	33 000±845	-		1 650 ± 650	-		1 000-50 000	< 50 000

* nd: not determined

**Source: Odindo et al. (2016)

3.3.2 Faecal matter-derived products

The biological, chemical and physical characteristics of LaDePa pellets are given in Table 3.3. The LaDePa pellets are low in moisture content and microbial load. Low moisture content makes their handling and transport easy. The absence of odour makes them pleasant to handle and unattractive for vectors, a characteristic required for a stability class 1 organic fertiliser according to Snyman et al. (2006).

The LaDePa pellets have high C content (38%) and previous studies (WRC K5/2220) have shown that they are slow-release fertilisers and function as a soil conditioner. Very low inorganic N (ammonium and nitrate) shows that the LaDePa pellets predominantly contain organic N, which has to be mineralised before being able to be taken up by plants. The mineralisation rate depends on climate, soil type and management practices, ranging from 24% in arid to 42% of sludge total N content in super humid regions (Ogbazghi et al., 2016). Therefore, LaDePa pellets should be applied before planting and the application rates should consider, inter alia, crop N requirements and available N based on annual mineralisation rates.

Total K is low, as expected in sewage sludges (Kominko et al., 2017). This implies that supplementary K is required if low K soils (e.g. peaty or lime rich soils with low clay content) are amended with LaDePa pellets. One option may be fortifying the pellets with K as recommended by the International Water Management Institute (IWMI) (Cofie et al., 2016).

According to Etter et al. (2015) faeces contain substantial amounts of pathogens and the World Health Organisation (1989) encourages treatment of excreta as the first step in ensuring its safety for unrestricted use in agriculture. The heating and drying during the LaDePa process deactivate and kill pathogens in the faecal matter, making LaDePa pellets pathogen-free.

The concentrations of trace elements in LaDePa pellets are below the minimum thresholds for agricultural use according to the Department of Agriculture Land Reform and Rural Development (2017), hence they are classified within pollutant class a (Snyman et al., 2006). This implies that there are no restrictions on their agricultural use with regards to accumulation of trace elements in the soil regardless of application rate (Herselman and Moodley, 2009, Snyman et al., 2006).

Coliforms, E. coli and viable helminths ova are absent in LaDePa pellets (Table 3.3). The absence of microorganisms is due to the thermal treatment undergone by LaDePa pellets (Septien et al., 2018). Therefore, LaDePa pellets qualify as microbial class A (Herselman and Moodley, 2009, Snyman et al., 2006). The handling, conveyance and end use of LaDePa pellets have no health implications to farm workers, their families and costumers of the agricultural product.

Table 3.3: Mean values for physicochemical and biological properties of LaDePa pellets and the Department of Agriculture Land Reform and Rural Development (DALRRD) (2017) limits.

Property	LaDePa	DALRRD limit
Odour	Absent	Absent
Water content (%)	15	< 40
Dry solids (g kg^{-1})	0.855	0.014
Total N (%)	3.5	NA**
Total P (%)	8.5	NA
Total C (%)	38	NA
K (%)	0.8	NA
Ammonium-N (mg kg^{-1})	nd	NA
Nitrate-N (mg kg^{-1})	nd*	NA
Orthophosphate (mg kg^{-1})	0.05±0.003	NA
pH	6.4±0.2	NA
As (mg kg^{-1})	6.3±1.7	40-75
Cd (mg kg^{-1})	nd	40-85
Cr (mg kg^{-1})	59±10	1 200-3 000
Cu (mg kg^{-1})	116±17	1 500-4 300
Ni (mg kg^{-1})	nd	420
Zn (mg kg^{-1})	507±152	2 800-7 500
E. coli (cfu g^{-1})	nd	100
Total coliforms (cfu g^{-1})	nd	100
Total viable helminth ova	nd	0

* nd: not detected; ** NA: not applicable

3.3.3 Urine and urine products

The characteristics of three urine-derived fertilisers (stored urine, NUC and struvite) are reported in Table 3.4. Nitrified urine concentrate and struvite do not have malodours, unlike stored urine. This is because the nitrate to ammonium ratio in NUC is 1:1 due to the nitrification process which stabilises the urine, thereby minimising N loses through volatilisation. Emission of ammonia during storage produces the malodours in stored urine. As a result, most farmers prefer NUC and struvite to raw stored urine (Wilde et al., 2019). The production of ammonia in storage increases the urine pH while nitrification is associated with a significant drop in pH (Etter et al., 2015). That is why stored urine has high pH while NUC has acidic pH (Table 3.4).

The concentrations of nutrients are much higher in NUC than stored urine (Table 3.4). This is due to the distillation process which removes water while retaining the nutrients from urine (Fumasoli et al., 2016). This concentration allows much easier transport. Low Ca concentrations in NUC affects production of some crops such as tomatoes (Magwaza et al., 2020) and therefore, supplementation of some nutrients may be needed.

Struvite is a solid crystalline material (Table 3.4) formed by precipitation of urine with a Mg salt. At Newlands Mashu, MgO was used due to its availability and cost. The process captures P from urine and hence struvite is a valuable P fertiliser, as confirmed by Nongqwenga et al. (2017). In addition, struvite contains both N and Mg but no K. This implies that in nutrient management programmes the concentrations of N and Mg in struvite should be considered when calculating crop nutrient requirements.

The human body excretes both toxic and some unwanted compounds such as pharmaceuticals through urine (Bischel et al., 2015). Pharmaceuticals are found in pure urine, stored urine and struvite because they are not degraded by either storage (Etter et al., 2015) or the struvite manufacturing process. Pharmaceuticals are not found in NUC because they are degraded during the nitrification process (Etter et al., 2015).

The results in Table 3.4 show that all the urine-derived fertilisers are sterile and do not contain pathogens. It has been shown that deactivation of pathogens depends on the method used for urine treatment and treatment conditions (Decrey et al., 2011, Etter et al., 2015, Fumasoli et al., 2016). During NUC production the nitrification process partially deactivates pathogens and the distillation at 80°C completes the deactivation process. In struvite, the major pathogen deactivator as reported by Decrey et al. (2011) is the drying process, and deactivation is higher at high temperatures and low humidity. Deactivation of pathogens during urine storage is caused by ammonia production (Etter et al., 2015) especially when stored at 20°C for 6 months (World Health Organisation, 2006).

Table 3.4: The physicochemical and biological properties of urine and its products based on VUNA study conducted at Newlands Mashu in comparison to Department of Agriculture Land Reform and Rural Development (2017) standards for a fertiliser.

Property	Unit	Stored urine	Nitrified urine concentrate	Unit	Struvite	DALRRD limits
Odour	-	Present	Absent	-	Absent	Absent
State	-	Liquid	Liquid	-	Solid	-
Chemical oxygen demand	g L^{-1}	4.8±1.1	4.9±0.3	-	-	-
pH (H2O)		9±0.2	3.9±0.1	-		-
Electrical conductivity	ds m^{-1}	1.7±0.6	2.6±0.14	-	-	-
Total N	g L^{-1}	3.9±1.6	47.6±4.9	%	5.9	-
Nitrate-N	g L^{-1}	-	22.8±1.2	-	-	-
Ammonium-N	g L^{-1}	3.9±1.6	22.3±0.8	-	-	-
Total P	g L^{-1}	0.2±0.03	3±0.4	%	18	-
Chlorides	g L^{-1}	2.7±0.3	35.7±3.4	-		-
K	g L^{-1}	1.1±0.1	16.2±2	%	0	-
Na	g L^{-1}	2.1±0.5	19.1±2	-	-	-
Ca	mg L^{-1}	13±1.7	260±90		-	-
Mg	mg L^{-1}	8±4	4.2±2.5	%	10	-
Mn	mg L^{-1}	nd	0.2±0.1	mg kg^{-1}	-	260-1 225
Co	mg L^{-1}	nd	0.1±0.1	mg kg^{-1}	-	5-38
Cu	mg L^{-1}	nd	0.2±0.1	mg kg^{-1}	-	1 500
Cd	mg L^{-1}	nd	<0.05	mg kg^{-1}	-	<40
Cr	mg L^{-1}	nd	<0.02	mg kg^{-1}	-	<1 200
Fe	mg L^{-1}	nd	2.9±1.3	mg kg^{-1}	-	-
Total coliforms	(cfu per 100 mL)	nd	nd	(cfu per 100 g)	nd	<10 000
Total viable helminth ova	ova L^{-1}	nd	nd	ova g^{-1}	nd	0

nd: not detected

3.4 Conclusions

The DEWATS effluents comply in most respects with both the FAO and DWS standard guidelines for irrigation water quality. Caution must be taken with the pathogen loads which prohibit unrestricted agricultural use of both the AF and HFCW effluents. Therefore, respective measures to minimise contamination of crops, exposure of farmers working with DEWATS effluent and their families should be considered to ensure that they are safely used. The LaDePa pellets are sterile and have potential for agricultural use as a soil conditioner and a slow release fertiliser. Furthermore, the LaDePa pellets are odourless and have very low trace element concentrations below the minimum thresholds for safe agricultural use, and hence are considered as a legally acceptable organic fertiliser that can be used without restrictions. Stored urine, NUC and struvite are free from pathogens and trace elements hence they can be safely used for agriculture as fertiliser sources. The concentrations of sodium and chlorides, and salinity (EC) are very high in stored urine and NUC so they might be problematic to crops, therefore care should be taken to monitor root zone salinity in crops amended with these urine products.

4 ASSESSMENT OF DEWATS EFFLUENT FOR AGRICULTURAL USE: DECISION SUPPORT SYSTEM APPROACH.

4.1 Introduction

The DEWATS effluent is a potential agricultural resource which provides water and nutrients required for crops under different agricultural systems; field and hydroponic systems (Magwaza et al., 2020). Several studies have been done to assess the potential of DEWATS effluent for agricultural use with special focus on its biological and physicochemical characteristics, effects on soil properties, crops and the environment. Bame et al. (2013) classified anaerobic baffled reactor (ABR) effluent as a medium to low sodic water (C2S1 class) based on the United States Soil Salinity laboratory classification for irrigation waters (United States Salinity Laboratory Staff, 1954). Furthermore, the effluent was found to contain low concentrations of heavy metals since it was of domestic origin (Musazura et al., 2015).

The impacts of DEWATS effluent on crops has been comprehensively studied. Increased crop growth and yields in crops irrigated with DEWATS effluent have been reported (Bame et al., 2014, Musazura et al., 2015, Odindo et al., 2016). Some other studies showed that the groundwater pollution risks from irrigation using DEWATS effluent are lower in an Aquic Haplustalf soil (Musazura et al., 2015, Musazura et al., 2019a, Musazura et al., 2019b) than in sandy and high organic matter soils (Musazura et al., 2019b). The Soil Water Balance (SWB-Sci) model was calibrated and validated for simulating N and P dynamics in soil irrigated with DEWATS effluent and short term simulations showed that the N and P are likely to accumulate in the upper 0.3 m of the an Aquic Haplustalf soil if high volumes of effluent are applied (Musazura et al., 2018b). It was recommended that irrigation scheduling techniques that consider room for rainfall and subsurface drainage management need to be considered in an Aquic Haplustalf soil (Musazura et al., 2015, Musazura et al., 2019a) to minimise environmental pollution.

Although the benefits and management strategies for using DEWATS effluent for agriculture have been documented, the impacts of water quality parameters described by the Department of Water and Sanitation (1996) have not been comprehensively assessed for different regions in South Africa. Irrigation water quality parameters such as the concentration of chlorides, boron, atrazine, microorganisms and macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) can have direct and indirect impacts on soil quality (environment), crop yields and quality and human health (Department of Water and Sanitation, 1996). du Plessis et al. (2017) developed a risk-based, site-specific irrigation water quality guideline based on the Department of Water and Sanitation (1996) generic guideline, and the latest local and international guidelines. The tool was developed in the form of a Decision Support System (DSS) to comply with the latest requirements of the Department of Water and Sanitation (2013) National Water Act.

Aims

The study aimed to assess the crop, environmental and health risks associated with DEWATS effluent irrigation using the Decision Support System (DSS) model.

Specific objectives

- To determine the land area requirements for agriculture in different soil types, agricultural systems and climatic regions.
- To use the AF effluent quality information in assessing its suitability as irrigation water for different crops (Swiss chard, maize and sorghum), soils (coarse sand, sand, sandy loam and clay) and in four agro-ecological regions of South Africa.
- To provide recommendations for optimising soil quality, crop yield and human health in DEWATS effluent irrigated soils across agro-ecological regions of South Africa.

4.2 Materials and methods

4.2.1 Description of the Decision Support System

The South African Department of Water and Forestry water quality guidelines of 1996 (Department of Water and Sanitation, 1996) was produced by a panel of experts following national and international guidelines. The guideline was developed based on the FAO water quality guidelines of agricultural importance (Ayers and Westcot, 1985, Food and Agriculture Organisation, 1992), WHO parameters of health significance (World Health Organisation, 1989), the United States Environmental Protection Agency (USEPA) parameters of environmental importance and other international guidelines. As knowledge was gained and practices changed with time, the South African Water Quality Guideline (SAWQG) was developed in 2017 to include developments not addressed in the 1996 guidelines (du Plessis et al., 2017). The guideline considers risk-based and site-specific approaches in compliance with the Department of Water and Sanitation (2013) revised general authorisation for wastewater use in agriculture.

A schematic diagram of the DSS is shown in Figure 4.1. It consists of two major components: the assessment of water quality for agricultural use and the water quality requirements for a specific use. The DSS follows an integrated approach, using the Lazarus computer code linking input data, calculation procedures and databases to produce output on irrigation water quality guideline.

Tier number 1 calculates the interaction of water components, crop and soil water uptake. The soil-water-crop interaction considers a 4-layer soil with an assumption that 40% of the crop water requirements are extracted from the top layer followed by the second layer (30%), the third layer (20%) and 10% from the bottom layer. The model calculates the steady-state concentration of the solution in each layer from the characteristics of the irrigation water and the leaching profile of the whole profile. An assumption is made that a leaching fraction of 0.1 prevails in the soil and there are no allowances made for rain. As a result, the calculated output for evaluating the fitness for use (FFU) for a specific water type and the water quality requirement (WQR) are always the same.

The tier 2 calculations are done using the modified SWB model (du Plessis et al., 2017). This is done to simulate the interaction between water quality, climate, and soil and crop type on water balance, soil quality, crop yield and quality, concentration of trace elements, irrigation equipment and microbial risks.

Water fluxes are simulated following a cascading approach (literally known as tipping bucket method); when each layer reaches soil water saturation point the water 'tips' to the next layer (Fessehazion et al., 2014). The soil component of the SWB model divides the soil into 11 different layers and the soil physical properties of volumetric permanent wilting point, field capacity and bulk density are specified for each layer (van der Laan, 2009). The texture of each layer is predefined and the default drainage parameters (drainage fraction and drainage rate) are available in the soil subcomponent. The effects of salinity on yield are estimated from electrical conductivity (EC) values calculated for each layer and averaged for the whole profile. The model allows the user to run simulations over several seasons (up to 45 years) to increase accuracy of the results.

The crop management component is included and the user must select irrigation management options such as irrigation system (surface vs sprinkler), irrigation timing (percentage soil moisture depletion, irrigation intervals in days or a fixed amount in mm) and the refill options (room for rainfall, field capacity, leaching requirement or fixed amount).

Wastewater contains elements which are required by plants, but some are toxic and significantly affect crop yield. Specific ions of concern include B, Na^+ and Cl^- which are present in some treated wastewaters. These ions are taken up by the crop through the transpiration stream, accumulate in the leaf tissues of sensitive crops and after exceeding certain thresholds kill the leaf tissues. Alternatively, the specific ion can be adsorbed through wetted foliage especially when sprinkler irrigation is used. The DSS is thus able to estimate yield, considering the impacts of root zone salinity and crop toxicity using Equation 4.1:

$$Y \text{ (yield)} = 100 - b\,(RZC - \alpha) \qquad \text{Equation 4.1}$$

where: b is the slope of the yield response curve exceeding the threshold concentration.

RZC is the root zone concentration of the constituent of concern and α is the threshold concentration of the element of concern.

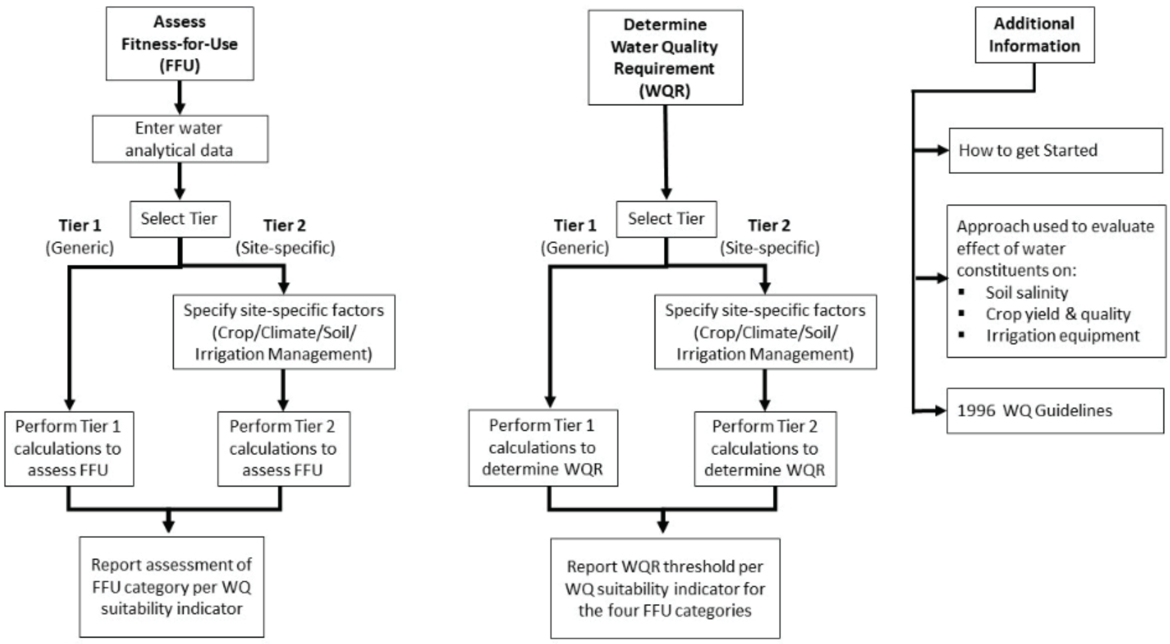


Figure 4.1: The structure of the risk-based, site-specific Decision Support System (DSS). Adapted from du Plessis et al. (2017).

The three important macronutrients which have significant effects on crop yield are N, P and K (Kalra, 1997). Treated wastewater contains macronutrients required by crops hence its use in agriculture helps to minimise fertiliser costs (Andersson et al., 2016). However, high concentrations of nutrients have direct and indirect drawbacks. Excessive amounts of N cause delayed maturity and uneven ripening in flowering plants. Nitrogen and P may cause non-point source pollution. Nitrate can leach into groundwater resources (Lal et al., 2015) and runoff losses of phosphorus into nearby rivers can cause eutrophication (Sharpley, 2016). Potassium is a less toxic cation which does not have any environmental impacts. The DSS calculates the N, P and K loading and removal by plants. The model assesses the suitability of the water quality component for use based on the percentage of the elements removed by plant uptake per amount of nutrients applied. The removal of 10% of the N, P and K from wastewater by plants is categorised as ideal, 10-30% acceptable, 30-50% tolerable and >50% unacceptable (du Plessis et al., 2017).

4.2.2 Model parameterisation

4.2.2.1 <u>Study sites</u>

Irrigation water of certain quality affects soil and crop quality differently due to differences in irrigation management practices and soil properties in various agroecological regions. Four different study sites belonging to different climatic regions classified according to Köppen-Geiger classification system (Conradie, 2012) were selected and are described in Table 4.1.

Table 4.1: The selected four agro-ecological regions of South Africa classified according to the Köppen-Geiger classification system (Conradie, 2012).

Climatic Region	Place	Coordinates	Altitude *(m.a.s.l)	Description
1	Pretoria	-25.7500; 28.26670	1 360	Warm temperate, Dry winter, Warm summer
2	Zebediela	-22.233300, 29.916670	500	Steppe, Hot Arid
3	Upington	-28.4500; 21.25000	775	Desert, Hot Arid
4	Riversdale	-34.100000; 21.266700	104	Steppe, Cold Arid (BSk)

*m.a.s.l. refers to meters above sea level

4.2.2.2 DEWATS effluent characteristics

The DEWATS effluent biological and physicochemical properties were given in Section 3.3.1 and were used to parameterise the DSS tool.

4.2.2.3 Soil types

Soils of different textures have different physical and chemical properties which influence inter alia soil moisture retention, microbiological processes and water fluxes. Spatial variations in soil types have impacts on the extent to which irrigation water of certain quality positively or negatively affects soil and crop quality (Bame et al., 2013). Therefore, four different soil texture types were selected for simulations and their physical properties obtained from the DSS are given in Table 4.2.

Table 4.2: Physical properties of the four contrasting soils used during the study.

Property	Sandy loam	Sand	Coarse sand	Clay
Initial salt content	Low	Low	Low	Low
Profile available water (mm)	120	80	40	150
Field capacity (m m^{-1})	0.22	0.15	0.08	0.33
Wilting point (m m^{-1})	0.1	0.07	0.04	0.18
Bulk density (g cm^{-3})	1.4	1.6	1.7	1.2

4.2.2.4 Crop type and management practices

The three different crops selected were maize (Zea mays L.), Swiss chard (Beta vulgaris) and sorghum (Sorghum bicolor). The crops were selected based on low microbial contamination risks in treated wastewater irrigation as per the WHO specifications (Food and Agriculture Organisation, 1992); maize has husks and the cob is produced away from the ground, Swiss chard is a vegetable consumed when cooked and sorghum is a crop that can be processed into silage or milled and used cooked (Pannar, 2020).

Different crops have different climatic requirements and South Africa is generally a subtropical country which experiences seasonal variations across the year and hence a crop rotation system of a summer and a winter crop was chosen. A surface irrigation system was chosen over sprinkler to minimise microbial risks. Musazura et al. (2019a) recommended the use of deficit irrigation scheduling that allows room for rainfall when irrigating using DEWATS effluent to minimise pollution risks and this was adopted in the current study. The irrigation timing was based on soil moisture depletion levels.

4.2.3 DSS model simulations

The parameterised DSS tier 2 was simulated for a period of 45 years. The output data on FFU was recorded for the DEWATS effluent. Its impacts on soil quality (root zone salinity, soil permeability, oxidisable C loading and trace element accumulation), crop yield and quality (root zone effects, leaf scorching when wetted, and crop and microbial health risks) and FFU of the irrigation equipment were assessed.

The water mass balances in the different climatic regions were used to calculate the land area that can be served by each DEWATS for each cropping system (crop rotation per year) (Equation 4.2). The total effluent production over a growing season based on a DEWATS daily effluent production of 35 m^3 (Musazura et al., 2018a) and the days of crop irrigation (before irrigation is stopped due to onset of leaf senescence) were calculated.

$$\text{Area } (m^2) = \frac{\text{Total effluent produced over growing season (L)}}{\text{Mean seasonal irrigation requirements (L } m^2\text{)}} \qquad \text{Equation 4.2}$$

The soil quality risks were assessed as shown in Appendix 4.1 and Appendix 4.2. The percentage of time that soil root zone salinity, soil permeability (surface infiltrability and soil hydraulic conductivity) and oxidisable C (COD) loading were predicted to fall within a certain category of FFU was determined. The accumulation of trace elements was assessed as the number of years in which a certain predicted irrigation amount elevated them to threshold levels in the topsoil (0.3 m depth).

The crop yield and quality for maize, sorghum and Swiss chard were then assessed using the criteria shown in Appendix 4.3. The percentage of time that root zone effects (salinity, B, Na^+ and Cl^-) fell within a certain category was assessed. The degree of leaf scorching due to Na^+ and Cl^- was assessed qualitatively. The contribution of irrigation water to N, P and K removal, directly or indirectly, was determined as a percentage of the time their removal at harvest was within FFU categories, taking into consideration the impacts of high nutrient concentrations. The total mean applied N, P and K through irrigation at harvest was also calculated.

The microbial risk assessment was done to predict excess infections per 1 000 persons per annum. However, atrazine damage was not assessed since it is not found in the DEWATS effluent.

4.3 Results and Discussion

4.3.1 The DEWATS effluent fitness for use

The output for the DSS showing the generic water quality for irrigation fitness (tier 1) is shown in Figure 4.2. The AF effluent contains nutrients (N, P and K) which are required for crop production but also there are some other possible concerns such as the total dissolved solids, suspended solids, EC, SAR, COD, pathogens and trace elements. However, it was reported in Section 3.2.2.1 that these are not a problem when AF effluent is used for irrigation, except for pathogens which need to be monitored and the effects of nutrients are relative to the crop type and crop water requirements.

Irrigation Water Fitness-for-Use (Tier 1)

Sample identification:	1: William Musazura
Site description:	48: Generic using conservative assumptions

Water Analysis

Major constituents (mg/L)			
Calcium	79.6	Bicarbonate	242.8
Magnesium	14.7	Chloride	36.0
Sodium	35.3	Sulphate	61.3
pH	7.6	Total Dissolved Solids (TDS)	469.7
Electrical Conductivity (mS/m)	9.0	Suspended Solids (SS)	91.0
SAR (mol/L)^0.5	1.0	Charge balance error: 11.8%	TDS / EC: 52.19

Biological Constituents		Nutrients (mg/L)	
E. coli (counts/100 mL)	2.5E+04	Total inorganic nitrogen (N)	57.3
Chemical Oxygen Demand (mg/L)	465	Total inorganic phosphorous (P)	9.3
		Total inorganic potassium (K)	14.2
Pesticides (µg/L)			
Atrazine	0.0		

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	0	0	Lead	0	0
Arsenic	0	0	Lithium	0	0
Beryllium	0	0	Manganese	0	0
Boron	0	0	Mercury	0	0
Cadmium	0	0	Molybdenum	0	0
Chromium	0	0	Nickel	0	0
Cobalt	0	0	Selenium	0	0
Copper	0	0	Uranium	0	0
Fluoride	0	0	Vanadium	0	0
Iron	0	0	Zinc	0	0

Figure 4.2: The DEWATS effluent showing fitness for agricultural use as determined by the Decision Support System.

4.3.2 Water balance and land area requirements

The water balances presented in Figure 4.3 show variations in water dynamics across climatic regions and soil types. Climatic region 1, which includes Pretoria, had the highest mean annual rainfall. The highest irrigation water requirements were reported in climatic region 3 especially on the sandy loam soil which also had high evapotranspiration due to the arid climate of areas such as Upington. In such areas, the land area required can be lower but high nutrient loading could be expected. The higher drainage water reported in climatic regions 1 and 2 were attributed to high rainfall so nutrient (N and P) leaching could be expected if DEWATS effluent was to be used for irrigation, especially on coarse-textured soils (Musazura et al., 2019b).

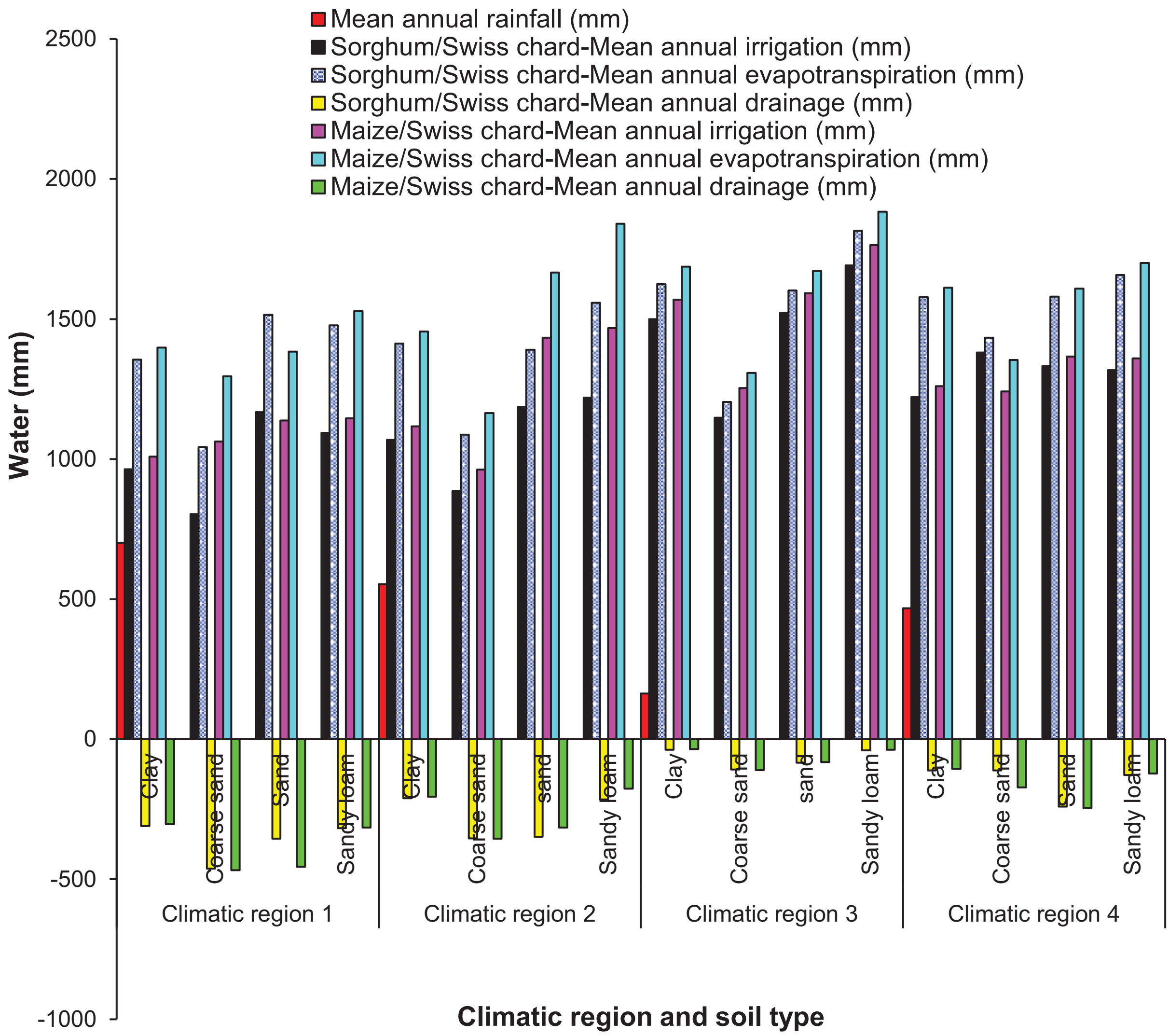


Figure 4.3: Annual mean water balance values for two cropping systems in four climatic regions on contrasting soil types, simulated over a period of 45 years.

Local authorities planning to integrate on-site sanitation with agriculture need information on the land area allocated to each treatment system, the crop types that can be safely produced and how to deal with potential environmental pollution. According to the Department of Environment and Conservation (2004), the land area that can be allocated for agriculture can be determined based on either water or nutrient balance, depending on climatic variations and soil type. The land area requirements for each DEWATS in various climatic regions, crop types and soil types based on crop irrigation requirements are shown in Figure 4.4.

More land area will be needed in climatic regions 1 and 2 than climatic regions 3 and 4. Variations in soil types are also shown. The coarse sand has the highest land area requirements especially under sorghum and Swiss chard rotation, in climatic region 1. This was attributed to high rainfall and low crop water requirements (evapotranspiration) in climatic regions 1 and 2 (Figure 4.4). Coarse textured soils have low water storage capacity hence require less irrigation which should be applied frequently per unit area.

The maize and Swiss chard rotation in climatic region 3 on the sandy loam soil had the lowest land areas requirement (0.8 ha). Loamy soils have a combination of clay, silt and sand properties; and high soil moisture retention and plant available water, making them ideal to absorb a greater effluent volume. Furthermore, aridity in climatic region 3 increases crop water demand and irrigation requirements per unit area.

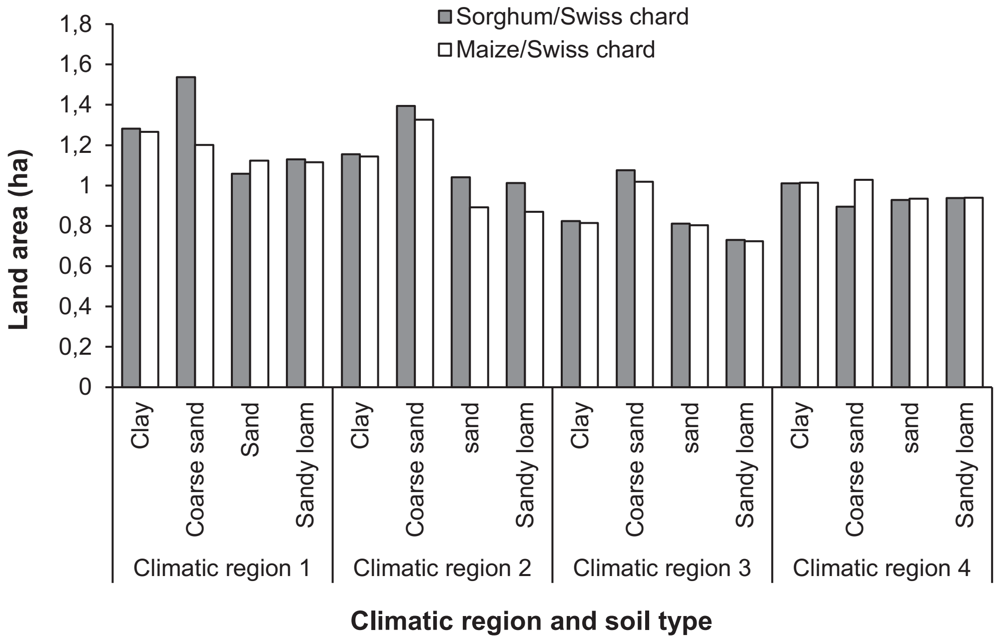


Figure 4.4: Land area requirements for two crop rotations, on four soil types and in four climatic regions based on a DEWATS with an effluent production rate of 35 m^3 day^{-1}

4.3.3 Soil quality risks

4.3.3.1 Soil root zone salinity and oxidisable C

Figure 4.5 shows the percentage of time that soil root zone salinity was predicted to fall within a certain category of FFU. The predicted soil root zone salinity was ideal for FFU in climatic regions 1, 2 and 4 as the EC was below 200 mS m^{-1} 100% of the time. In climatic region 3 some tolerable ranges (20% of the time) in clay and sandy loam soils were found. Due to low rainfall and high irrigation water demand in climatic region 3, irrigation could load more total dissolved salts into the soil and low drainage reported in Figure 4.3 minimises leaching of salts.

The simulated oxidisable C loading in DEWATS irrigated soils was very low especially in climatic region 1 where irrigation requirements were very low (Figure 4.3). The worst case scenario was in the sandy loam soil in climatic region 3, where irrigation was higher, and showed that COD loading was acceptable (94% of the time). This was expected since mean COD was 465 mg L^{-1}, which was much lower than the maximum limit of 5 000 mg L^{-1} for irrigating with 50 m^3 of effluent per day (Department of Water and Sanitation, 2013). Therefore, COD loading is not a challenge in DEWATS effluent irrigation regardless of climatic region and soil type and this was validated with studies reported in Section 3.3.1.

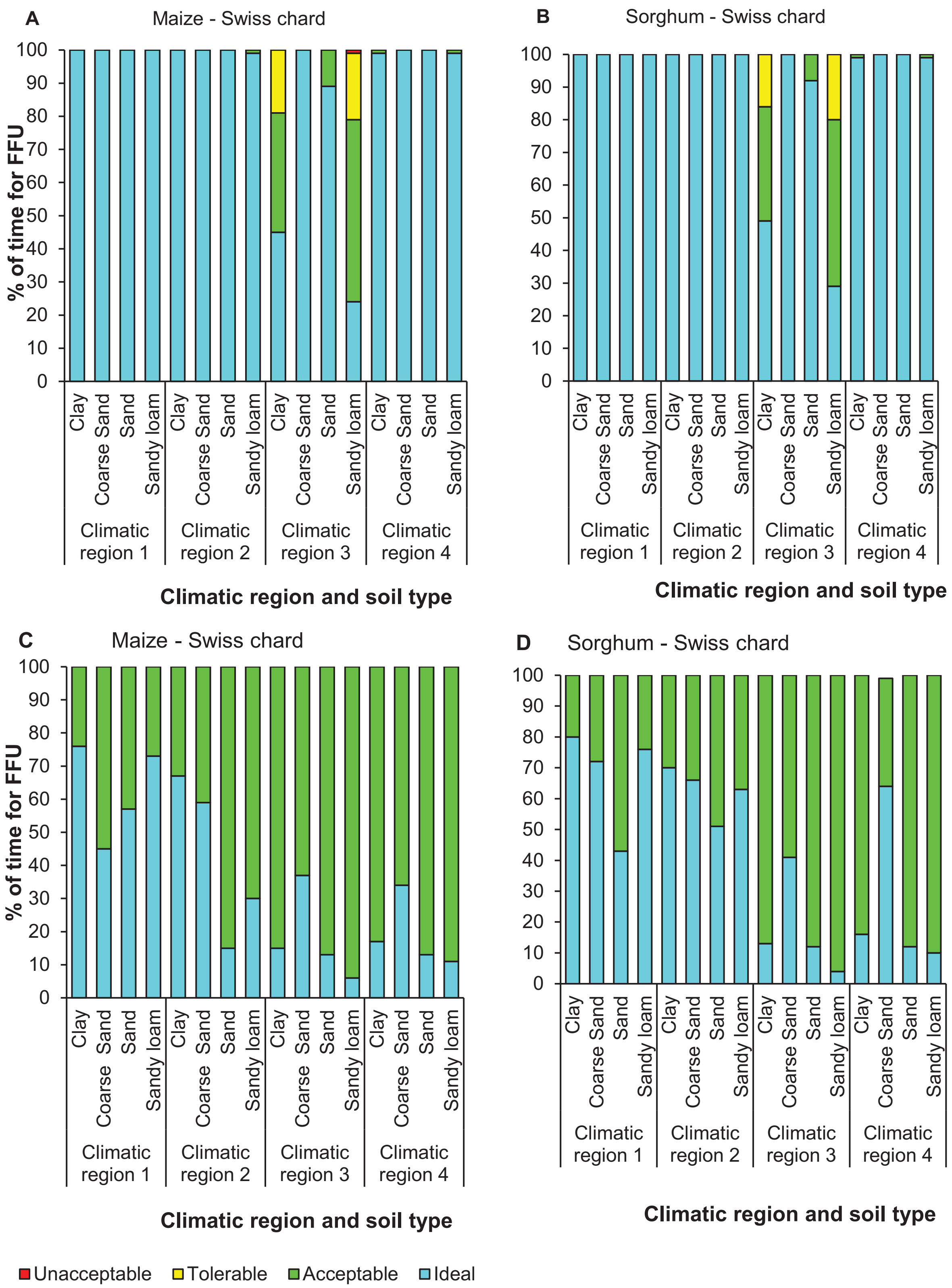


Figure 4.5: Percentage of time that root zone salinity (A and B) and oxidisable C (C and D) are predicted to fall within the category of fitness for use (FFU) (unacceptable, tolerable, acceptable and ideal), depending on soil type, climatic region and cropping system.

4.3.3.2 Soil permeability

Hydraulic conductivity is the rate at which water moves through a porous material. This is affected by the interaction of the soil exchangeable sodium percentage (ESP) and the EC. There are certain levels to which soil water EC should be reduced to effect a 10-15% reduction in hydraulic conductivity in a soil with a specific ESP (du Plessis et al., 2017). Generally, as the soil EC increases at a certain soil ESP the risk to the hydraulic conductivity decreases. The percentage of time that hydraulic conductivity was predicted to fall within a certain category of FFU is presented in Figure 4.6A and B. The expected degree of reduction in hydraulic conductivity was predominantly zero in climatic region 3, which experiences the lowest mean annual rainfall compared to the other regions. Therefore, high crop water requirements in region 3 (arid) is associated with high effluent application rates, and low rainfall in such areas minimises leaching of salts. The soil EC is increased and the accumulation rate of Na is low because DEWATS effluent has a low sodium adsorption ratio (SAR), thereby lowering the risks of reduced soil hydraulic conductivity.

There is no significant reduction in soil infiltrability expected when DEWATS effluent is used for irrigation regardless of climatic zone (Figure 4.6C and D). This is because infiltration is affected by various factors ranging from raindrop impact, irrigation type, and the SAR and EC of the water. When the effluent EC is <20 mS m^{-1} and SAR is <2 the degree of reduction in infiltration is slight. Therefore, since the DEWATS effluent has very low EC and sprinkler irrigation was not chosen, a reduction in soil infiltration was not expected.

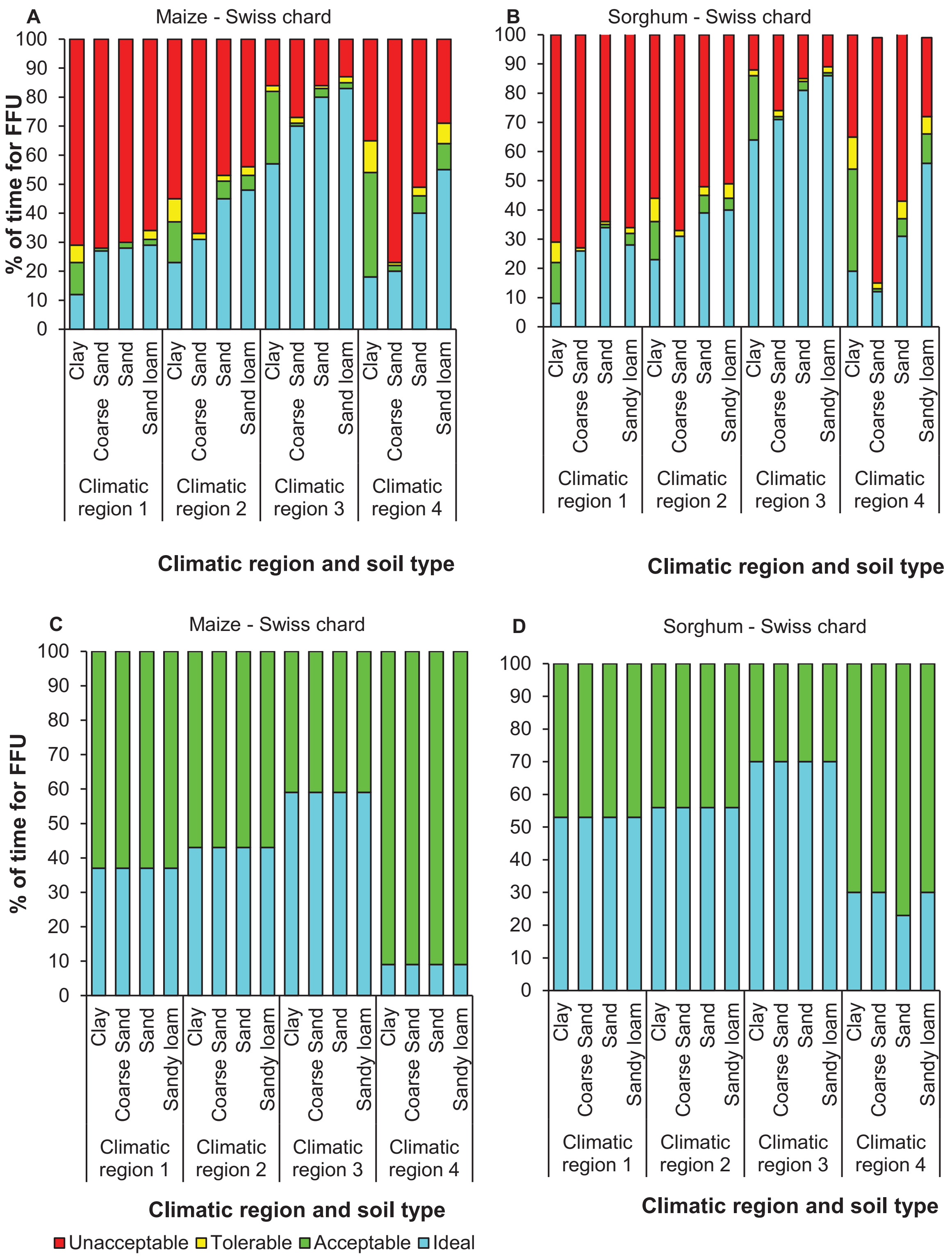


Figure 4.6: Percentage of time that soil hydraulic conductivity (A and B) and soil infiltrability (C and D) are predicted to fall within the category of fitness for use (FFU) (unacceptable, tolerable, acceptable and ideal), depending on soil type, climatic region, and cropping system.

4.3.4 *Crop yield and quality*

4.3.4.1 Root zone effects, leaf scorching and microbial risks

The potential toxicity effects of root zone salinity (B, Cl and Na) in DEWATS effluent irrigated soils on crop yield were assessed (Appendix 4.3). The 45-year simulation showed that the percentage of time the FFU required for soil salinity to reduce potential crop yield by at least 10% when DEWATS effluent is used was within the ideal category. This is because concentrations of B, Cl and Na were below the minimum threshold for irrigation water quality (Table 3.4). Therefore, maize, Swiss chard and sorghum irrigated using DEWATS effluent are not susceptible to toxic effects of salts and other specific ions, despite differences in sensitivities to salinity between the three crops (maize: moderately sensitive; sorghum and Swiss chard: moderately tolerant).

Sodium and chloride ions can also be toxic to plants if applied to foliage through sprinkler irrigation. However, the use of DEWATS effluent via surface irrigation does not scorch leaves since the foliage is not wetted as reported in Appendix 4.3.

The DSS reported no microbial contamination risks based on excess infections per 1000 persons per year for all crops used during the study (Appendix 4.3) as none are consumed raw. Furthermore, the use of surface irrigation prevents foliage wetting (Swiss chard), sorghum panicles are a distance away from the soil surface and maize has husks that cover the grain.

4.3.4.2 Nutrient (N, P, K) loading and uptake

The contribution of DEWATS effluent to estimated N, P and K removal by crops is reported in Appendix 4.4 (N), Appendix 4.5 (P) and Appendix 4.6 (K). The simulated N, P and K applied through DEWATS effluent irrigation are shown in Figure 4.7. Results showed that 348-471 kg N ha^{-1}, 63-77 kg P ha^{-1} and 96-117 kg K ha^{-1} could be applied to maize through DEWATS effluent irrigation on the four soils, assuming there was no residual fertility. The simulated nutrients that can potentially be applied to sorghum were 335-423 kg N ha^{-1}, 59-69 kg P ha^{-1} and 96-120 kg K ha^{-1}. Maize requires 191 kg N ha^{-1}, 45 kg P ha^{-1} and 195 kg K ha^{-1} for a target yield of 9.5 tons ha^{-1} (Roy et al., 2006) and the same amounts apply to grain sorghum for a target yield of 8 tons ha^{-1} (Pannar, 2020). Therefore, N and P were almost double the amounts required for optimum maize production while K was slightly in short supply. The South African average maize yield is about 4 tons ha^{-1} with 60 kg N ha^{-1}, 12 kg P ha^{-1} and 16 kg K ha^{-1} applied (Grain SA, 2019), and so application of DEWATS effluent can potentially boost maize and sorghum production in South Africa.

Swiss chard is a leaf vegetable that requires 105-150 kg N ha^{-1}, 65-124 kg P ha^{-1} and 105-150 kg K ha^{-1} (Department of Agriculture Land Reform And Rural Development, 2020). The potential application of 301-386 kg N ha^{-1}, 59-69 kg P ha^{-1} and 64-96 kg K ha^{-1} using DEWATS effluent (Figure 4.7) can provide adequate P and K, depending on soil nutrient status. Furthermore, high N content is reported to increase foliage growth and nitrate concentrations to about 276 mg kg^{-1} of nitrates when 400 kg N ha^{-1} is applied as ammonium nitrate (Engelbrecht et al., 2010). Libutti et al. (2020) reported that the application of 278 kg N ha^{-1} can increase the Swiss chard nitrate content to levels below the maximum standard established by the European Commission regulations Nº 1881/2006 and 1258/2011 for fresh spinach, which is 3 500 mg kg^{-1} or approximately 350 mg kg^{-1} dry mass. Therefore, elevated N levels from irrigation using DEWATS effluent have no effects on Swiss chard quality as nitrates are within acceptable thresholds.

The simulated percentage of nutrients that can potentially be applied through DEWATS effluent was more than 50% almost all of the time during the growing season for all three crops (Appendix 4.4, Appendix 4.5 and Appendix 4.6). Therefore, since more than 50% of the N, P and K that can be removed through plant uptake emanated from DEWATS effluent it was considered unacceptable/unfit for use. According to du Plessis et al. (2017), wastewater contributing >50% of nutrients for plant uptake prohibits the room for nutrient management. Consequently, overapplication of N, P and K affects sensitive crops, especially in highly fertile soils. Nutrients exceeding crop requirements may also negatively impact the environment through N leaching or P runoff losses to nearby rivers (Lal et al., 2015).

There are several options available to manage the effects of excessive nutrient loading in wastewater applied to soils. Tesfamariam et al. (2009) suggested the use of sod grass to remove extra nutrients. Studies in Section 5.5 consider the use of high densities of sorghum to remove extra nutrients. Plants with deep and dense root system such as vetiver grass may be grown as buffer crops (Food and Agriculture Organisation, 2003).

The first approach is to apply nutrients based on crop requirements. Crop nutrient requirements can be related to total nutrients removed by the crop, where N is considered the most limiting factor and these values are obtained from the South African fertiliser handbook (Fertiliser Society of South Africa, 2007). In addition, it is recommended to consider the impact of residual fertility by analysing the soil before planting. Therefore, the effluent should be applied based on net crop N requirements. Alternatively, the effluent may be blended with freshwater to meet the N requirements or else more dilute horizontal flow constructed wetland (HFCW) effluent may be used.

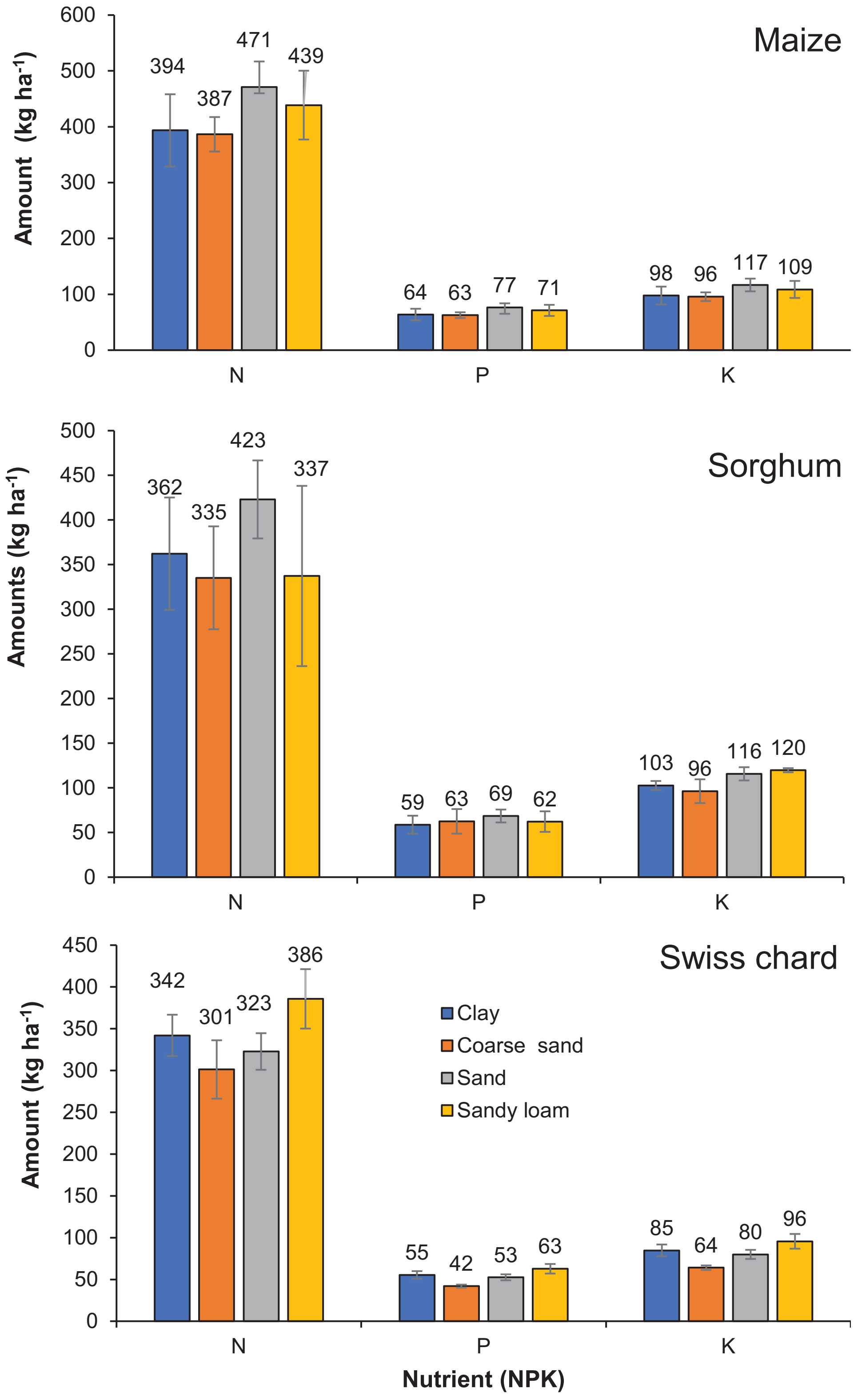


Figure 4.7: Simulated nitrogen (N), phosphorus (P) and potassium (K) (mean ± standard error of mean deviation; n = 4) applied through irrigation using DEWATS effluent to three crops on four different soil types.

4.3.5 Trace elements

Trace elements are hazardous to the environment, crops and end consumers of the products irrigated with wastewater. However, the accumulation of trace elements even when soils are irrigated with DEWATS effluent for over 200 years is negligible (results not shown). Therefore, DEWATS effluent can safely be used without significantly loading heavy metals to the soil. This corroborates findings by Levy et al. (2011) that domestic treated wastewater is low in heavy metals unless contaminated with industrial effluent. Furthermore, one advantage of an on-site system such as DEWATS over conventional wastewater treatment systems is that it minimises the chances of having industrial effluent being illegally discharged into the treatment system.

4.3.6 Irrigation equipment

The DEWATS effluent contained tolerable levels of suspended solids with a pH that has no significant impacts on clogging of the irrigation equipment (Table 4.3). The risks of equipment clogging when irrigating with DEWATS effluent are insignificant due to low concentrations of Mn, Fe and microorganisms. Therefore, DEWATS effluent is ideal for use with irrigation equipment. Directed irrigation of treated wastewater using drip systems is the most recommended method by the WHO to minimise microbial risks and increase irrigation efficiency (Food and Agriculture Organisation, 1992). However, this system is susceptible to clogging and even though the DEWATS effluent is within tolerable ranges, measures may need to be taken to counteract possible clogging problems. According to Costa et al. (2016), some of the methods include acidification and installation of filters with a backwash system.

Table 4.3: The fitness for use of DEWATS effluent based on selected characteristics that cause clogging of drippers.

Clogging of Drippers										
Fitness-for-use	Fitness for Use Category determined by the potential of an irrigation water constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50		<7.0		<0.1	0.0	<0.2	0.0	<1	0.025
Acceptable	50 - 75		7.0 - 7.5		0.1 - 0.5		0.2 - 0.5		1 - 2	
Tolerable	75 - 100	91	7.5 - 8.0	7.6	0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	

4.3.7 Microbial effects

No microbial risks were associated with the use of DEWATS effluent (results not shown).

4.4 Conclusions

The water balances assessed across four soil types in four agroecological regions of South Africa showed a variation in irrigation requirements for the two agricultural systems. Higher irrigation requirements were reported for climatic region 3 (Desert arid) followed by climatic regions 4 (Steppe, cold), 2 (Steppe, hot) and 1 (Warm temperate, dry winter, warm summer). There were variations in amount of drainage water in all climatic regions and soil types with greater drainage found in climatic regions 1 and 2 especially in the coarser-textured soils. Therefore, nutrient leaching is expected to be high in those regions. More land area (>1 ha) was required to absorb DEWATS effluent from a 35 m^3 production capacity plant in climatic regions 1 and 2 compared to climatic regions 3 and 4. In climatic regions 1 and 2 more land area was required on coarser-textured soils, especially under a sorghum and Swiss chard rotation.

There were no soil quality problems with regards to root zone salinity, soil infiltrability, and oxidisable carbon loading with DEWATS effluent irrigation. Reduced hydraulic conductivity can be expected in all climatic regions but will be least in climatic region 3 (arid area).

The DSS predicted that root zone salinity, Cl, Na and B from DEWATS effluent irrigation have no effects on crop toxicity. There are no leaf scorching risks associated with Na and Cl since the foliage is not wetted during surface irrigation, which also prevents microbial contamination risks. Furthermore, the DSS showed that the maize, Swiss chard and sorghum are at low risk of microbial contamination since they are processed before consumption.

Irrigation using DEWATS effluent contributes >50% of the total N, P and K supply, hence its effects were found to be unacceptable by the DSS. However, the production of leaf vegetables, such as Swiss chard, can be done since they are likely to benefit from high N concentrations with no quality deterioration. Flowering crops such as maize and sorghum may be at risk to excessive N and hence care must be taken through soil analysis before irrigation. Also, excess N may be of environmental concern which needs proper irrigation management practices such as giving room for rainfall to minimise N leaching, especially in sandy soils.

There were no effects of DEWATS effluent on irrigation equipment. However, although the effluent pH and suspended solids were tolerable, it was recommended to consider management practices such as periodic acidification of the irrigation water and installation of a filtration system.

5 THE EFFECTS OF HUMAN EXCRETA-DERIVED MATERIALS AND DEWATS EFFLUENT ON CROPS, SOILS AND ENVIRONMENT

5.1 Introduction

Human excreta-derived materials (HEDMs) are potential agricultural resources. Apart from several studies using other types of wastewater, DEWATS effluents of domestic origin have been confirmed to improve soil chemical properties (Bame et al., 2013, Bame et al., 2014), crop growth, yield and nutrient uptake (Musazura et al., 2015, Musazura et al., 2018a). Furthermore, potential impacts of DEWATS effluent on environmental pollution have been documented (Musazura et al., 2015, Musazura et al., 2019a) and based on reported results various irrigation management approaches are recommended on various soil types. Some of these techniques involve subsurface drainage management in clay soils and irrigation scheduling giving room for rainfall in sandy loam soils. The effluent is more of an irrigation water source than nutrients since, according to studies reported by Musazura et al. (2018a), the horizontal flow constructed wetland (HFCW) effluent could not meet the N requirements for banana throughout the growing season in a sub-tropical (Durban) climate. Although HFCW effluent has low N content the major advantage for its use is low pathogen loads (Amoah et al., 2018, Musazura et al., 2019a), meaning that it has a low to moderate restriction for irrigation (Table 3.1) thereby posing fewer health risks to farmers and consumers.

In housing developments, municipalities are mandated, through the National Sanitation Policy White Paper on Basic Household Sanitation (2001), to provide sanitation in a manner that is environmentally safe, dignified and sustainable (Masindi and Duncker, 2016). Use of effluent for agriculture minimises the discharge of pollutants into rivers. The water required for irrigation varies with the season; sometimes agricultural systems may not use all the effluent depending on crop type, land availability and irrigation management practices. Therefore, there is a need for studies that investigate the storage of effluent for other uses, the expansion of the land area as a way of assimilating the available effluent and the use of frequently harvested crops at high densities. Furthermore, how the low nutrient in the HFCW effluent may be supplemented with other HEDMs such as struvite or nitrified urine concentrate (NUC) is not known.

Aims and objectives

- To assess nitrogen (N) and phosphorus (P) release patterns of struvite in combination with commercial fertiliser, and DEWATS effluent in a low nutrient soil.
- To investigate the environmental impacts of DEWATS effluent irrigation regarding N and P removal from agricultural fields under different irrigation techniques, planting densities and fertiliser combinations.
- To monitor the long-term effects of irrigating using DEWATS effluent on soil chemical properties at Newlands Mashu.

5.2 Laboratory incubation: nitrogen and phosphorus release patterns from a Cartref (sandy) soil amended with DEWATS effluent and struvite.

5.2.1 Materials and methods

A soil incubation study was done at the School of Agricultural, Earth and Environmental Sciences (SAEES), Pietermaritzburg Campus, University of Kwazulu-Natal, South Africa. The soil used was the E horizon of a Cartref (Cf) soil; Typic Haplaquept (Soil Classification Working Group, 1991), the properties of which are given in Table 5.1. The experiment was designed in a single factor treatment structure with struvite (12.8% P), urea (46% N), single superphosphate (SSP; 10.1% P), struvite + urea, and SSP + urea as treatments, which were replicated 3 times to give 15 experimental units (5 L containers). A second experiment using the anaerobic filter (AF) effluent was laid out with the following treatments: AF effluent, struvite + AF effluent, SSP + AF effluent and the control (no fertiliser applied) with three replicates and a total of 12 experimental units (5 L containers). The physical and chemical properties of the soil used during the study are shown in Table 5.1.

Table 5.1: The initial physical and chemical properties of the Cartref soil used for the incubation study.

Property	Unit	Value
Bulk density	g cm^{-3}	1.43
Clay	%	12
Silt	%	15
Sand	%	73
Field capacity	m m^{-1}	0.24
Permanent wilting point	m m^{-1}	0.12
Organic C	%	<0.5
Total N (MIR)	%	0.05
Extractable P	mg kg^{-1}	0.7
pH (KCl)	-	4.21
Total cations	$cmol_c$ kg^{-1}	1.2
Acid saturation	%	18
Exchangeable K	$cmol_c$ kg^{-1}	0.01
Exchangeable Ca	$cmol_c$ kg^{-1}	0.4
Exchangeable Mg	$cmol_c$ kg^{-1}	0.4
Exchangeable acidity	$cmol_c$ kg^{-1}	0.18
Extractable Cu	mg kg^{-1}	0.2
Extractable Mn	mg kg^{-1}	0.7
Extractable Zn	mg kg^{-1}	0.2

The containers were drilled in the sides to allow aeration. Air-dried soil (2 kg) was placed into each container and fertiliser applied (Table 5.2) as recommended by the Fertility and Analytical Services

(FAS). The FAS recommended fertiliser rates were doubled to magnify the effects of fertilisers in the soil.

Table 5.2: The fertiliser application rates of struvite, single superphosphate (SSP) and urea to meet the doubled rates recommended for maize.

Treatment	Application rate (g kg^{-1} soil)	Application rate (kg ha^{-1})
Struvite	0.254 g	469
SSP	0.305 g	600
Urea	0.234 g	435

This experiment was conducted under controlled room temperature conditions maintained at 25°C, 80% relative humidity and 100% soil field capacity using distilled water or DEWATS effluent.

Soil samples were taken at 0, 1, 3, 7, 14, 21, 28, 35, 42, 49 and 56 days. Inorganic N was extracted using a soil: solution ratio of 1:10 in a 2M KCl solution following the method of Mynard and Kalra (2008). Phosphorus was extracted with Ambic 2 solution according to The Non-Affiliated Soil Analysis Work Committee (1990) and analysed with a UV/VIS spectrophotometer (SAFAS, Monaco, France) by the molybdenum blue method of Murphy and Riley (1962).

All the data were subjected to analysis of variance (ANOVA) using the Genstat 19th edition (VSN International, 2017). Differences between means were separated using the standard error of means generated using Microsoft Excel.

5.2.2 Results and discussion

5.2.2.1 Soil pH

The soil pH during incubation was monitored in all treatments (Table 5.1). There were no significant variations in pH values during the whole incubation period. The soil pH ranged between 4.1 and 5.1 (struvite) and 4.4 to 5.1 (AF effluent). Soil pH is a key driver of soil nutrient dynamics since it affects microbial activity in organic matter degradation as well as N and P transformations. The mineralisation of organic compounds to ammonium-N is a microbially driven process. The ammonium is further transformed into various products such as nitrates (nitrification) and ammonia (volatilisation). A recent review by Neina (2019) showed that the pH range for optimum microbial activity is 5.5-8.8, so the observed soil pH was slightly below the minimum optimum pH.

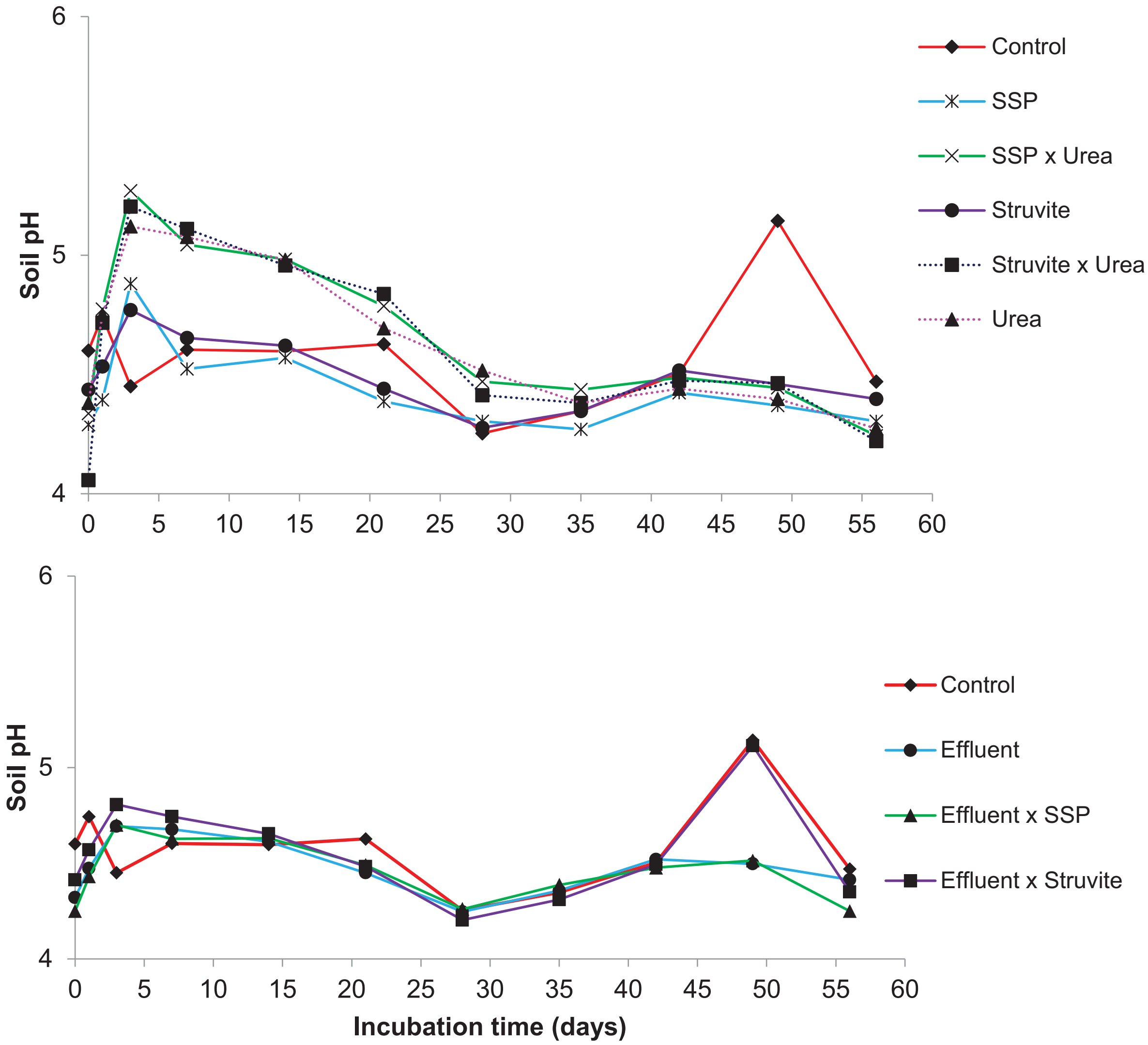


Figure 5.1: The pH (mean ± standard error of mean deviation; n=4) of struvite/single superphosphate (SSP)/ urea and DEWATS effluent/SSP/struvite amended sandy soil.

5.2.2.2 <u>Nitrogen release patterns.</u>

The nitrogen (ammonium-N and nitrate-N) release patterns are shown in Figure 5.2. There was a decrease in ammonium-N and an increase in nitrate-N over time due to the nitrification process taking place in all the treatments of both experiments. The pattern was characterised by an initial rise of ammonium-N due to the mineralisation of residual N in the soil. As the N release progressed over time their concentrations differed across treatments. A combination of struvite and urea released more N than struvite alone and this could have been due to hydrolysis of urea in the soil. No difference was reported with regards to N release patterns and concentrations between struvite and SSP since they both behave the same as reported by Nongqwenga et al. (2017).

The nitrogen release patterns for DEWATS effluent alone and in combination with solid fertilisers (SSP and struvite) are shown in Figure 5.2. There were no significant differences in N release patterns between treatments. This contrasts with studies by Zhou et al. (2016) who reported higher cumulative mineralisation and N release in soils irrigated with treated wastewater compared to freshwater. Although struvite contains some N, a combination of effluent and struvite did not alter the magnitude of N released as in the SSP + effluent treatment. Therefore, struvite and SSP have no effects on N release patterns. Comparing the concentrations of N released by the urea in Figure 5.2, the DEWATS effluent released much lower concentrations, despite being an N source (Table 3.2). This could be due to soil water storage which limited the amounts of N that could have been loaded by the effluent. This implies that DEWATS effluent applications in agricultural systems must focus on it as a water source when applied following standard irrigation management practices as recommended by Musazura et al. (2019a) and that sometimes applied volumes might not meet crop nutrient requirements (Musazura et al., 2018a).

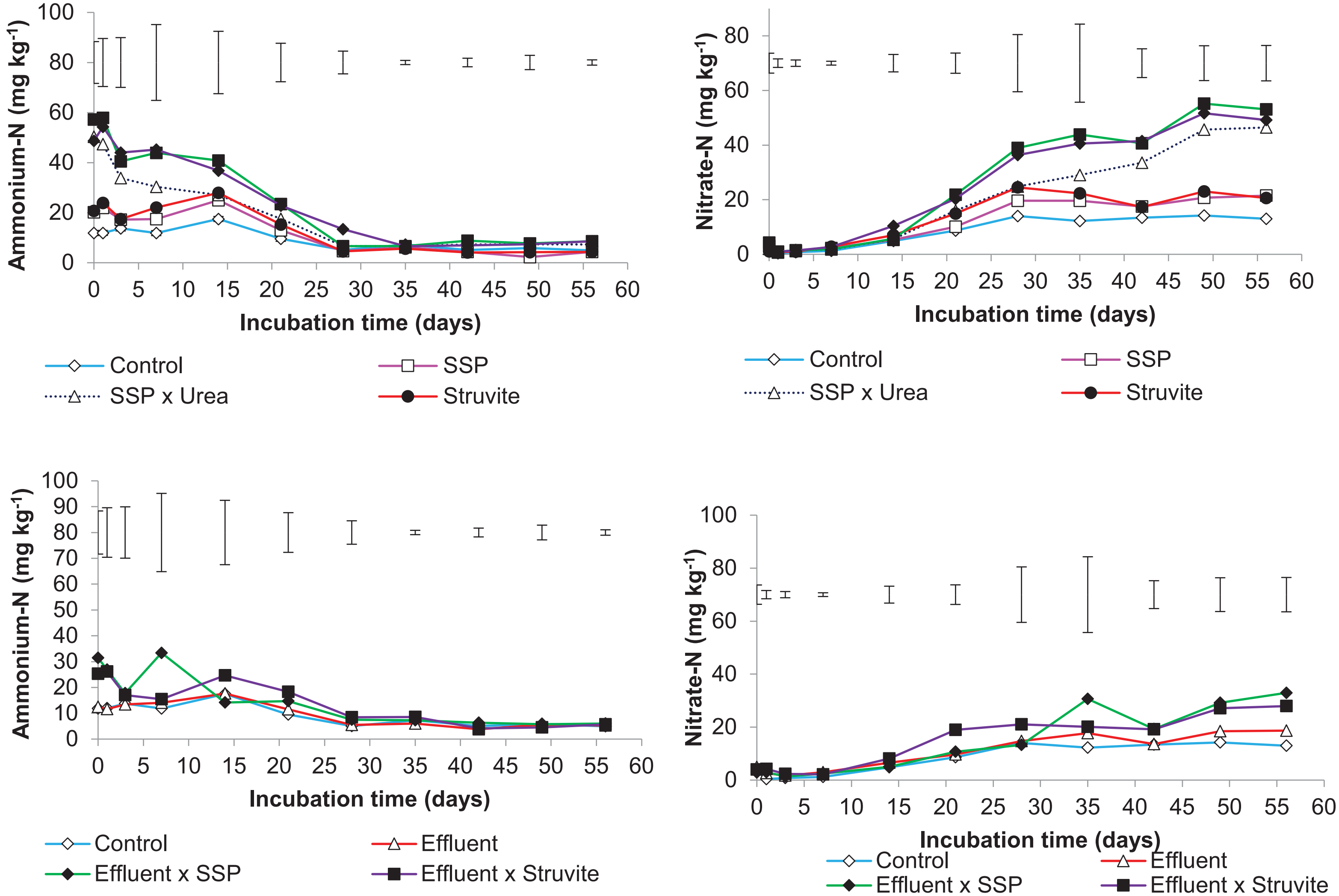


Figure 5.2: The ammonium-N and nitrate-N release patterns for struvite/single superphosphate (SSP)/ urea and DEWATS effluent/SSP/struvite amended sandy soil.

5.2.2.3 Phosphorus release patterns.

The P release patterns (Figure 5.5) were not significantly different for all the struvite/SSP/urea treatments regardless of their combination. Although the struvite and DEWATS effluent showed a faster P release pattern than other treatments, the difference was not statistically significant ($p>0.05$). Lack of significant differences across all treatments including the control is an indication that the release patterns could have been affected by soil residual fertility and the soil properties.

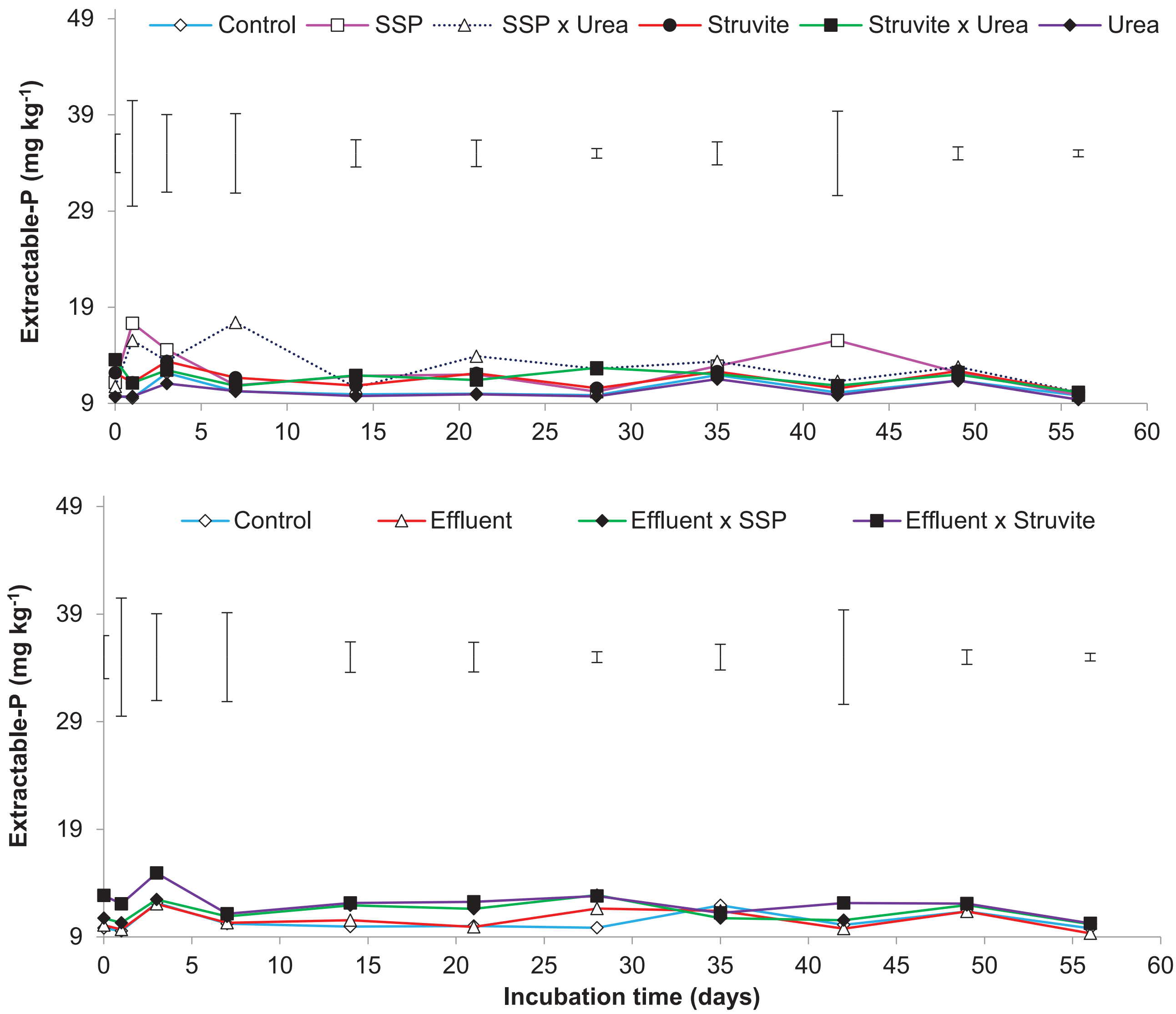


Figure 5.3: The phosphorus (P) release patterns for struvite/single superphosphate (SSP)/ urea and DEWATS effluent/SSP/struvite amended sandy soil.

5.3 Greenhouse pot trial 1: The effect of struvite and DEWATS effluent on nitrogen and phosphorus dynamics and maize yield in a sandy Cartref soil.

The N and P release patterns for struvite and DEWATS AF effluent in different combinations with SSP and urea have been investigated in the previous section. The objective of this study was to investigate the effects of different fertiliser combinations on maize growth, yield, nutrient uptake and soil N and P content.

5.3.1 Materials and methods

The study was conducted in the Controlled Environment Facility (CEF) at the Agriculture Campus of the University of KwaZulu-Natal, Pietermaritzburg, South Africa (29° 37″S, 30° 24′E). The pot experiment was carried out as a 4x3 factorial study in a completely randomised design (CRD) with three replicates. The factors were four fertiliser combinations (struvite + urea, struvite + AF effluent, SSP+AF effluent and SSP + urea) and three fertiliser application rates (no fertiliser, half optimum recommended rates and optimum recommended rates as given by the FAS) with three replicates to give a total of 36 pots. The soil used was a Cartref form (Cf; Typic Haplaquept) (Soil Classification Working Group, 1991, Soil Survey Staff, 2014). Soil was collected from the topsoil (0-0.3 m depth) at KwaDinabakubo (29°44'S; 30°51'E). The soil was sieved through a 2 mm mesh and fertilisers were added at the rates given in Table 5.3 and mixed using a concrete mixer.

Table 5.3: The amounts of fertilisers and effluent applied during the study to meet the maize nitrogen and phosphorus requirements.

Combination	Urea (g pot^{-1})	Struvite (g pot^{-1})	SSP (g pot^{-1})	Effluent (L pot^{-1})
Urea + Struvite	2.2	0.15	0	0
Urea + SSP	2.3	0	3.1	0
Effluent + SSP	0	0	3.1	38.9
Effluent + Struvite	0	2.3	0	21.4

The soils (20 kg) were packed to a bulk density of 1.44 g cm^{-3} (Musazura et al., 2019b). Planting was at a seeding rate of three seeds per pot and these were later thinned (21 days after planting) to one plant per pot (Figure 5.4). The irrigation was added based on soil water depletion to maintain 70% of plant available water as determined using Equation 5.1.

$$\text{Readily available water (RAW) content (\%)} = \text{PAW} \times \text{SAWDL} \times \text{soil mass} \qquad \text{Equation 5.1}$$

where: PAW= plant available water (%), SAWDL = soil available water depletion level (%) and soil mass = soil contained per pot (taken to be 20 kg).

The PAW was determined from the difference between field capacity and permanent wilting point values of the Cf soil, calculated from the Soil Water Balance (SWB-Sci) model calculator using soil texture values according to methods described by (Musazura et al., 2019a). The soil allowable depletion level of 50% was used for maize and the mass of irrigation deficits were determined by weighing the pot before every irrigation event which were spaced at 3-4 day intervals.

Visual crop growth variables collected weekly were plant height and leaf number. Plant height was measured from the soil surface to the uppermost leaf. Chlorophyll content was measured at tasselling using a CCM 200 chlorophyll content meter (Opti-science Inc., USA). Maize leaf samples were collected from the ear leaf at the tasselling stage. The plant samples were oven-dried at 70°C for 72 hours and ground using a Wiley mill equipped with 20-, 40- and 60-mesh screens according to methods described by Kalra (1997). Samples were digested in concentrated HCl and analysed at the FAS for macro and micronutrients following methods described by Riekert and Bainbridge (1998). Plant tissue N concentrations were analysed using the LECO ® TruSpec Micro CNS analyser and other nutrients were determined using the acid digestion method followed by inductively coupled plasma optical emission spectroscopy (ICP-OES; Vista MPX) according to standard methods (Riekert and Bainbridge, 1998). Biomass (fresh and dry mass) was determined after destructive harvesting of plants at 4, 8 and 16 weeks (harvest) after planting. The plants were cut 0.01 m above ground level and fresh mass was measured directly after harvesting using a 5 kg balance with accuracy of ± 0.01g. Dry mass was then determined after drying the plants at 70°C for 72 hours.

Leachates and soil N and P dynamics were monitored during the study. Soil samples were collected at four and eight weeks after planting and analysed for inorganic N and extractable P, following standard methods described in Section 5.2.1.

5.3.2 Results and discussion

5.3.2.1 Nitrogen and phosphorus from DEWATS effluent

Based on the irrigation scheduling approach of maintaining 70% RAW in the soil, the AF effluent provided adequate N and P to meet the maize crop requirements throughout the growing period (Table 5.4). Musazura et al. (2019b) reported excess N and P loading in the Cartref soil irrigated with AF effluent to 100% field capacity under banana and attributed this to the length of the growing period and volumes of effluent applied. Therefore, in this study, the AF effluent was a fertiliser and a water source for the maize when applied to 70% field capacity.

Table 5.4: Nitrogen (N) and phosphorus (P) applied by irrigation with anaerobic filter DEWATS effluent in comparison to optimum maize nutrient requirements.

Nutrient	DEWATS effluent ($mg\ L^{-1}$)	Nutrients applied ($g\ pot^{-1}$)	Maize requirements ($g\ pot^{-1}$)
N	61	1.3	1.07
P	10.5	0.24	0.32

5.3.2.2 Maize growth

The mean squares for maize growth in different treatments are reported in Table 5.5. A significant interaction between fertiliser combinations and application rates over time ($p<0.001$) is shown with regards to plant height.

Table 5.5: Mean squares for maize leaf number and plant height between irrigation treatments (DEWATS effluent vs tap water) at three fertiliser application levels (no fertiliser, half recommended and full recommended).

Source of variation	Degrees of freedom	Leaf number	Plant height
Combinations	3	10	0.4***
Application rates	2	85***	7***
Time	7	2353***	26***
Combinations x application rates	6	14***	0.3***
Combinations x time	21	4	0***
Application rates x time	14	12***	0.6***
Combinations x application rates x time	42	4	0***
Residual	1056	4	0
Total	1151		

Significant difference at 5%*, 1%** and 0.1%***

The maize growth rate (plant height) in different treatments is shown in Figure 5.4. The growth rate for the two fertiliser combinations (SSP + effluent and struvite + effluent) at full fertiliser recommendation rates were greater compared to other treatments. The other fertiliser combinations that included urea at the half and full recommendation rates had a slightly lower growth rate probably due to the application method, urea is a fast releasing fertiliser compared to the effluent and would usually be split applied. The lowest growth rate found in the zero-fertiliser treatment (control) confirmed the low fertility of this soil.

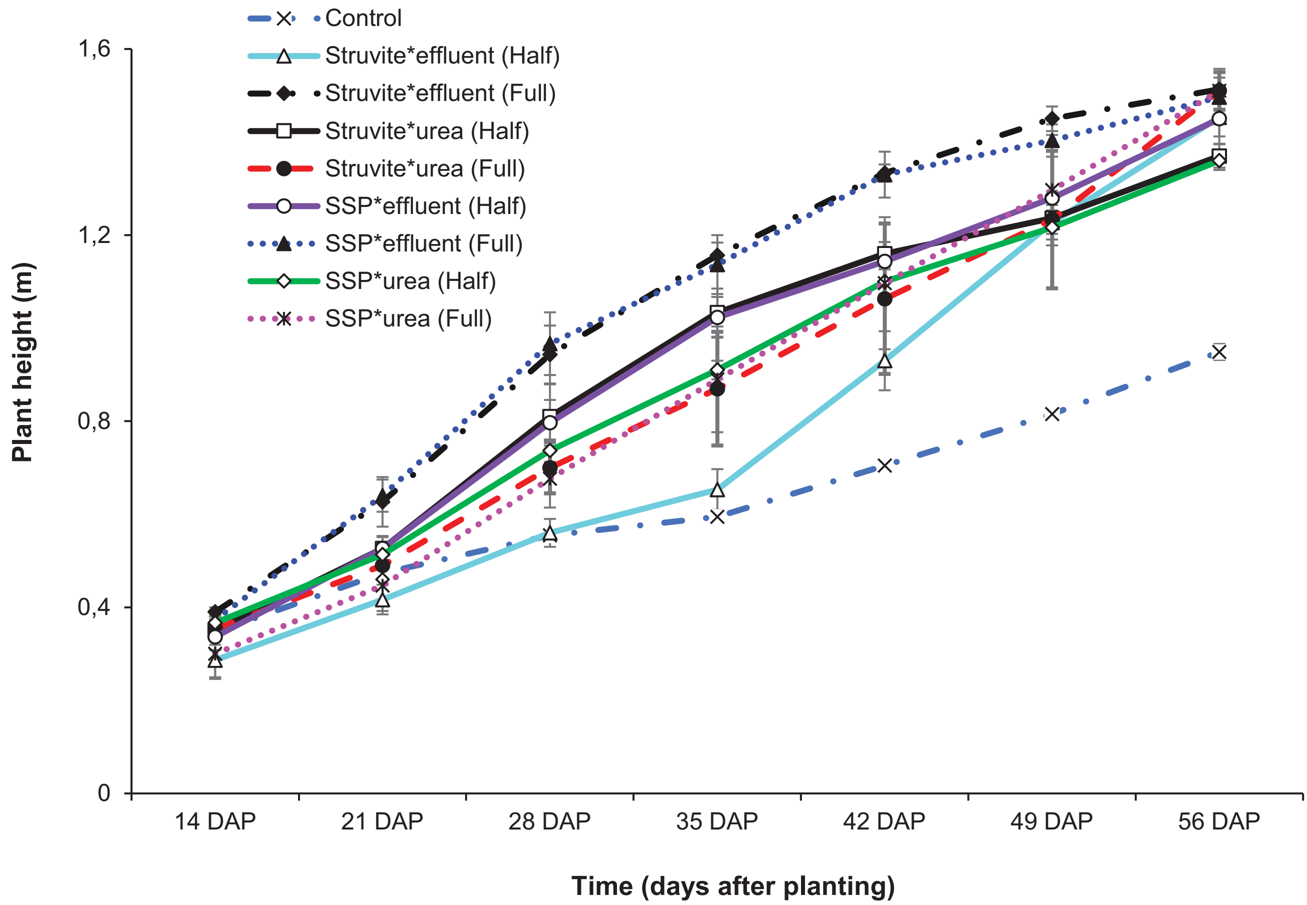


Figure 5.4: Maize plant height (n=3; means ± standard error of mean deviation) in Cartref soil amended with different fertiliser combinations applied at different recommendation rates (full (optimum), half optimum and no fertiliser).

The visual difference in plant height between some of the different fertiliser combinations and application rates are shown in Figure 5.5. This shows that the struvite and effluent perform similarly to SSP and urea in providing the N and P required for optimum maize growth especially in this sandy soil that is low in nutrients, thereby confirming findings from previous studies (Section 4.2.3).

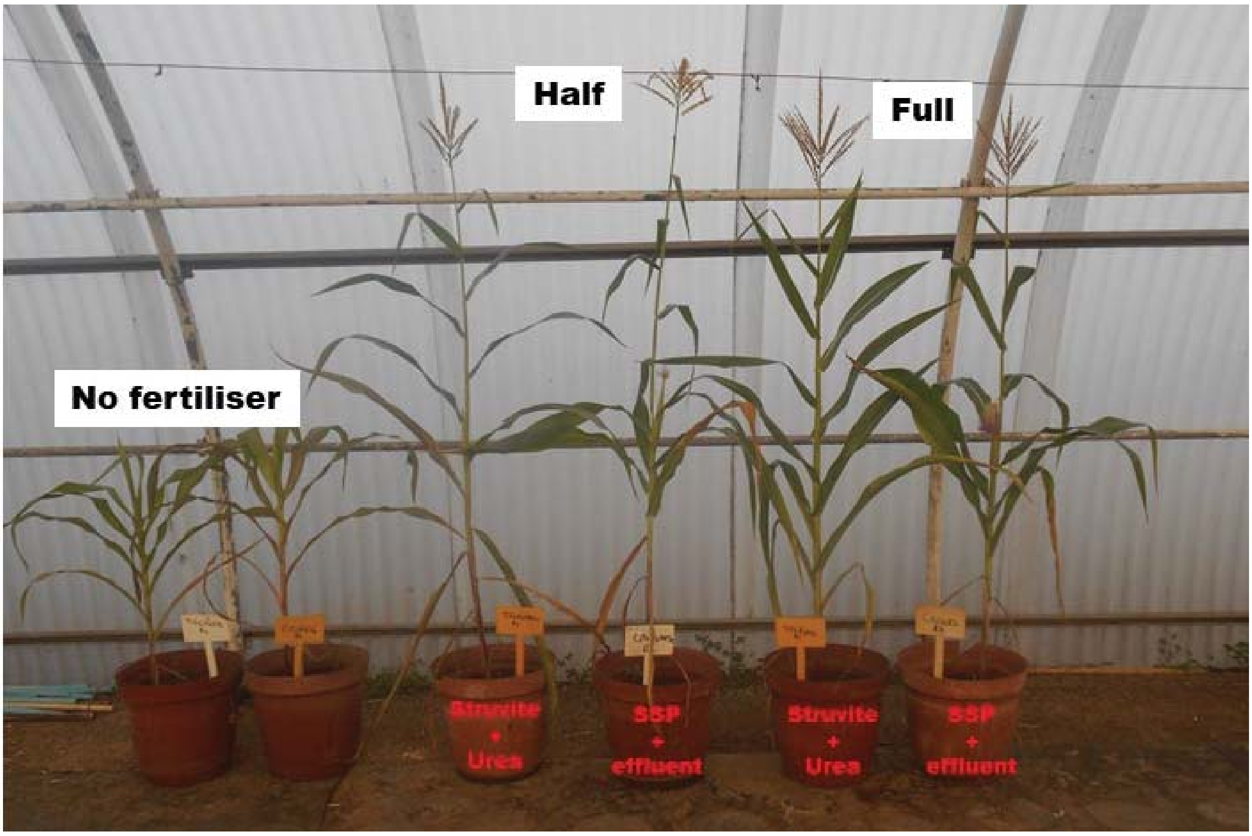
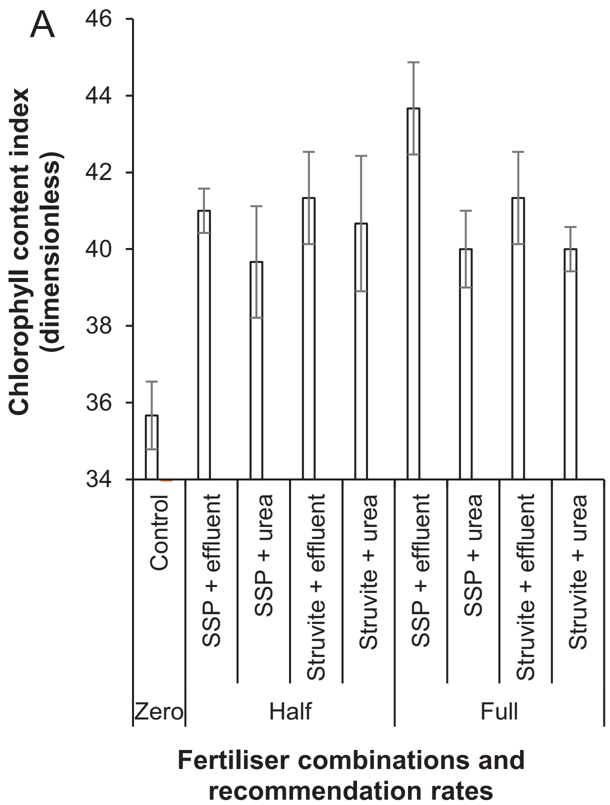


Figure 5.5: Maize growth response to two fertiliser combinations at different recommended rates at 56 days after planting.

A significant interaction ($p<0.05$) between the fertiliser combination treatments and application recommendation rates was found with regards to chlorophyll content (Figure 5.6 A). The SSP + effluent at the full recommended rate had the highest chlorophyll content compared to other fertiliser combinations. The other treatments showed a significantly higher chlorophyll content than the control. The chlorophyll content is an indicator of N sufficiency in plants (Kalra, 1997) and sometimes can be related to water stress (Mabhaudhi and Modi, 2013). Since the control was limited by nutrients the chlorophyll content, in this study, was thus related to N sufficiency. Therefore, it can again be concluded that the HEDMs provided adequate N and P to support maize growth.

Maize yield is the number and mass of kernels per cob per unit area, however, in this study the crop did not reach the harvest stage. Therefore, cob mass was used as an indicator to estimate yield performance between different fertiliser combinations (Figure 5.6B). The control had the least cob mass followed by SSP + urea (half) and struvite + urea (half), which also had lower plant height (Figure 5.6B). The higher cob mass in the struvite + effluent treatment at both half and full fertiliser rates agreed with findings by Nongqwenga et al. (2017) who reported a significant increase in maize growth with struvite in a similar Cartref soil.



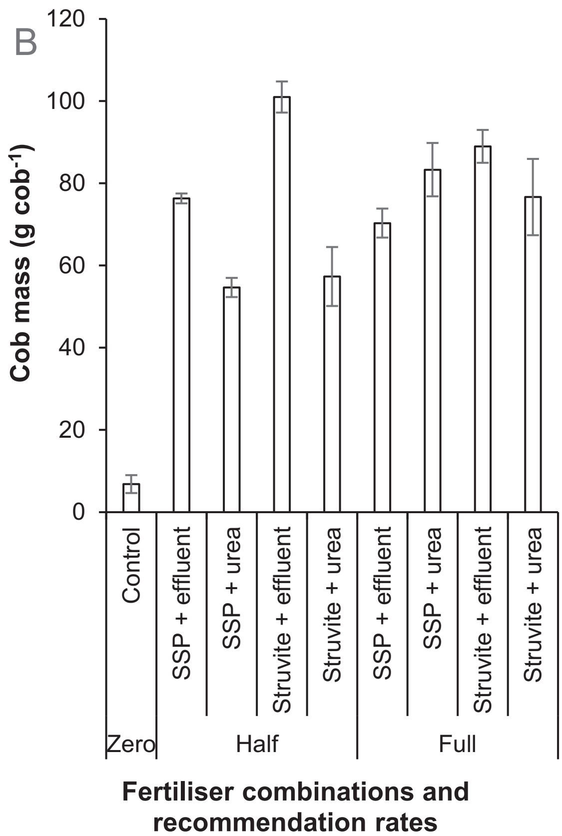
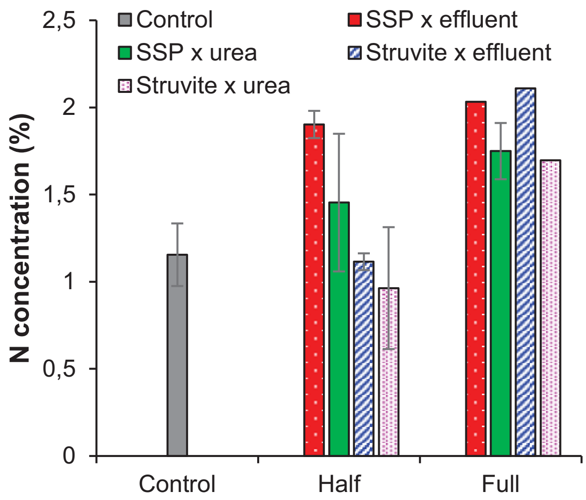
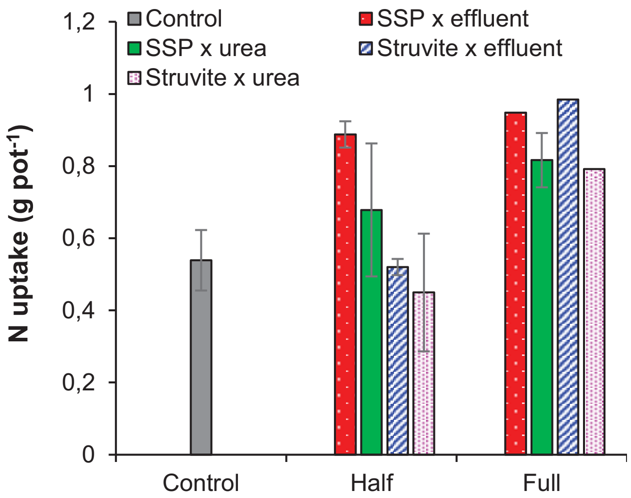


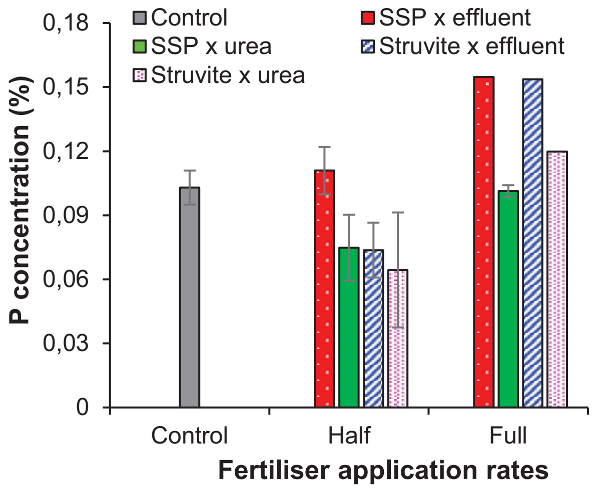
Figure 5.6: A: Maize chlorophyll content and B: cob dry mass (n = 6; mean ± standard error of mean deviation) for different fertiliser combinations and application rates after crop harvesting.

5.3.2.3 Nitrogen and phosphorus uptake

The N concentration for maize ranged from 0.98-2.1% while the P concentrations were between 0.06 and 0.15% regardless of treatment (Figure 5.7). The nutrient sufficiency ranges for maize at tasselling are between 2.8 and 3.5% N and 0.25-0.5% P, therefore regardless of the treatments applied there was insufficient uptake. Low nutrient uptake could be attributed to the conditions encountered in the growing tunnel because of load shedding, which resulted in high temperatures that may have affected maize growth. However, a comparison within the treatments showed higher N concentrations in SSP + effluent and struvite + effluent treatments, which also exhibited higher maize growth (plant height and chlorophyll content) and shows the impacts of high nutrient uptake due to application of effluent in combination with other fertilisers on maize growth. The effluent improved P uptake when compared to combinations that used urea as it provided more P. Therefore, the effluent can be used in combination with other HEDMs to assist in supplying maize fertiliser needs.







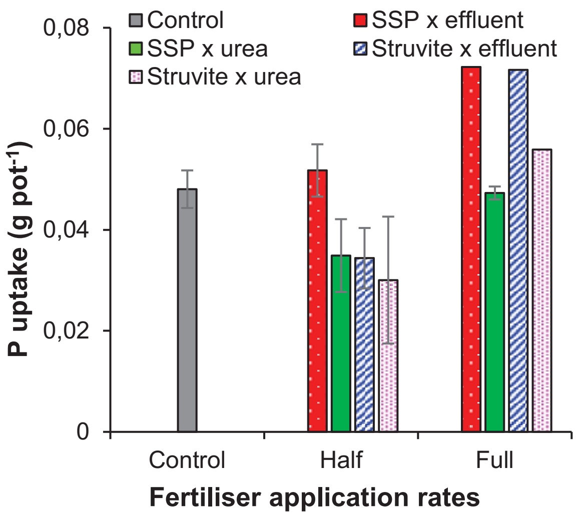


Figure 5.7: The plant tissue nitrogen (N) and phosphorus (P) concentration and amounts taken up by the maize plants per pot (n=4; mean ± standard error of deviation) in a Cartref soil amended with different fertiliser combinations and application rates at 56 days after planting.

5.3.2.4 Soil nitrogen and phosphorus

The final soil N content (Figure 5.8A) was significantly higher in SSP + effluent treatment at the full recommended rate. This is an indication that the effluent released more N, although, at a slower rate, and that some remained in the soil. The SSP + urea and struvite + urea had the lowest N contents in the soil despite urea being a readily available N source and this could be due to the application method used. The urea was applied as a once-off fertiliser and could have been lost before harvest. Based on this it can be deduced that the effluent can constantly provide plant-available N across the whole season. The irrigation approach used prohibited leaching since leachates were not detected from the pots. The N left in the soil is available for plant uptake and can support later crops (Musazura et al., 2019b).

The struvite + urea and SSP + urea at full recommended rates showed very low soil P contents (Figure 5.8B) and were similar to struvite + effluent at the half recommendation rate. The possible reason for the former treatments is the inability of urea to provide extra P and for the latter, although effluent provided some P, the concentrations were very low. Further analysis showed that the residual P was significantly higher in SSP + effluent at the half and full recommended rates. Even the median value for P in SSP + effluent (half recommended rate) was more skewed to the bottom. High P concentrations were also found in the control. Phosphorus is a less mobile nutrient and there were no leachates reported during the study. Since the study focused on bioavailable P, reported higher P concentrations in the control could have been made bioavailable during the experiment.

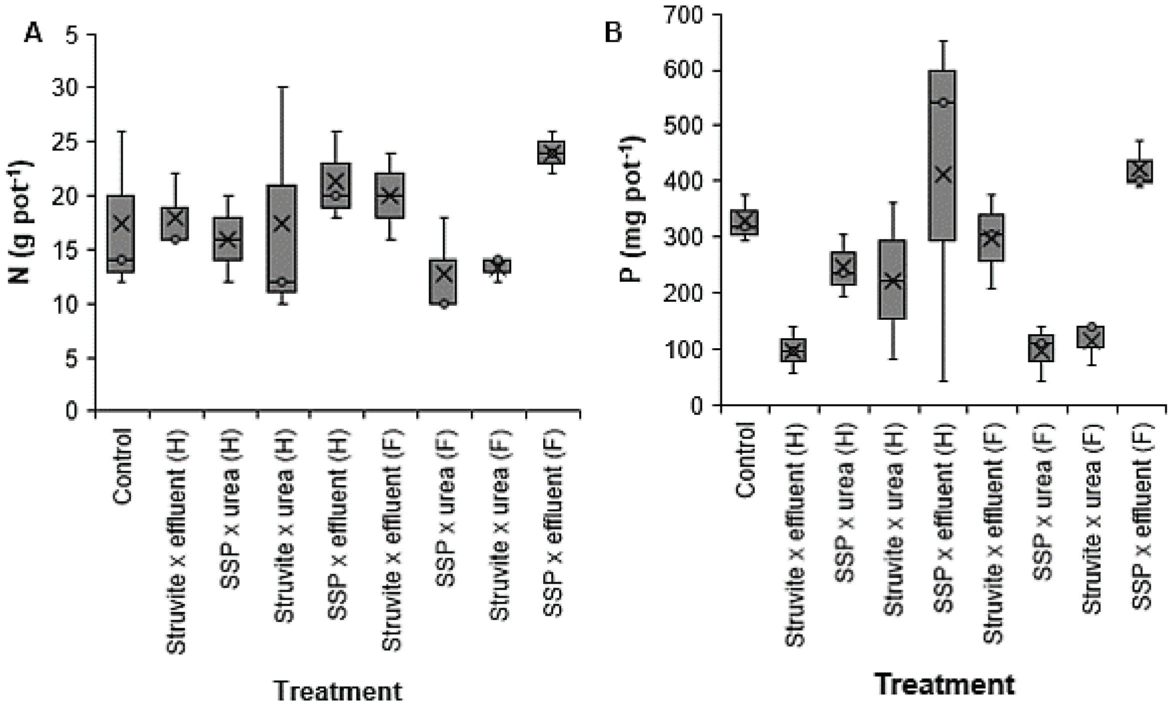


Figure 5.8: Boxplots for A: nitrogen (N) and B: phosphorus (P) content (means (x), median (o) and quartiles, n = 6) of the Cartref soil amended with different fertiliser combinations and application rates (zero (control), half (H) and full (F)) at harvest (56 days after planting).

5.4 Field study 1: Effects of DEWATS effluent on sorghum growth at different planting densities.

Irrigating banana and taro crop with DEWATS effluents (AF and HFCW) was found to provide high N and P concentrations in the rooting zone of a clay soil which, when not taken up by crops, can potentially pollute the groundwater, especially during high rainfall (Musazura et al., 2019a). Growing crops with deep roots that can be harvested frequently may allow maximum water and nutrient uptake thereby indirectly acting as a wastewater treatment option. From previous studies (WRC K5/2220) banana and taro could not achieve efficient water and nutrient removal since the taro grew poorly as an intercrop as the banana canopy increased. However, most wastewater irrigation guidelines encourage the growth of biomass plants that are frequently harvested to maximise water and nutrient removal when fertigation is done based on maximising effluent utilisation (Food and Agriculture Organisation, 1992, Food and Agriculture Organisation, 2003, United States Environmental Protection Agency, 2012). Forage sorghum is a crop that can potentially produce biomass and can be harvested frequently. Therefore, this experiment aimed to investigate the potential of forage sorghum at different planting densities to remove water and N and P through biomass in a clay soil irrigated with DEWATS AF effluent.

5.4.1 Materials and methods

5.4.1.1 Study site

A field study was done at Newlands Mashu research site, Durban, KwaZulu-Natal, South Africa (30°57'E, 29°58'S). As described by Musazura et al. (2019a) the site is characterised by high humidity, and has a sub-tropical climate with a mean annual rainfall of 1 000 mm and an annual temperature range of 16-33°C. The soil at the site is a clay loam of the Sepane (Se) form, Katdoorn family (Se 1210); Aquic Haplustalf (Soil Classification Working Group, 1991, Soil Survey Staff, 2014).

5.4.1.2 Experimental design, establishment and trial management

The experiment was laid out as a single factor analysis in a randomised complete block design (RCBD) with three plant populations: 20 000 plants ha^{-1} (low plant density), 30 000 plants ha^{-1} (medium plant density) and 50 000 plants ha^{-1} (high plant density).

The land was disked and levelled before planting. Each plot had an area of 4 m x 1 m. The plant spacing was 1.2 m x 0.25 m for the low plant density (LD), 0.6 m x 0.25 m for the medium density (MD) and 0.3 m x 0.25 m for the high density (HD). The LD had two rows with eight plants per plot, the MD had three rows with twelve plants per plot and the HD five rows with twenty plants per plot. Sorghum seeds (Sorghum bicolor L. Moench) of the PAN 688 variety purchased from McDonald's seeds, Pietermaritzburg were planted on 15 June 2017 at 25 mm soil depth at a rate of three seeds per planting station, later thinned to one per planting station.

Total emergence was recorded two weeks after planting. A surface irrigation method was used to apply a fixed amount of AF effluent three times a week at a rate of 30 L per plot per irrigation event, which equated to 35 m^3 of effluent ha^{-1} which was the daily effluent produced by the DEWATS at Newlands Mashu. The weather station installed at Newlands Mashu operated from 2013 to 2018, however the weather information covering the whole study period (2012 to 2019) was obtained from the nearby weather station at the South African Sugar Research Institute, Mt. Edgecombe. Plant height and leaf number were monitored weekly. Plant height was measured from the soil to the tip of the tallest leaf. Chlorophyll content was measured using a CCM 200 chlorophyll meter (Opti-sciences Inc., USA) one week before harvesting on the third fully exposed leaf of each plant. Harvesting was done 16 weeks after planting; above ground biomass was collected and fresh mass was measured. The material was then oven-dried at 60°C for 72 hours to determine dry mass

5.4.1.3 Nitrogen and phosphorus balance

The plant N and P uptake was estimated following Equation 5.2.

$$\text{Nutrient uptake (kg ha}^{-1}\text{) = NC (\%) * Biomass (kg m}^{-2}\text{) * 10 000 m}^{2} \qquad \text{Equation 5.2}$$

where: NC is the average nutrient (N; 3.5% and P; 0.3%) concentrations based on plant tissue analysis reference value for sorghum crop harvested during the vegetative stage obtained from Campbell (2009); biomass is the dry mass.

The soil nutrient analysis was done before planting and after harvesting. A total of five subsamples were collected from each plot at 0.3 m depth and bulked to form a composite sample that was submitted to FAS for nutrient analysis following methods described by The Non-Affiliated Soil Analysis Work Committee (1990).

The amount of N and P applied was determined following Equation 5.3.

$$\text{Nutrients applied (kg ha}^{-1}\text{) = Irrigation (L ha}^{-1}\text{) x Concentration (kg L}^{-1}\text{) x 1 kg} \qquad \text{Equation 5.3}$$

where: Nutrients applied is the mass of nutrients applied through irrigation with DEWATS effluent, Irrigation is the total volume of effluent applied per each plot; concentration is the effluent concentration as measured from the effluent characterisation data.

A simple mass balance was done to estimate N and P removal by the sorghum at the different planting densities following Equation 5.4.

$$\text{Soil storage (kg ha}^{-1}\text{) = Fertigation nutrients (kg ha}^{-1}\text{) - Crop uptake (kg ha}^{-1}\text{)} \qquad \text{Equation 5.4}$$

where: soil storage is the net accumulation of nutrients in the soil; fertigation nutrients are the nutrients applied through DEWATS effluent; crop uptake is the proportion of nutrients taken up by plants.

5.4.1.4 Data analysis

Data were analysed by analysis of variance (ANOVA) using the GenStat 19th edition statistical package (VSN International, 2017). Where significant differences were reported ($p<0.05$), the Tukey multiple comparison procedure was used to compare differences between means.

5.4.2 Results and discussion

5.4.2.1 Effects of DEWATS effluent on sorghum growth at different planting densities

The plants grown at LD had higher plant height compared to plants under MD and HD (

Table 5.6). This was attributed to competition for nutrients and water between plants, which is an advantage as high planting densities can consume as much nutrients and water as possible when irrigated with DEWATS effluent.

Table 5.6: Chlorophyll content index and plant height (n=3; mean ± standard error of deviation) of sorghum plants at three different planting densities fertigated with DEWATS effluent.

Growth variable	Low density	Medium density	High density
Chlorophyll content (Unitless)	24 ± 1.3^{a}	24±0.4^{a}	22 ± 1.7^{a}
Plant height (m)	0.53 ± 0.03^{a}	0.40 ± 0.04^{b}	0.24 ± 0.03^{c}

Superscripts a, b and c denote significant differences within each row at p<0.05

Higher fresh plant biomass was found in the HD treatments compared to the LD (Figure 5.9). This was due to more plants increasing yield per unit area. This, therefore, implies that more effluent can be applied per unit area of more densely populated sorghum plants where intense uptake of nutrients from the soil as well as utilisation of more effluent is expected. According to Musazura et al. (2018a) management of effluent in different seasons is a challenge as investment in storage facilities must be taken into consideration. Furthermore, if storage facilities are established continuous annual surplus effluent ends up overflowing, requiring emergency attention at some point. These systems work well in full reuse schemes where the effluent which is produced continuously is used for agriculture without discharging into water bodies. This minimises pressure on managing storage overflows which are against the general authorisation of the South African National Water Act (Act. 36 of 1998) (Department of Water and Sanitation, 2013).

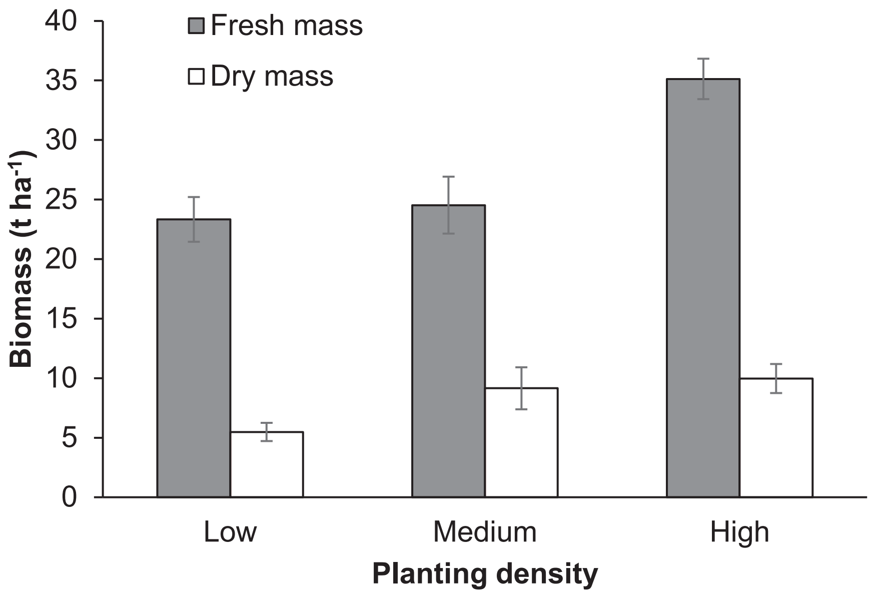


Figure 5.9: Sorghum fresh and dry biomass (n=3; mean ± standard error of deviation) at three planting densities following irrigation with DEWATS effluent.

5.4.2.2 Crop uptake and soil storage of nitrogen and phosphorus

The simple N and P mass balance (Table 5.7) shows that based on the irrigation rate of 360 mm per growing season, the AF effluent provided more N and P than was taken up by sorghum at all three planting densities. However, if HFCW effluent had been used there would have been a deficit for N at MD and HD, while the net P accumulation would have remained high. Therefore, the use of HFCW effluent at HD and MD may increase N removal but not P.

The accumulation of surplus N and P corroborates previous studies done by Musazura et al. (2019a). The authors reported that N and P accumulated in the topsoil of the same clay loam soil. Therefore, there are concerns about their impacts on the environment during high rainfall periods. The P may be discharged into surface water resources through non-point source transport of sediment P and/or dissolved P (Kleinman et al., 2011, Sharpley, 2016, Sharpley et al., 2001). It is therefore recommended to implement P losses mitigation strategies such as tilling which has been reported to minimise surface runoff as suggested by Kleinman et al. (2011). Reid et al. (2018) suggested methods such as maintaining a buffer area from the edge of the field and growing of sward grass. According to the South African general authorisation of the National Water Act, the buffer distance between the field and the water course should be at least 100 m. Sharpley (2016) recommended conservation methods in the field to allow P retention and its use for crop growth. Depending on availability of land, the effluent may not be used on certain fields in some periods to allow use of residual P by crops (United States Environmental Protection Agency, 2012).

Table 5.7: Nitrogen (N) and phosphorus (P) mass balances (kg ha^{-1}) from crop uptake, effluent application and soil storage in sorghum fertigated with anaerobic filter (AF) effluent and scenarios when horizontal flow constructed wetland (HFCW) effluent is used at low, medium and high planting density.

	AF effluent			**HFCW effluent**		
	Low	Medium	High	Low	Medium	High
N uptake	192	320	349	192	320	349
P uptake	14	23	25	14	23	25
N applied	619	619	619	205	205	205
P applied	100	100	100	187	187	187
Remaining soil N	427	299	270	13	-115	-144
Remaining soil P	87	78	76	80	71	69

A further analysis was done to assess the land area requirements based on N and P as limiting factors (Table 5.8). In general, when the effluent is applied with the assumption that P is the most limiting nutrient, a much larger land area is required than when N is considered. Furthermore, application of wastewater sludge or treated wastewater on crops considers N as the most limiting nutrient (Food and Agriculture Organisation, 2003, Snyman et al., 2006, Tesfamariam et al., 2020). If HFCW effluent is applied while considering N as the limiting nutrient, a smaller land area is required especially at medium and high planting densities. The use of AF effluent requires threefold the area of land than when using HFCW effluent. Regardless of the planting density or effluent strength, P management is required.

Table 5.8: Land area required (ha) for sorghum at low, medium and high planting densities based on nitrogen and phosphorus as limiting factors using anaerobic filter (AF) and horizontal flow constructed wetland (HFCW) effluents.

Limiting	AF effluent			HFCW effluent		
nutrient	Low	Medium	High	Low	Medium	High
Nitrogen	3.5	2.0	1.8	1.1	0.6	0.6
Phosphorus	7.5	4.5	4.0	7.0	4.0	4.0

5.5 Field study 2: Nitrogen and phosphorus removal by rice irrigated with DEWATS effluent using different irrigation techniques.

5.5.1 Introduction

The use of DEWATS effluent as an irrigation water source has been widely investigated with special focus on the agronomic performance of various crops (Odindo et al., 2016). For the practical guidelines on the agricultural use of HEDMs, understanding the technical aspects such as management of effluent in different seasons is needed and this has been partly documented (Musazura et al., 2018a). Further information on irrigation techniques that maximise effluent utilisation in agricultural fields is required. Forage sorghum was found to be a crop with the potential to be able to remove N and P and water from agricultural systems irrigated with DEWATS effluent but rice (Oryza sativa) may be another option. Rice is a crop that is cooked and therefore poses an insignificant microbial risk to consumers, and it has a specialised root system that takes up N, even under flooded conditions. The effects of different irrigation techniques on rice growth and yield have been reported by Busari et al. (2019). However, this section aims to further assess the impacts of various irrigation techniques using DEWATS effluent in removing N and P from agricultural soils. This is a potential option to minimise groundwater and surface water pollution resulting from the movement of high N and P concentrations, as recommended by Musazura et al. (2019a). This study specifically explored the effects of different irrigation techniques using AF effluent on (i) rice N and P removal from the soil, (ii) the potential for environmental pollution in agricultural systems under rice production and (iii) the provision of recommendations for the best irrigation management using rice as a crop in wastewater management.

5.5.2 Materials and methods

A field study was conducted at Newlands Mashu and the full description of the study site has been reported by Musazura et al. (2019b). The field was laid out in a Randomised Complete Block Design (RCBD) with three treatments (alternate wetting and drying (AWD), continuous wetting without flooding (WWF), and continuous flooding (CF) with three replicates. The study was done over two cropping periods; the first crop was planted in September 2017 and the second crop in January 2018 (Busari et al., 2019). Lateral movement of effluent to adjacent plots was prevented by insertion of a PVC damp proof membrane to 0.6 m depth in the soil. Planting was done in 4.5 m^2 plots at a spacing of 0.25 m x 0.25 m. A surface irrigation method was used to irrigate the crops. Crop yield biomass was measured after each harvest. The N and P mass balance was done following methods described in Section 4.5.1.3. Some of the variables specific to rice were obtained from literature. The average N and P concentrations for rice biomass used during the study were 3.2% N and 0.24% P, assuming the sampling was done at flowering stage (spike initiation) when the maximum nutrient uptake is reached (Campbell, 2009).

5.5.3 Results and discussion

5.5.3.1 Water balance, land requirements and N and P loading

A simple water balance was done to estimate the land area required when different irrigation techniques are employed based on rice irrigation data (Table 5.9). The three irrigation techniques had impacts on the volumes of effluent applied. More effluent was applied though CF and WWF than AWD (a water-saving technique). The crop water use was higher than the volume of effluent applied, thereby confirming that more effluent could have been used during the study. The maximum crop water used was reported in the CF treatment in 2018 (2 694 mm), which was slightly lower than the value of 3 000 mm year^{-1} used by Papadopoulos et al. (2009) to irrigate paddy rice. This shows that rice can maximally utilise the quantities of effluent produced from the DEWATS at Newlands Mashu.

The land area required to absorb all the effluent produced from the DEWATS was smaller under rice than under forage sorghum (Section 5.4). This implies that paddy rice fields may be used for beneficial utilisation of large effluent volumes. In addition, Pham and Watanabe (2017) reported that rice produced through fertigation with treated wastewater may be used for animal feed. This has further advantages such as full maximisation of land available, reduction in storage requirement or even overflowing of excess effluent.

Table 5.9: A simple water balance for two rice cropping seasons of the amounts of effluent irrigated by alternate wetting and drying (AWD), continuous flooding (CF) and continuous wetting without flooding (WWF), total crop water use and land area estimated to utilise the DEWATS effluent based on Newlands Mashu daily production capacity.

Year	Treatment	Actual irrigation* (mm)	Total crop water use* (mm)	Area required** (m^2)
2017	AWD	888	1 238	424
	CF	1 638	1 988	264
	WWF	1 468	1 819	289
2018	AWD	1 040	1 281	410
	CF	2 453	2 694	195
	WWF	2 368	2 604	202

*Busari et al. (2019)

**Calculated

The amounts of N and P applied by the three irrigation techniques are given in Table 5.10. Roy et al. (2006) reported that rice requires up to 160 kg N ha^{-1} and so the amounts applied by all the irrigation techniques were greatly in excess of this value. However, much N will be lost through denitrification as reported by Zou et al. (2009). The P requirement for improved rice varieties is about 80 kg ha^{-1} (Roy et al., 2006) and this was achieved through all irrigation techniques across both seasons.

Table 5.10: Nitrogen (N) and phosphorus (P) loading based on effluent applied by alternate wetting and drying (AWD), continuous flooding (CF) and continuous wetting without flooding (WWF) irrigation techniques at Newlands Mashu across two rice growing cycles (2017 and 2018).

Year	Treatment	Actual irrigation (mm)	N (kg ha^{-1})	P (kg ha^{-1})
2017	AWD	888	509	83
	CF	1 638	939	152
	WWF	1 468	841	137
2018	AWD	1 040	596	97
	CF	2 453	1 406	228
	WWF	2 368	1 357	220

5.5.3.2 Nitrogen and phosphorus uptake

The amounts of N and P removed through rice uptake from the field irrigated with AF effluent using different irrigation techniques are shown in Figure 5.10. The values were calculated with an assumption that residues (straw) were not removed since they have very low nutrient content per dry mass. Based on the yields reported by Busari et al. (2019), the lower N and P uptake reported in the WWF treatment (2017) was caused by lower yields which the authors attributed to birds; otherwise, N and P uptake did not significantly differ between treatments.

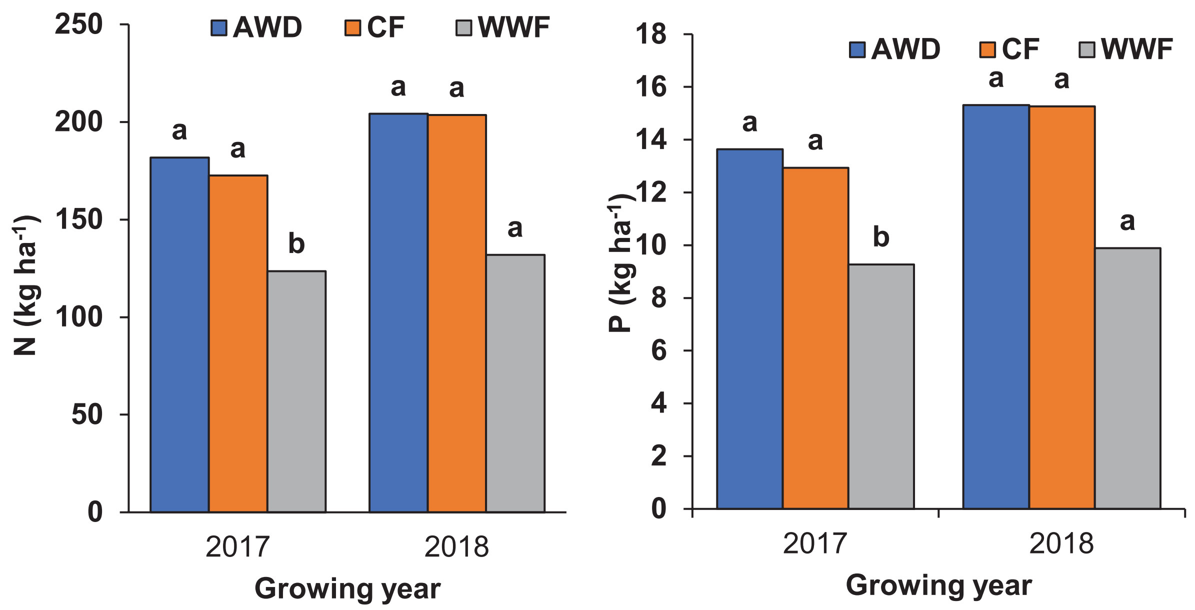


Figure 5.10: Nitrogen (N) and phosphorus (P) removed by rice per dry mass of seed harvested for two cropping seasons following irrigation with DEWATS effluent by alternate wetting and drying (AWD), continuous flooding (CF) and continuous wetting without flooding (WWF), (a and b denote significant differences ($p<0.05$) for each growing year).

5.5.3.3 Nitrogen and phosphorus mass balances

Table 5.11 shows that the net N accumulation in the soil fertigated with DEWATS effluent using the AWD approach was just negative while the P was positive for all irrigation methods. This corroborates other studies done using treated wastewater. Studies by Lal et al. (2015) reported that long term irrigation with treated sewage wastewater leads to accumulation of macronutrients in the soil. Musazura et al. (2019a) confirmed high N concentrations in the top 0.3 m of a clay soil fertigated with AF effluent. Furthermore, previous studies conducted at the same site confirmed that the movement of N and P below the root zone was very low and that they accumulated in the root zone where they were available for uptake by plants (Musazura et al., 2015). Therefore, accumulation of P in soil is of concern regardless of irrigation technique used. The loading of P in soil may be beneficial since soil mineral particles have the capacity to retain it as it will be adsorbed on clay-size minerals. However, runoff management practices explained in Section 5.4.2.2, should be considered to minimise possible environmental pollution.

Excessive N loading may negatively affect crop yield by prolonging the vegetative stage and this should be taken into consideration. According to Busari et al. (2019), the rice yields obtained were within the expected yield ranges, implying that the yield was not affected by excessive N. This could have been due to flooding that creates anaerobic conditions in which some N is lost through denitrification as reported for paddy rice fields irrigated with sewage wastewater in the southeast of China (Zhou et al., 2016).

Table 5.11: Nitrogen (N) and phosphorus (P) mass balances for two rice cropping seasons following irrigation with DEWATS effluent by alternate wetting and drying (AWD), continuous flooding (CF) and continuous wetting without flooding (WWF) based on amounts applied and taken up by the crop.

Year	Treatment	N (kg ha^{-1})			P (kg ha^{-1})		
		Applied	Plant uptake	Net	Applied	Plant uptake	Net
2017	AWD	169	182	-13	122	14	108
	CF	311	173	139	224	13	212
	WWF	279	124	155	201	10	192
2018	AWD	198	204	-7	143	15	127
	CF	466	204	263	336	15	321
	WWF	450	132	318	324	10	315

5.6 Field monitoring studies; Long term effects of DEWATS effluent irrigation on soil chemical properties at Newlands Mashu, Durban

5.6.1 Introduction

The use of treated wastewater in agriculture should be monitored to find out if it is serving its purpose without negatively impacting soils, human health, the environment and crop yield (International Organisation for Standardisation, 2016). Monitoring provides a basis for either intervention programmes or termination of the activity.

Long term fertigation using treated wastewater has been reported to affect soil chemical and biological properties. Several authors reported increased soil nutrient content and organic C after a long period of fertigation with wastewater (Ahmadifard and Kalbasi, 2014, Christou et al., 2014, Liu et al., 2017), which also increases soil biological activity (Lopes et al., 2016). Most studies on long term effects of wastewater have been done on farms that were managed by farmers, and such sites do not exist in South Africa. Furthermore, there are few studies done on-station (researcher managed) to monitor long term effects of wastewater fertigation. The DEWATS effluent has been used to fertigate various crops at Newlands Mashu since 2012 under researcher-managed conditions (Busari et al., 2019, Musazura et al., 2015, Musazura et al., 2018a). The specific objectives were to (i) monitor DEWATS effluent irrigation activities at Newlands Mashu with special focus on types and volumes of effluent use, crops used and their subsequent N and P removal from the soil, (ii) understand the effects of long term fertigation using DEWATS effluent on soil chemical properties, and (iii) provide recommendations for technical aspects such as land area requirements in different communities, crop choices, irrigation management strategies and environmental pollution mitigation strategies with regards to N and P management.

5.6.2 Materials and methods

5.6.2.1 Study site and materials

The pilot DEWATS plant at Newlands Mashu was installed in 2011 to assess its suitability as an on-site sanitation option and the potential of the effluents for agricultural use. An initial field plot of 33 m x 27 m (Musazura et al., 2015) which was later reduced to 33 m x 18 m was used and the full description of the site was reported by Musazura et al. (2019a).

5.6.2.2 Field studies

Field studies commenced in January 2012 to investigate the effects of DEWATS effluent on crop production. The first study investigated the effects of DEWATS on Swiss chard growth and nutrient uptake (Musazura et al., 2015). Plastic 2 L bottles perforated at the bottom were used to mimic a drip irrigation system and the study was done over three crop cycles. The following study used banana and taro grown in an intercrop and this was done over 3 years, from November 2013 to July 2016 (Musazura et al., 2018a, Musazura et al., 2019a). The final two experiments are reported in Sections 5.4 and 5.5. The two effluent types (AF and HFCW) and test crops used over the whole experimental period at Newlands Mashu are given in Table 5.12.

Table 5.12: A summary of field experiments at Newlands Mashu using anaerobic filter (AF) and horizontal flow constructed wetland (HFCW) effluents from February 2012 to July 2018.

Period	Crops	Effluent source
February 2012-April 2013	Swiss chard	AF
November 2013-April 2015	Banana and taro intercrop	HFCW
April 2015-July 2016	Banana and taro	AF
June 2017-October 2017	Sorghum	AF
October 2017-July 2018	Rice and taro	AF

5.6.2.3 Soil analysis

Long term soil data collected from Newlands Mashu since the onset of irrigation using DEWATS effluent to the present (2012 to 2019) was collated. During each experimental period, soils were sampled before and after harvesting of each crop. The soils were sampled at different depths; in some cases, at 0.3 m only (Musazura et al., 2015) and sometimes at three depths (0.3, 0.6 and 0.9 m) but here the focus is on the topsoil (0.3 m depth), where nutrient content and soil microbial activity are high. In each plot, five subsamples were collected and bulked to form composite samples which were labelled and sent to the FAS for analysis of pH (in KCl), mid infrared spectroscopy (MIR) organic C, MIR-N, extractable P, K, Ca, Mg, Cu and Zn. All the soil analyses were done according to the standard methods for soil analysis (The Non-Affiliated Soil Analysis Work Committee, 1990).

5.6.2.4 Data analysis

Data were analysed using analysis of variance (ANOVA) in the GenStat 19th edition statistical package (VSN International, 2017). Tukeys multiple comparison test was used to separate differences between means where significant differences were reported ($p<0.05$).

5.6.3 Results and discussion

5.6.3.1 <u>Climatic data for Newlands Mashu over a period of seven years</u>

The monitored climatic data (rainfall, maximum and minimum temperature and relative humidity) at Newlands Mashu from January 2012 to December 2018 are shown in Figure 5.11. The weather was characterised by monthly average relative humidity of between 39 and 95% and temperatures of between 10.4 and 29.9°C. Unusually high rainfall totals were measured in March 2012 (309.2 mm) and July 2016 (294.4 mm).

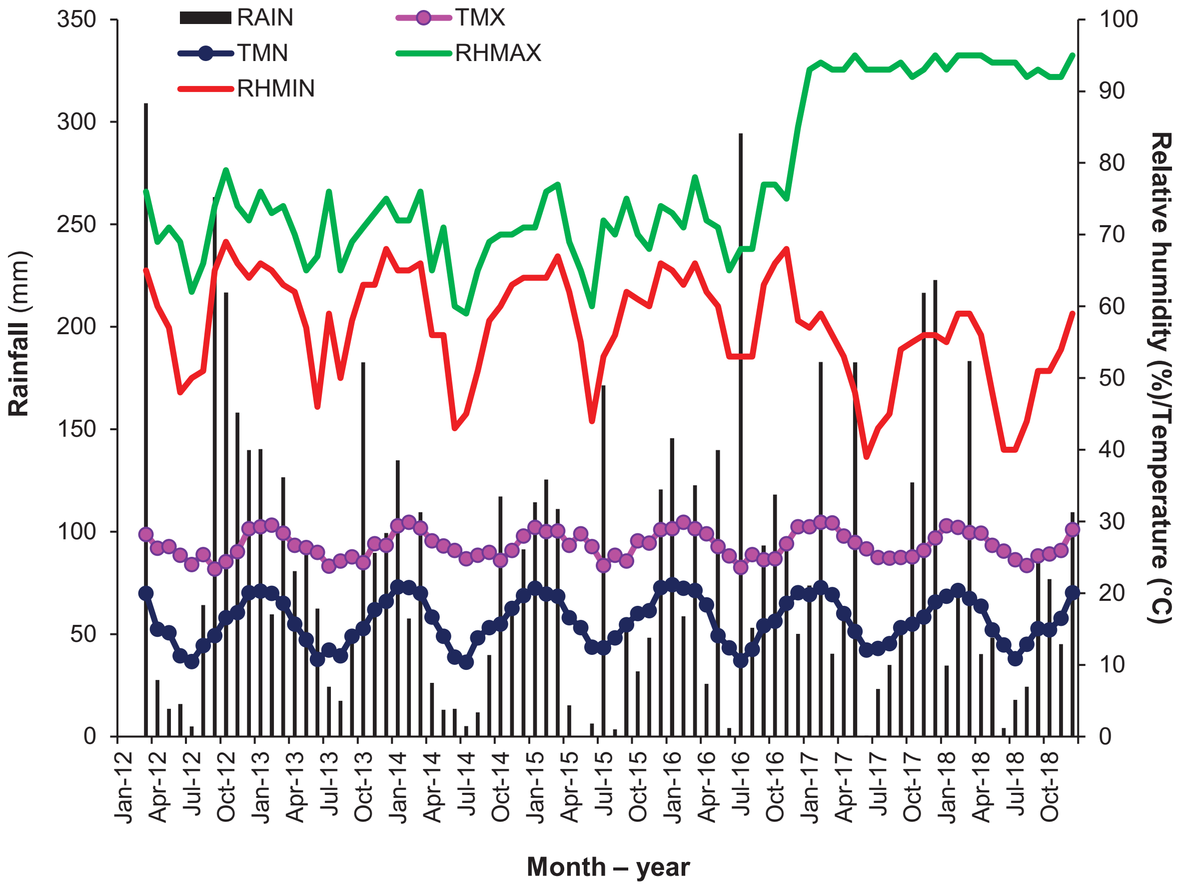


Figure 5.11: Rainfall (RAIN), maximum and minimum relative humidity (RHMAX and RHMIN) and maximum and minimum air temperatures (TMX and TMN) at Newlands Mashu from the onset of irrigation using DEWATS effluent (January 2012) to December 2018.

5.6.3.2 Irrigation water and nitrogen and phosphorus mass balances

The amounts of effluent applied to the various crops over a period of 75 months at Newlands Mashu are given in Table 5.13. The Swiss chard required more land area to fully utilise effluent produced from the DEWATS since a water-saving irrigation approach (soil water depletion giving room for rainfall) was used. Therefore, in areas such as informal settlements were sewage water flow rates are very low due to low water consumption (Crous et al., 2013), and taking into consideration erratic rainfall patterns currently experienced in South Africa, Swiss chard can be successfully grown using DEWATS effluent. Crops such as banana and taro in an intercrop system and forage sorghum have moderate potential to consume all the DEWATS effluent per unit area when fixed amounts of effluent are applied without saturating the soil. Rice is a crop that has the potential to consume more effluent per unit area. This is because of fertigation techniques that maintain soil moisture above saturation point

Table 5.13: Estimated land requirements for various crops based on design capacity and effluent applied during each study for a total period of 75 months.

Experimental period	Crop type	Irrigation approach	Effluent applied (m^3 ha^{-1})	Effluent produced (m^3)	Land required (ha)
May 2012-April 2013	Swiss chard	Room for rain	1 495	4 200	2.8
November 2013-April 2015	Taro/Banana	Fixed amount	11 300	7 210	0.6
April 2015-July 2016	Banana	Fixed amount	16 420	7 280	0.4
June 2017-October 2017	Forage sorghum	Fixed amount	3 600	1 680	0.5
October 2017-July 2018	Rice	Saturation	16 417	5 250	0.3

The results reported in Table 5.14 show that some crops used during the study could remove N and P from fields irrigated with DEWATS effluent. Negative cumulative N and P reported between May 2012 and April 2013 were attributed to high nutrient removal by Swiss chard. During that period an irrigation scheduling approach that considers room for rainfall was used and so only minimum amounts of nutrients were applied (Musazura et al., 2015).

The taro and banana intercrop removed excess N and P from the soil despite having consumed large effluent volumes (Musazura et al., 2018a) and this was due to use of the HFCW effluent which was relatively less concentrated with nutrients. The banana and taro grew well, the yields were not compromised, and soil nutrients were supplemented by residual fertility. During the following banana growing period, AF effluent (high in N and P) was used in larger volumes (Table 5.14), and taro was not grown since it could not survive in an intercrop system. This contributed to excess N and P loading.

The uptake of N by sorghum was higher than that applied through effluent due to high planting densities. On the other hand, excess P was applied and accumulated in the soil. Irrigation techniques used for rice production kept the soil at or near saturation point thereby loading more nutrients. The most important issue is the fate of the nutrients; their losses through runoff, leaching, crop uptake or volatilisation.

Table 5.14: Cumulative nitrogen (N) and phosphorus (P) loading in the field irrigated with DEWATS effluents based on a simple mass balance of nutrient applied vs nutrients taken up through crop biomass over a period of 75 months.

Date	Applied N	Applied P	N uptake	P uptake	Surplus N	Surplus P	Cumulative N	Cumulative P
	(kg ha^{-1})							
May 2012-April 2013	91	7	300	31	-209	-24	-209	-24
November 2013-April 2015	220	49	728	84	-508	-35	-717	-59
April 2015-July 2016	909	240	629	39	280	201	-437	142
June 2017-October 2017	199	53	287	21	-88	32	-525	174
October 2017-July 2018	960	299	170	13	790	286	265	460

5.6.3.3 Soil chemical properties

Changes in soil chemical properties at Newlands Mashu in plots irrigated with DEWATS effluent over a period of seven years have been monitored and results are presented as mean squares (Table 5.15). Significant changes in exchangeable Ca ($p<0.05$), K ($p<0.001$) and total cations ($p<0.05$) were found between the two irrigation treatments (tap water + fertiliser vs DEWATS effluent) over time. Soil pH significantly ($p<0.01$) differed between the irrigation treatments.

Table 5.15: Mean squares for changes in soil chemical properties for plots under two irrigation treatments (tap water + fertiliser vs DEWATS effluent) over seven years at Newlands Mashu.

Source of variation	Degrees of freedom	P	K	Ca	Mg	Total cations	pH	N	Org. C
Block stratum	2	1 153	0.01	6	3.2	18	3	0	0.5
Time	5	1 773*	0.01	5**	2.6***	12**	0.1	0.02***	2***
Treatment	1	32	0.02	5*	0.1	5	1**	0	0
Time x Treatment	5	316	0.06***	4*	0.7	6*	0.1	0	0.1
Residual	22	603	0.01	1	0.3	2	0.1	0	0.2
Total	35								

Significance difference at 5%*, 1%** and 0.1%***

Exch. acid is the exchangeable acidity

Org. C is the organic C

The differences in soil pH between the two irrigation treatments (DEWATS effluent vs tap water + fertiliser treatments) are shown by the boxplots in Figure 5.12. The mean value for soil pH in DEWATS effluent irrigation treatments was significantly higher compared to tap water + fertiliser treatment. This was due to the presence of basic cations in the effluent which buffer the soil pH. These results correspond to findings by Bame et al. (2014), who reported the ability of ABR effluent to buffer pH in an acidic, high organic C soil (Inanda form). This implies that long term fertigation using DEWATS effluent improves soil pH, especially in acidic soils that are prone to P deficiency. Most soil microbial activities depend on soil pH (Adrover et al., 2010), and higher soil pH may improve microbial activities such as mineralisation.

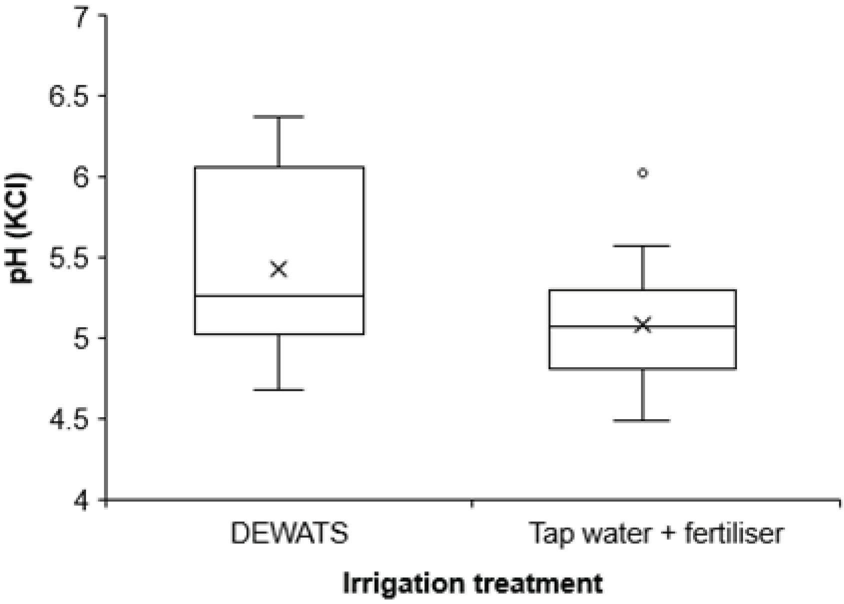


Figure 5.12: Boxplots showing mean values (denoted by x), range, first and third quartile and outlier values (o) for soil pH between the two irrigation treatments over seven years (February 2012 to January 2019), n=18.

The changes in soil exchangeable Ca and K from the plots after seven years of irrigation using DEWATS effluent are shown in Figure 5.13. The soil Ca content increased significantly from time 3 (August 2012) to time 4 (April 2013) and significantly declined at time 5 (May 2015). The K content was significantly lower at time 5 (May 2015) than other periods.

The reasons behind these changes were attributed to the different crops and irrigation systems used over the period. Continuous fertigation using DEWATS effluent significantly increased soil Ca content and due to the high cation exchange capacity of the soil at Newlands Mashu, leaching was probably lower. As time progressed, banana was then planted in soil previously under Swiss chard. Therefore, the decrease in soil Ca, K content and total cations at time 5 were due to their uptake by the banana crop. Furthermore, during the first banana growing cycle (November 2013-May 2015), HFCW effluent was used and the irrigation was delayed until June 2014 (Musazura et al., 2018a). The use of HFCW effluent and the short irrigation period as well as the application of lower effluent volumes (Table 5.16), contributed to less addition of cations to the soil than those taken up by the plants. The high exchangeable K concentrations in tap water + fertiliser treatments were attributed to the addition of KCl fertiliser.

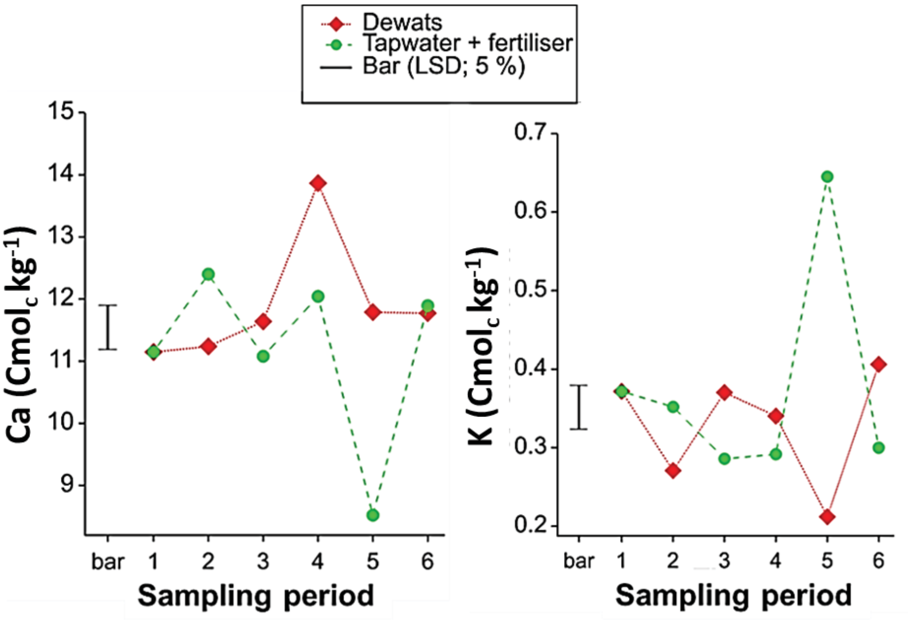


Figure 5.13: Changes in soil exchangeable calcium (Ca) and potassium (K) from the onset of irrigation using DEWATS effluent (February 2012) to June 2016 sampled at different periods (1: February 2012; 2: April 2012, 3: August 2012, 4: April 2013, 5: May 2015 and 6: June 2016).

Significant ($p<0.05$) changes in soil inorganic N (nitrate and ammonium-N) concentrations from the first banana cropping (November 2013-May 2015) to 31 January 2019 were measured (Figure 5.14). The soil inorganic N increased significantly after the second banana harvest (15 July 2016) and the land was left fallow until June 2017. Rice was then planted in September 2017 under flooded conditions using DEWATS effluent until April 2018. However, nutrient loading from fertigation of rice (Table 5.14) did not significantly increase soil inorganic N. This could have been attributed to the techniques used. Rice was grown under flooded conditions and an impermeable PVC plastic sheet was buried in the soil (0.5 m deep), which could have hastened the denitrification processes as reported by Zhou et al. (2009) in paddy rice fields. Several events occurred during the study period. Very heavy rainfall experienced after banana harvesting in June 2016 caused flooding (Figure 5.11), poor drainage at the experimental site (Musazura et al., 2019b) and flood irrigation techniques during rice production (September 2017 to April 2018) could have played a role in the denitrification processes in the soil at Newlands Mashu.

The mass balance showed that irrigation using DEWATS effluent from February 2012 to April 2018 was expected to cause net P accumulation (Table 5.7). The largest amounts of P came from rice irrigation, but the soil P concentrations were not significantly different from the initial ones. Several studies at the site reported very low P leaching (Musazura et al., 2015, Musazura et al., 2018a, Musazura et al., 2019a) thereby ruling out the possibility of losses through leaching. Surface runoff could also be ruled out since the field is only gently sloping (Musazura et al., 2019a). The crop modelling study by Musazura et al. (2018b) predicted a significant accumulation of P within the top 0.3 m over time, thereby giving a picture of low leaching losses from the soil. It was further confirmed that irrigating banana using AF effluent on clay soils is likely to increase soil P (Musazura et al., 2019b). Therefore, insignificant accumulation of P in the soil over prolonged irrigation using DEWATS effluent at Newlands Mashu could have been attributed to other factors such as the passive flow of effluent through cracks since the

Sepane soil at the site contains 2:1 expanding soil clay minerals which allows water to flow through cracks in the dry periods. In addition, other field management operations may also have contributed to the removal of soil P in irrigated soil. There was extensive weed growth in the field during the non-growing period (July 2018 to February 2019), which were subsequently removed from the fields and at the same time no effluent was being applied over that period.

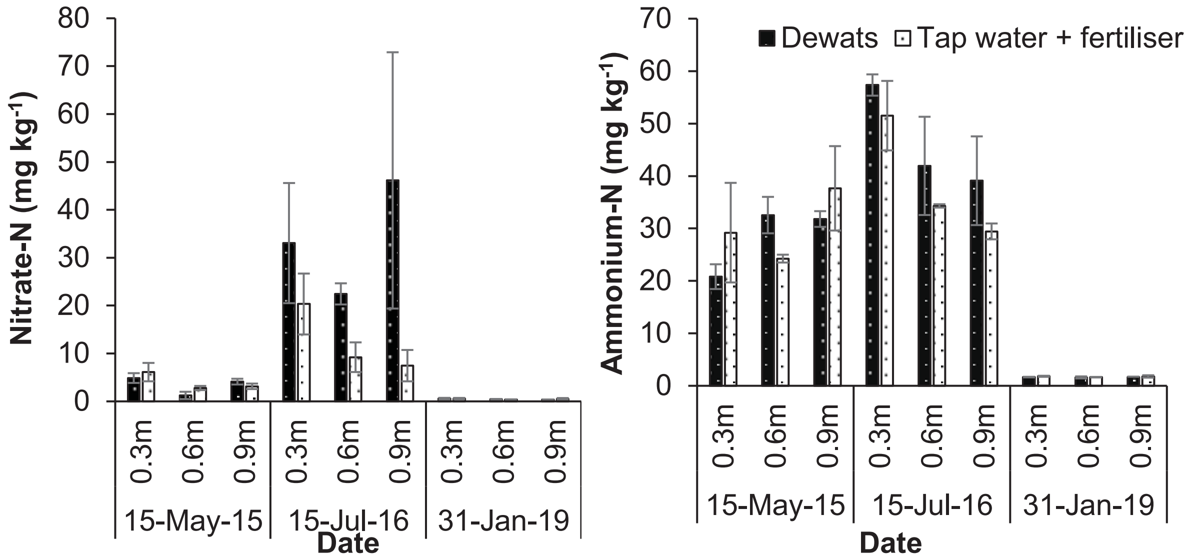


Figure 5.14: Mean ± standard error of deviation (n=3) for changes in soil inorganic N (nitrate and ammonium) at three depths in the Sepane soil irrigated with DEWATS effluent on 15 May 2015 (end of banana/taro crop), 15 July 2016 (end of second banana crop) and at 31 January 2019 (after rice production).

5.7 Conclusions

Application rates of 435 kg ha^{-1} urea (N) and 465 kg ha^{-1} struvite or 600 kg ha^{-1} SSP (P) were required for maize production. Based on these rates, N release patterns for struvite were similar but differed in magnitude. A combination of struvite + urea released the highest concentrations of N. The N release patterns for DEWATS effluent were different from urea; N release rates and magnitudes were generally lower for the effluent. The DEWATS N release was limited by soil water storage, confirming that the effluent can be used as a source of water rather than nutrients depending on the crop type and growing period. The P release patterns did not differ between the struvite and SSP thereby making the former an alternative P fertiliser that can be used in combination with the effluent.

Irrigation to maintain 70% soil water content using DEWATS effluent provided adequate N required for maize growth. The crop growth rates between SSP + effluent and struvite + effluent were comparable. These treatments exhibited higher N and P concentrations in the maize plant tissue as well as uptake. This confirms earlier conclusions that an HEDM such as struvite can be used to substitute for commercial fertilisers. The effluent is a better N fertiliser which is also able to provide some extra P and can be used in combination with other fertilisers to improve maize growth.

There were significant differences in forage sorghum growth quality parameters such as plant height and dry mass per unit area between different planting densities due to inter and intra plant competition at the high density population. Crop growth was a good indicator that the high plant density created a demand for water and nutrients, which significantly increased the biomass produced per unit area as well as the potential for nutrient removal per unit area. However, the efficiency of such systems depends on the effluent quality and available land area. The HFCW effluent can be applied to crops based on N as the limiting nutrient. However, when AF effluent is used a larger land area of almost threefold the size used for HFCW is required. Based on the findings reported, P was shown to be the most important nutrient of environmental concern regardless of the type of effluent used or planting density. The accumulation of P may lead to non-point source pollution through surface runoff, therefore different management strategies such as maintaining a buffer area between field and water source, are required. The buffer area must be planted with crops such as sward grass or vetiver grass to maximise P uptake before it reaches the water body, and some crops such as sod grass can be used to remove excess N. Tilling the land and conservation methods can also be used to minimise surface runoff to nearby water resources.

The effluent applied to rice through various irrigation techniques ranged from 888 mm to 2 450 mm, being low in AWD and high in CF. All the irrigation techniques, except for AWD, provided more N and P than required for rice production, However, analysis of rice yields showed that they were not significantly different as a result of the irrigation techniques and the values were within the optimum ranges for the rice cultivar. The land area required to utilise all effluent produced based on the DEWATS design capacity were lower for the CF and WWF treatments (about 250 m^2) than the AWD treatment (about 400 m^2). If the effluent was used as a fertiliser source the land area for CF and WWF treatments would need to be quadrupled while for the AWD treatment double the area would be needed. The P removal per unit area was very low under all irrigation techniques while N removal was high in the AWD treatment. Therefore, runoff management through conservation methods and creating a buffer area between the irrigation area and nearby rivers are recommended.

In areas with high wastewater production and less available land, high water consuming crops such as forage sorghum can be grown at high density. When considering crops such as banana, taro and rice, nutrient management practices must be considered to avoid leaching in coarser-textured soils and surface runoff from clayey soils. The extent of effluent treatment is also important. The HFCW effluent has lower nutrient concentrations than the AF effluent, and therefore adds fewer nutrients to the soil. Phosphorus is the most important nutrient for non-point source pollution. It is taken up by crops in small quantities, adsorbed and retained in most soils (depending on their mineralogy and organic matter content), and can be transported to rivers either in solution or attached to soil particles.

Long term irrigation with DEWATS effluent improved soil pH and its use in poor, P deficient, acidic soils is likely to be beneficial. Accumulation of cations (Ca and K) depends on the crop grown, irrigation volumes and effluent concentration. The K accumulated in the soil is most likely to be depleted by banana if fertilisers are not supplemented. Long term irrigation with DEWATS effluent did not significantly increase the soil inorganic N as calculated by the mass balances. It was mostly lost through denitrification processes due to the different irrigation techniques used for different crops as well as other processes that affect the soil N concentration. However, leaching from the field site at Newlands Mashu was negligible.

6 AGRICULTURAL USE OF HUMAN EXCRETA-DERIVED MATERIALS IN AGRICULTURE: A CASE STUDY AT VULINDLELA, PIETERMARITZBURG

6.1 Introduction

A key strategic objective of the current project was based around the requirement of “Empowerment of Communities”. To achieve this objective, Vulindlela a rural subdistrict within the Msunduzi district municipality near Pietermaritzburg was chosen. Working with communities within Vulindlela presented an opportunity to demonstrate how the project can empower communities, through either community members’ participation or evidence of specific knowledge/innovations that communities can use once the project has been completed. Representatives of the Vulindlela community approached the University of KwaZulu-Natal to discuss ways to collect, process and utilise human excreta from ventilated improved pit latrines (VIPs), which were not being emptied by the local municipality.

Based on 2013 statistical data, the area has 85 033 houses and a population of 161 562, which is expected to increase at a rate of about 2% per annum by the year 2030 (Msunduzi Municipality, 2016). Vulindlela has been poorly developed. It is characterised by high levels of unemployment and teenage pregnancies, poor levels of education and poor access to income generation opportunities. Furthermore, Vulindlela has the highest HIV infection rate in Africa, with high levels of infection found especially in girls between the ages of 15 and 23 years (Msunduzi Municipality, 2016).

Households in Vulindlela have access to basic services such as water, electricity, roads and VIPs. Despite having this basic sanitation, the municipality did not have plans to empty them as this was deemed logistically infeasible due to the rugged terrain of the area as well as the emergence of unplanned settlements. Since the VIPs were designed with no plan for emptying, accumulation of human excreta in the pits is causing an environmental and health hazard. Community members try to dig new pits next to the existing toilets which worsens the situation (Zimu, 2018, personal communication).

The National Development Program (NDP) of 1994 encourages the demarginalisation of the rural poor through the encouragement of research and development into technologies that promote agricultural production value chains (Msunduzi Municipality, 2016). Therefore, this case study aimed to generate baseline information on how the human excreta can be recovered, processed and safely used for sustainable agriculture in a socially acceptable way, minimising environmental pollution and improving agricultural production systems in the resource-constrained community of Vulindlela.

Specific objectives:

- To co-identify challenges affecting sanitation, human excreta management and food production systems and to discuss and co-propose potential solutions for sustainable agricultural production through safe and socially acceptable nutrient recovery and reuse in Vulindlela.

- To co-select the common food crop produced in Vulindlela, assess its potential agronomic response to human excreta derived materials (HEDMs) and resulting environmental impacts using the SWB-Sci model.

6.2 Materials and methods

6.2.1 Study site

Vulindlela, located to the west of Pietermaritzburg (Figure 6.1), is within the sub-humid agro-ecological region of South Africa and receives an annual rainfall of 979 mm. Most of the areas in Vulindlela are characterised by slopes up to 12%.

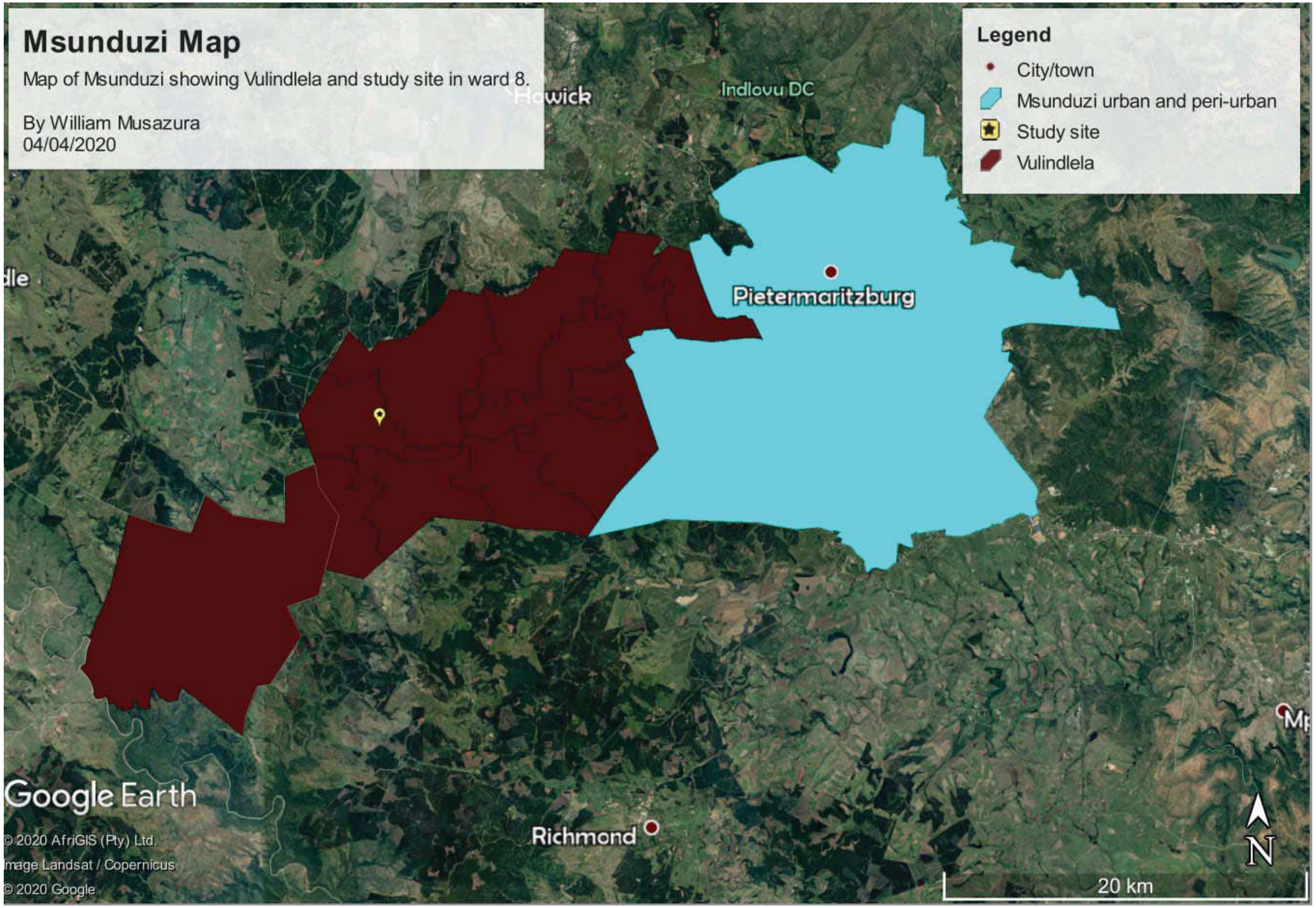


Figure 6.1: Map of Msunduzi local municipality showing the location of Vulindlela and the study site.

6.2.2 Community engagement

A community-based participatory research approach (CBPR) was established through stakeholder meetings and participatory rural appraisals. This aimed to engage the community, understand their social dynamics and agricultural production systems to ensure that the study was inclusive and participatory. Furthermore, societal problems are complex and dynamic in nature, and hence require different perspectives from various experts. The approaches to the social study are summarised in Figure 6.2

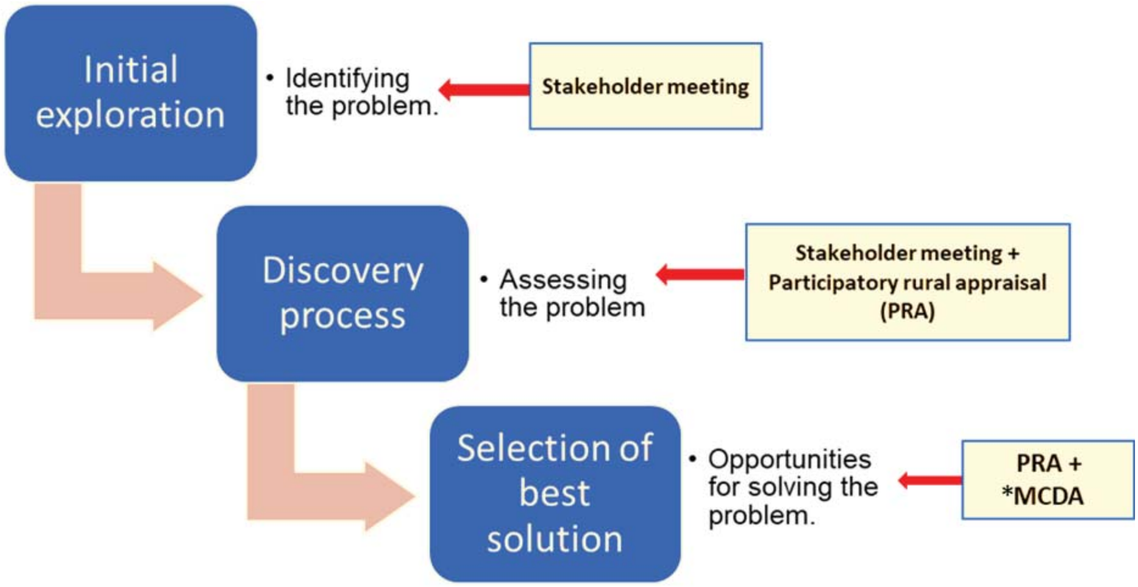


Figure 6.2: Summary of methods used for stakeholder consultation and community engagement at Vulindlela. *MCDA: multi-criteria decision analysis.

6.2.2.1 Stakeholder meeting

A stakeholder meeting, that involved various people in the municipal water and sanitation sector (Riaz Jogiat from Umgungundlovu District Municipality and Mark Greatwood from Msunduzi municipality), Vulindlela community representatives (Mr Linda Zimu and Ms Gugu Dlamini), and researchers from Crop Science (Dr Alfred Odindo and Dr William Musazura), Agricultural Economics (Mr Simmon Gwara) and Chemical Engineering (Prof. Chris Buckley) Departments at the University of KwaZulu-Natal was convened on 10 December 2018 (Figure 6.3). The agenda of the meeting was to (a) identify innovative solutions to treat and reuse human excreta from currently installed VIPs in Vulindlela and (b) find ways of developing sustainable waste management systems that are directly and/or indirectly beneficial to the community as a way of empowering the unemployed youths and women and (c) alleviate human health risks.

The meeting aimed to discuss the following issues:

1. What are the human excreta waste management challenges faced by communities in Vulindlela?

2. How can we leverage potential sanitation technologies to provide opportunities for the recovery and processing of human waste in Vulindlela?

3. What are the potential food value chains?

4. Are there potential markets for food produced from waste-based fertiliser sources?

Some of the influential stakeholders (traditional leadership), who are in control of the land in Vulindlela could not attend the meeting, hence a catch-up meeting was scheduled on 7 June 2019 at Vulindlela where Mr Sokhela, representing the traditional leadership, was briefed.

Figure 6.3: A presentation during the stakeholder meeting at the Crop Science Department, University of KwaZulu-Natal involving farmers to formulate research questions addressing the societal problems at Vulindlela concerned with waste treatment.

6.2.2.2 Production systems analysis in Vulindlela.

A participatory rural appraisal (PRA) was done on 3 July 2019 at Vulindlela Ward 7 Councillor's Offices according to the methods of Gill et al. (2008) (Figure 6.4). A focus group discussion facilitated by the researcher was held with a group representing people of different social backgrounds from Vulindlela including unemployed youths, women, traditional leaders and members of agricultural cooperatives. The issues discussed were:

What are the main commodities farmed by cooperatives?

What is the extent of production?

What are the yields?

Where is the produce market?

Where are the farmers buying their inputs?

At what scale is livestock farming taking place?

What are the possibilities of using Servontein prison waste?

Figure 6.4: Participatory rural appraisal held at the Councillors Office in Ward 7 on 3rd July 2019.

6.2.2.3 Selection of the best cropping enterprise at Vulindlela.

Based on the discussion a multi-criteria decision analysis (MCDA) was conducted to decide on a crop of choice for a profitable food value chain. The MCDA is a technique used in decision making by assessing the pros and cons of various options available (Adem Esmail and Geneletti, 2018). The various cropping enterprises at Vulindlela were assessed based on climatic requirements, availability of markets, knowledge of the production system, production costs (pest and disease control and fertiliser requirements), technological demands and potential pathogen risks when HEDMs are used. Potential crops, which are actively being produced in Vulindlela were identified with yellow maize proving to be a major option.

6.2.3 Biophysical characterisation

The biophysical properties of the study area need to be assessed as this is required to track the impacts of technological interventions on the environment. This section, therefore, reports on soil properties, climatic variations and potential agronomic practices for Vulindlela.

6.2.3.1 Characterisation of soils at the study site

A study area of 2 500 m^2 (50 x 50 m) was provided by the traditional leadership to support biophysical studies. Soil samples were collected at three different depths (0-0.3, 0.3-0.6 and 0.6-0.9 m). Three subsamples collected from each layer were then bulked to form a composite sample. Soil inorganic N was analysed using the Discrete Autoanalyser (Thermofisher Scientific, Waltham, MA USA) after extraction in a 1:10 soil:2M KCl solution, followed by filtering through a Whatman ® No. 2 paper (Mynard and Kalra, 2008). Available P was extracted using Ambic-2 solution (Hunter, 1974) followed by the molybdenum blue procedure (Hunter, 1974, Murphy and Riley, 1962). Soil pH (in water and KCl) and organic C were measured at the Soil Science laboratories, University of KwaZulu-Natal, following standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990).

6.2.3.2 Climatic information at Vulindlela

There were challenges in acquiring historical weather data (maximum and minimum air temperatures, solar radiation, reference evapotranspiration (Eto), wind speed and precipitation) for Pietermaritzburg. However, data from Ukulinga Research Station (Pietermaritzburg) was obtained from the South African Sugar Research Institute (SASRI) database and the data ranged from 1995 to 2011. The weather patterns are characterised by hot and rainy summer periods followed by cool, dry winters. Daily temperatures range from as low as <5°C to approximately 40°C, indicating some possibilities of frost during winter.

6.2.3.3 Chemical characteristics of potential human excreta-derived materials.

The study focused on LaDePa pellets, struvite and NUC. The characteristics of these materials have been given in 3.

6.2.3.4 Agronomic practices for maize

Maize (Zea mays L.) is a staple crop in South Africa and is adapted to various environments depending on the variety. The crop grows well in areas with 500-700 mm of water per year. Maize requires between 120 to 140 frost-free days and a maximum temperature of 32°C. Flowering occurs well at temperatures between 19 and 25°C. Every tonne of grain removes about 15-18 kg of N and 2.5-3.0 kg of P ha^{-1}, hence a yield target of 12 tonnes ha^{-1} requires about 200 kg N ha^{-1}, 36 kg P ha^{-1} and 195 kg K ha^{-1} depending on soil analysis results. The volumes of HEDMs required per hectare to meet maize N and P requirements were determined from Equation 6.1 (solids) and 6.2 (liquids):

$$\text{Amount (kg ha}^{-1}\text{)} = \frac{CR}{CN1} * 1\,000 \text{ (kg ha}^{-1}\text{)} \qquad \text{Equation 6.1}$$

$$\text{Amount (L ha}^{-1}\text{)} = \frac{CR}{CN2} * 1\,000 \text{ (L ha}^{-1}\text{)} \qquad \text{Equation 6.2}$$

where: CR is the crop nutrient (N, P and K) requirement in kg ha^{-1}; CN1 is the nutrient concentration of the solid HEDM in g kg^{-1}; CN2 is the nutrient concentration of the liquid HEDM in g L^{-1}.

6.2.4 Scenario analysis on maize yield in Vulindlela: Crop modelling using SWB Sci model.

The use of different HEDMs in promoting sustainable agriculture which increases maize yields while minimising environmental potential was assessed using scenario analysis. Scenario analysis is a technique which provides a tool for integrating knowledge through scanning the future in a systematic way (Swart et al., 2004). Agricultural systems processes are very complex and dynamic, being driven by climatic, economic, cultural and biological variables and hence crop models have been used to simplify such dynamics for decision making (Boote et al., 2013). Weather data for Ukulinga, Pietermaritzburg (representing Vulindlela) was used to run SWB-Sci model simulations under different irrigation management practices (dryland vs irrigated) and fertiliser amendments (no HEDMs applied vs combinations of NUC, struvite and LaDePa pellets). The full description of the SWB-Sci model is given in 6.0.

6.2.5 Data analysis

Qualitative data for the production systems analysis was presented as a table of questions and responses, and the best cropping enterprise was determined using a decision matrix. Quantitative data were subjected to analysis of variance (ANOVA) at a 5% significance level using the GenStat 19th edition statistical package (VSN International, 2017).

6.3 Results and Discussion

6.3.1 Production systems analysis.

Crops which are commonly grown in Vulindlela are maize, dry beans, winter vegetables, sweet potatoes and madumbe, which agrees with findings by Nzimande (2004), who studied crops grown in community gardens of people in the Zimiseleni and Ifalesizwe areas of Vulindlela. However, the production of vegetable crops is done in the home gardens and production at large scale is limited by water scarcity. During a site visit, some of the crops seen included maize, dry beans and taro (Figure 6.5). The proceedings of the focus group discussion and questions and responses captured during the meeting are given in Table 6.1.

Figure 6.5: Crops identified in the fields of farmers in Vulindlela during a visit showing (A) dry bean and madumbe and (B) maize.

Farmers in Vulindlela have access to about 5 ha of land, which can be acquired through traditional leadership (Msunduzi Municipality, 2016). Identification of markets is a major challenge being faced by farmers. The uMkhondeni morning market in Pietermaritzburg is a potential vegetable market but the farmers are unable to access it due to stringent competition with large scale commercial farmers. There is the Radical Agrarian Socio-Economic Transformation (RASET) programme which contracts farmers to produce crops used in government institutions (prisons, hospitals and schools). Although the programme empowers small scale farmers, some respondents were dissatisfied with it since they do not trust government-related projects. They also raised the problem of delayed payments of pay-outs. Furthermore, the current research is aiming to use human excreta waste, and farmers under RASET have no flexibility in choosing the agro-systems to follow. Therefore, there is room for research on how HEDMs can be used in such programmes for an effective circular economy. Regardless of the market challenges discussed, the best market for agricultural produce in Vulindlela is a nearby commercial livestock farmer, who buys yellow maize for livestock feed.

Water scarcity is a problem in Vulindlela and this prevents winter vegetable (cabbages, Swiss chard and carrots) production. Therefore, dryland maize and beans are major crops grown during summer. In winter, the land is left fallow for animals to feed on crop residues. Furthermore, the remnant seed from the previous season is used and this is generally low yielding. According to the farmers, hybrid seeds are too expensive for them and some follow traditional methods of crop production.

The community have positive perceptions of the importance of human excreta as a resource rather than waste. They showed interest in valorising human excreta for business and/or crop production. The cooperatives are characterised by unemployed youths and women, and such business opportunities are beneficial for employment creation and the cooperatives were optimistic about the Kenyan export market.

Table 6.1: Understanding agricultural production dynamics in Vulindlela, with special reference to commonly grown crops, input constraints, market opportunities and potential for recovering human excreta waste for agricultural use.

Question	Response
What are the main commodities farmed by cooperatives?	Maize, Dry bean, Vegetables (Beetroot, Swiss chard, Cabbages, Butternuts and Carrots), Sweet potatoes and Madumbe. Crop rotation practised. Water is a problem hence dryland production practised.
What is the extent of production?	About 5 ha per person.
What are the yields?	Generally, very low due to the use of open-pollinated varieties.
Where is the produce market?	Maize is sold to the livestock farmers around. Vegetables are marketed in different channels; the informal markets and supermarkets. There is an opportunity for Radical Agrarian Socio-Economic Transformation (RASET). Difficulties in accessing uMkhondeni morning market due to competition.
Where do farmers purchase inputs?	RASET programme expected to provide. Some seed is reused.
What is the extent of livestock production?	Livestock not produced for commercial purposes.
What are the possibilities of using prison waste/ human excreta waste for cooperatives in Servontein?	"…. if there are potential business opportunities for waste recovery, we will utilise them…"

6.3.2 Selection of the best enterprise.

Maize was selected as the best agricultural enterprise for Vulindlela based on the decision matrix in Table 6.2.

Table 6.2: Decision matrix showing the best cropping enterprise for the Vulindlela farmers based on eight criteria.

Enterprise	Climatic requirements	Market availability	Local expertise	Technology needs	Pathogen risk	Value addition	Pests and disease	Production costs	Average score
Maize	5	5	5	5	5	5	4	3	4.6
Sweet potato	3	2.5	5	4	2	3	3	4	3.3
Butternut	4	3	5	5	4	3	3	4	3.9
Madumbe	3	4	5	5	4	2	4	4	3.9

Scale:	0	1	2	3	4	5
	Worst	Very bad	Bad	Good	Very good	Best

6.3.3 Soil chemical properties of the study site in Vulindlela.

Table 6.3 gives the physical and chemical properties for the soil at Vulindlela. As expected, there was a significant change in clay, sand, extractable P and organic C content with depth. Clay content increased with depth while sand, extractable P and organic C decreased with depth.

Table 6.3: Some physical and chemical properties of the soil samples collected at three depths from the study site at Vulindlela (mean ± standard error of difference; n = 3).

Property	0.3 m	0.6 m	0.9 m
Clay (%)	25±0.7c*	44±3b	58±2.3 a
Silt (%)	22±2.3b	17±3.3c	25±3.3a
Sand (%)	53±2.4a	39±5.2b	17±1.2c
Textural class	Sandy clay loam	Clay loam	Clay
Organic C (%)	2.4±0.2a	1.0±0.1b	0.5±0.1c
Ammonium-N (mg kg^{-1})	3.2±0.3a	3.3±0.4a	2.9±0.2a
Nitrate-N (mg kg^{-1})	nd	nd	nd
Extractable P (mg kg^{-1})	15.7±3a	9±2.1b	3.7±1.2c
pH (KCl)	5.6±0.3a	5.6±0.2 a	5.5±0.2a

* The superscripts a, b and c indicate means that are significantly different at 5% level within each row.

6.3.4 Agronomic practices for maize

Nitrified urine concentrate, struvite and LaDePa pellets are mainly sources of N, P and organic C, respectively (Chapeyama et al., 2018). The amount of HEDMs required to meet the maize N, P and K requirements are given in Table 6.4. Low amounts of struvite can be applied to meet maize P requirements and in addition crop N fertiliser requirements are reduced. The NUC is an important source of N, K and some P, hence low volumes are required. When LaDePa pellets and struvite are used for maize, K is required since it is in very low quantities (LaDePa) and absent in struvite. This has implications on logistics and costs for each HEDM if it must be produced off-site. Fortification of HEDMs allows more nutrients to be incorporated per smaller unit volume of HEDM thereby enhancing its value and effectiveness.

Table 6.4: The amount of struvite, nitrified urine concentrate (NUC) and LaDePa pellets required to meet maize nitrogen, phosphorus and potassium requirements.

Element	Struvite (kg ha^{-1})	NUC (kL ha^{-1})	LaDePa (kg ha^{-1})
Nitrogen	3 333	5	5 714
Phosphorus	277	18	2 353
Potassium	-	12	24 400

6.3.5 Crop modelling using SWB Sci model

6.3.5.1 Maize yields under dryland and irrigated production.

Maize crop yields under different production systems (dryland and irrigated) were simulated using the SWB Sci model and the results are shown in Figure 6.6. Irrigation scheduling leaving room for rainfall may increase maize yield to a target of 12 t ha^{-1}. According to Schulze and Walker (2007), maize yields in South Africa are generally low, hence such a yield is rarely achievable due to other limitations such as weeds, pests and diseases. The authors did simulations using the CERES maize model and found that high yields of 3.9 t ha^{-1} under dryland production are expected in KwaZulu-Natal and this agrees with some of the simulations in this study. Simulated high yields (>4 tons ha^{-1}) under dryland production for Vulindlela were reported in 1996, 2000, 2002, 2004 and 2009, out of 18 years simulated. Therefore, dryland production in Vulindlela is relatively poor with farmers using low yielding, unimproved maize varieties. Sometimes production is constrained by inputs such as fertilisers which are very expensive and hence relatively low yields are expected. For long-term planning, investment in the irrigation system is crucial if they are to maximise maize production even in winter when they can produce green maize.

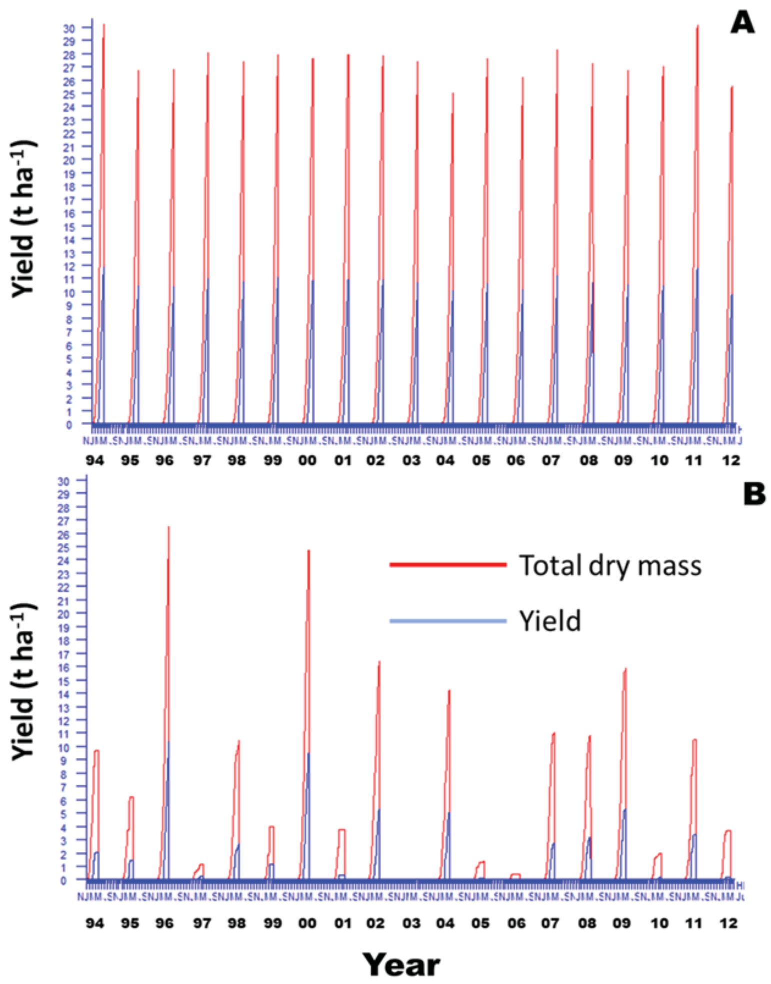


Figure 6.6: Simulated top dry mass and maize yield from (A) irrigated and (B) dryland production systems over a period of eighteen years.

6.3.5.2 Nitrogen uptake

There was a significant difference ($p<0.05$) in N uptake between the irrigated and dryland production systems and between the fertiliser applications (no HEDMs applied vs HEDMs) (Figure 6.7). Higher top biomass and grain N uptake were simulated in irrigated maize compared to dryland maize. This was related to yield per unit area as shown in Figure 6.6. The ability of HEDMs to increase crop yield was evidenced by significantly higher top biomass and grain N uptake, especially under the irrigated system.

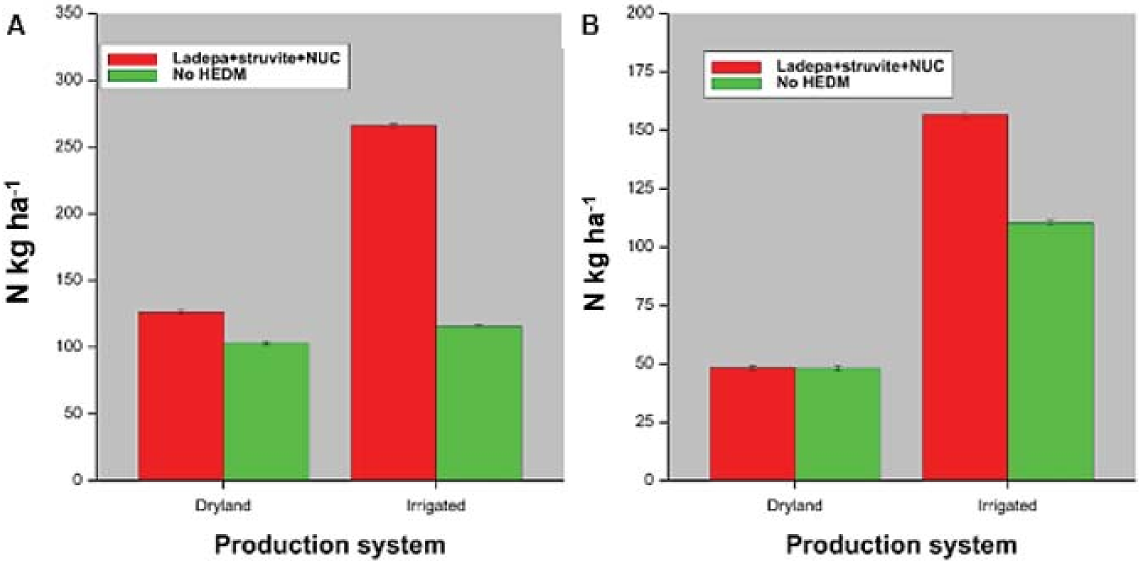


Figure 6.7: Simulated (A) top biomass nitrogen (N) and (B) maize grain N uptake produced under two production systems (irrigated vs dryland) and application of HEDMs vs no HEDMs applied showing mean ± standard error of mean differences (n=3 653).

6.3.5.3 Nitrate and phosphorus in the soil

The simulated accumulation of nitrate and P in the soil profile under different fertiliser applications (HEDMs application vs no HEDMs) and production systems (irrigated vs dryland) are shown in Figure 6.8. The use of HEDMs increased the concentrations of nitrate-N and P in the soil over time. Although the same fertiliser application rates were applied, the greater accumulation under the dryland system was due to less uptake by plants. Furthermore, the mobility of nitrates in comparison to orthophosphates is evident in no fertiliser + dryland production (Figure 6.8); nitrate concentrations were higher during the earlier period but declined later, while not much change was shown for P.

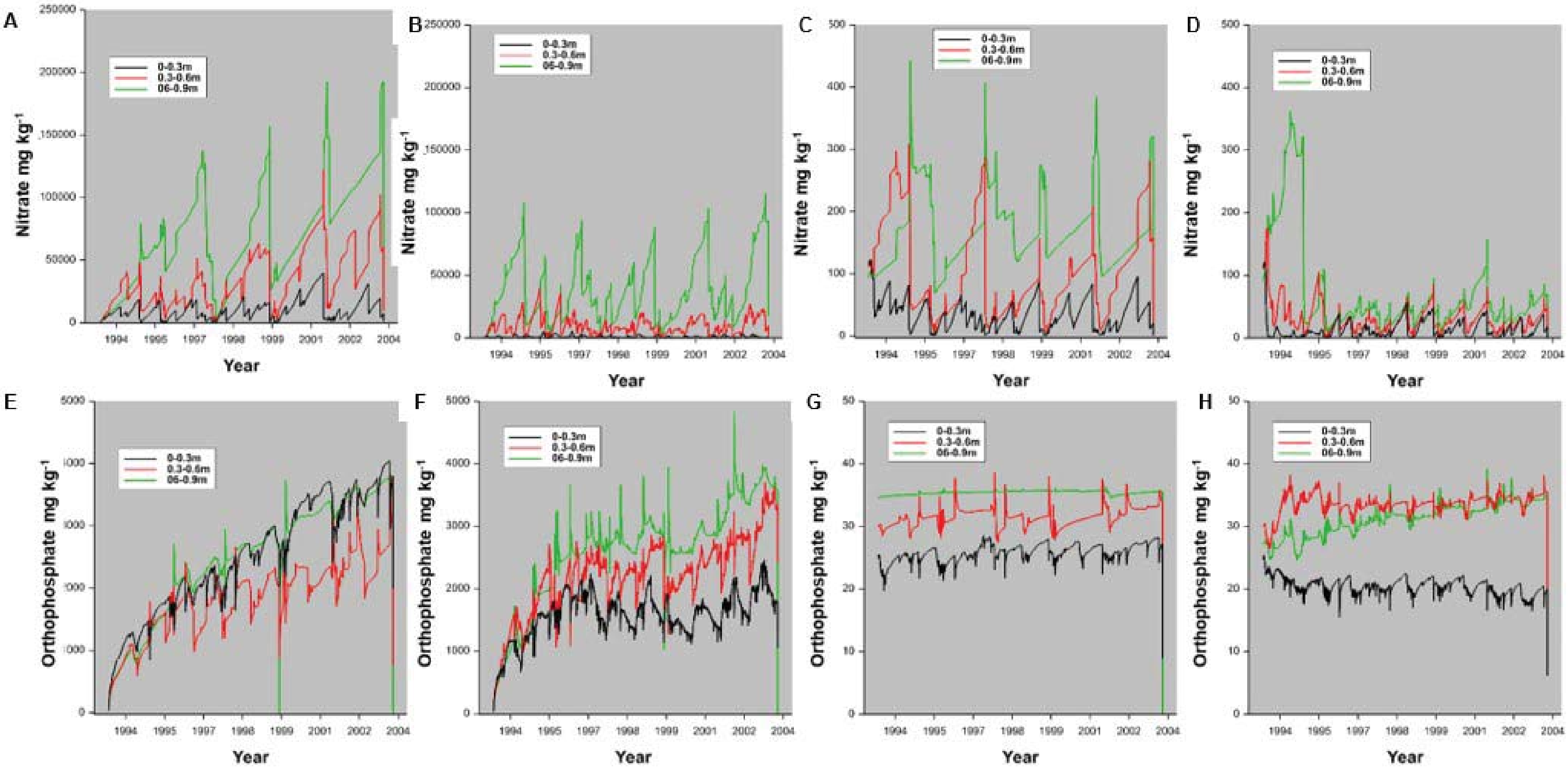


Figure 6.8: The concentrations of residual nitrate and orthophosphate within three layers of the soil profile (0-0.3, 0.3-0.6 and 0.6-0.9 m) for two production systems (irrigated vs dryland) and HEDMs application vs no fertiliser. *A and E (HEDMs combination; dryland), B and F (HEDMs combination; irrigated), C and G (No fertiliser; dryland), D and H (No fertiliser; irrigated).

6.3.5.4 Nitrate and phosphorus leaching

The simulated concentrations of mobile nitrates and orthophosphates are reported in Figure 6.9. High nitrate and orthophosphate mobility was shown in irrigated systems with HEDM application. Very high nitrate and orthophosphate leaching was reported in 1999 for HEDMs applied under dryland production, a year in which very high rainfall was reported (Figure 6.9). The model was adjusted to auto irrigate, allowing room for rainfall, so the extent of nitrate and orthophosphate leaching was not very high (Figure 6.9), thereby confirming the importance of the SWB-Sci model as an irrigation and nutrient management tool in sustainable agriculture.

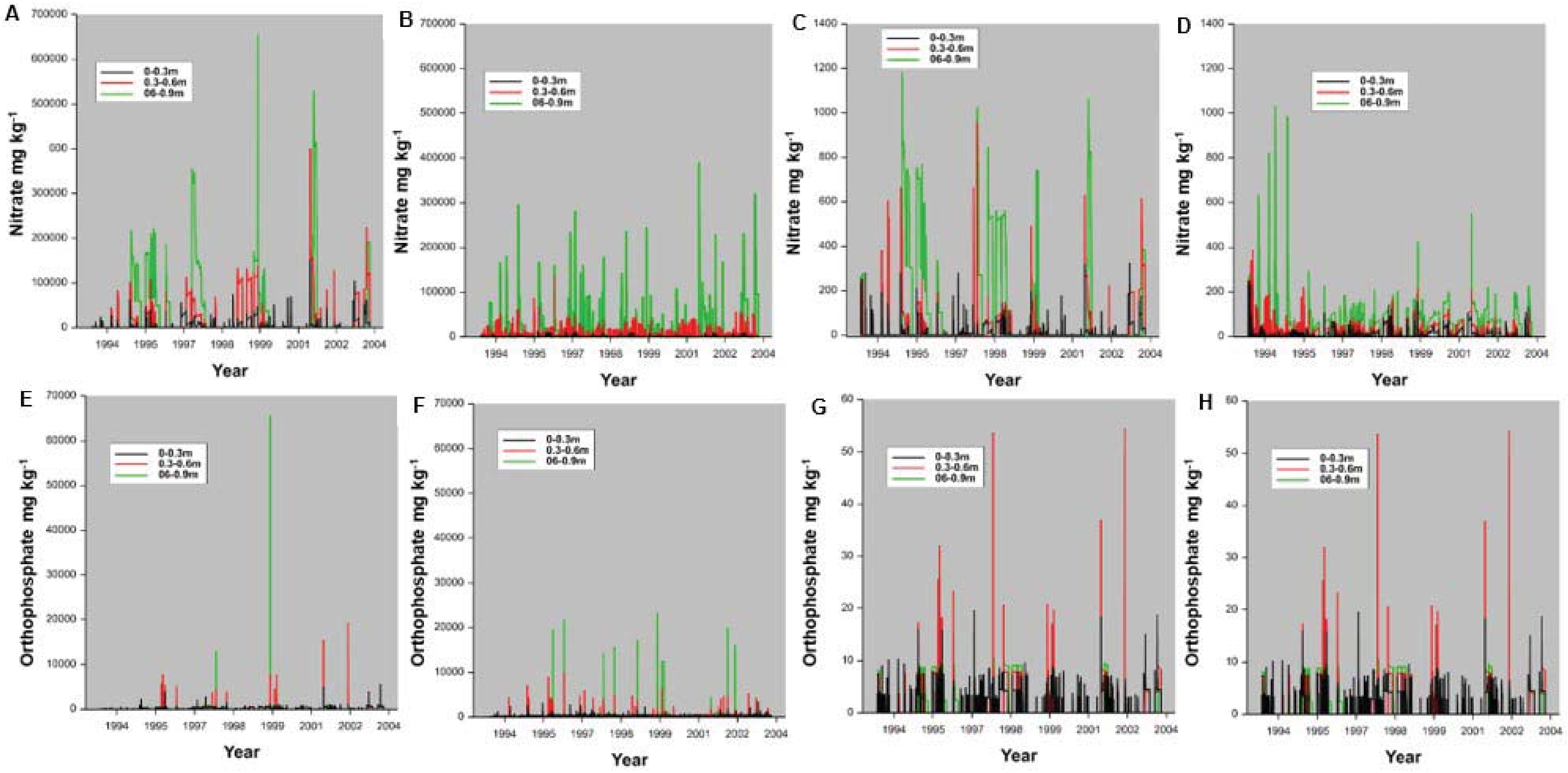


Figure 6.9: The mobility of nitrate and orthophosphate within three layers of the soil profile (0-0.3 m , 0.3-0.6 m and 0.6-0.9 m) for two production systems (irrigated vs dryland and HEDMs application vs no fertiliser). *A and E (HEDMs combination; dryland), B and F (HEDMs combination; irrigated), C and G (No fertiliser; dryland), D and H (No fertiliser; irrigated).

6.4 Conclusions

The community of Vulindlela (traditional leadership, cooperatives and farmers) and scientific experts successfully engaged to discuss human excreta waste management in Vulindlela. From the PRA, it was found that there is a need and a desire to find ways to empty the VIPs and to subsequently valorise the latrine contents into fertilisers. Several HEDMs have been identified as potential fertilisers and these included LaDePa pellets, struvite and NUC. Therefore, the current innovative sanitation solutions such as UDDTs provide opportunities for human waste recovery which can be processed into these agricultural resources.

In addition, yellow maize was selected as an important commonly grown crop in Vulindlela, which can be produced using the HEDMs since the climate is conducive for its production, the farmers have enough technical knowledge to manage it, the market is available, it does not need sophisticated technology to produce it, it is less susceptible to pests and diseases, has potential for value addition (e.g. stock feed or maize meal) and its production costs are low.

The findings on the volumes required for each HEDM to meet maize N, P and K requirements showed that about 277 kg ha^{-1} of struvite is required (to meet P), 5 kL ha^{-1} of NUC (to meet N) and 2.3 tons ha^{-1} LaDePa pellets (to meet P, without considering mineralisation rate), and NUC is the only HEDM with high K. Therefore, the HEDMs should be used in combination or fortified to increase their nutrient values.

Simulations of maize production using HEDMs showed that the higher yields (>10 t ha^{-1}) are obtainable in Vulindlela under irrigated production. Dryland production sometimes gives high yield (>4 t ha^{-1}) in some years, depending on rainfall but this is not reliable. Furthermore, the use of various HEDMs in combination proved to increase maize N uptake, which plays a role in crop yield, and this is effective under irrigation at Vulindlela.

The application of HEDMs increase soil N and P, especially in irrigated soils. High N and P concentrations and dynamics in the soil increase bioavailable nutrients required for optimum maize production. However, good nutrient management through irrigation scheduling is recommended. Therefore, HEDMs can potentially be used sustainably as fertilisers for maize production in communities such as Vulindlela.

7 CONCLUSIONS AND FUTURE RECOMMENDATIONS

7.1 Conclusions

The WRC K5/2777 project emanated from the WRC K5/2220 project to address outstanding issues required for the development of guidelines to enable the agricultural use of various human excreta derived materials (HEDMs) emanating from on-site sanitation systems. The specific aims of the project were to:

1. Monitor the long-term chemical and physical effects on soils of DEWATS effluent used for irrigation, and the effects on production of different crops, and risks of microbial contamination at Newlands Mashu research site, Durban.
2. Assess the safety of HEDMs with respect to i) pathogen contamination during handling, food production and consumption, and ii) the risk of adding pollutants to the environment.
3. Generate information on the fertiliser value of HEDMs and develop guidelines integrating sustainable agricultural production in the planning and design of low-cost sanitation technologies in peri-urban and rural areas.

The SAWQG (DSS) and long-term monitoring of DEWATS effluent irrigation showed that:

- The long-term use of DEWATS effluent has no impacts on soil COD, root zone salinity, corrosion of irrigation equipment, soil infiltrability and accumulation of trace elements.
- Soil hydraulic conductivity reduction risks are high in many agroecological regions of South Africa except arid areas.
- The use of AF effluent based on crop water requirements may load excessive N and P, exceeding crop requirements, which may contaminate the environment.
- There were no significant changes in soil chemical properties, including nutrient content, except for soil pH that slightly increased.

The fertiliser values of various HEDMS have been assessed.

- The DEWATS effluent provides N, P and K required for crop growth. However, these nutrients are not in balanced proportions.
- LaDePa pellets are slow-release organic fertilisers which are low in K but high in C, N and P.
- Urine stored at 20°C for 6 months is sterile and can provide nutrients required for crop growth, but the smell makes it undesirable to farmers.
- Struvite is a non-odorous phosphorus fertiliser that is poor in K. Besides being a P fertiliser, struvite contains some N (6%) which should be considered in nutrient management practices.
- The NUC is the most compact and portable liquid fertiliser that has the same amounts of nutrients as fresh urine. The disadvantage of using NUC e.g. in hydroponics systems, is the low Ca content, which might be associated with the development of disorders such as blossom end rot in tomato and sweet peppers.

- The HEDMs can potentially increase yields of crops such as maize when grown in combination and under irrigated conditions especially in low-income communities of South Africa.

The guideline for safe and environmentally sustainable agricultural use of human excreta-derived materials has been developed as a separate report.

7.2 Recommendations

- There is a need for innovative wastewater treatment solutions to reduce the microbial load of DEWATS effluent so that it can be used for unrestricted crop production. The same applies to exploring further methods to remove pharmaceuticals from urine.
- Challenges related to technological investments in the installation of sanitation infrastructure, legal framework, social perceptions, policy and health-related issues should be addressed for successful implementation.
- Future projects should consider the sustainability of using HEDMs through the identification of resilient food and sanitation value chains by engaging different stakeholders.
    - One example would be the partnership with the rural-urban nexus (RUNRES project) that aims to establish a nutrient loop to improve city region food system resilience. As part of this project a transdisciplinary innovative platform (TDIP) is being created. The TDIP provides a mechanism whereby different stakeholders engage with scientists and the community in the coproduction of knowledge. This platform provides information on how different challenges (biophysical, legal and socio-economic) can be tackled to promote sustainable circular economies contributing to safe, economically, socially and legally acceptable utilisation of human waste, and thus improving food and waste value chains.
    - The project also seeks to identify viable sanitation innovations that will be tested and validated in communities before scaling up to other areas. Therefore, the WRC and RUNRES should work synergistically to achieve the goals of waste recovery and reuse, and a circular economy.

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APPENDICES

Appendix 4.1: Soil quality with a specific amount of irrigation (calculated by the DSS).

Parameter	Fitness for use	Ranges
Root zone salinity:	EC (mS m^{-1})	
	Ideal	0-200
	Acceptable	200-400
	Tolerable	400-800
	Unacceptable	> 800
Soil Permeability	Degree of reduced Permeability	
	Ideal	None
	Acceptable	Slight
	Tolerable	Moderate
	Unacceptable	Severe
Oxidisable Carbon Loading	COD Load (kg ha^{-1} per month)	
	Ideal	0-400
	Acceptable	400-1000
	Tolerable	1000-1600
	Unacceptable	>1600

Appendix 4.2: Soil quality (trace elements) thresholds from irrigation with a specific amount of water of a certain quality (calculated by the DSS).

Fitness for use	Number of years of irrigation before trace elements reach accumulation threshold in topsoil
Ideal	> 200
Acceptable	150 to 200
Tolerable	100 to 150
Unacceptable	< 100
Trace element	Soil accumulation threshold ($mg\ kg^{-1}$)
As	50
Be	50
Cd	5
Cr	50
Co	25
Cu	100
F	1 000
Pb	100
Li	1 250
Mn	100
Hg	1
Mo	5
Ni	100
Se	10
U	5
V	50
Zn	500

Appendix 4.3: Crop yield and quality with a specific amount of irrigation (predicted by the DSS).

Parameter	Fitness for use	Range
Root zone effects:	Relative crop yield (%)	
	Ideal	90-100%
	Acceptable	80-90%
	Tolerable	70-80%
	Unacceptable	< 70%
Leaf scorching when wetted	Degree of leaf scorching	
	Ideal	None
	Acceptable	Slight
	Tolerable	Moderate
	Unacceptable	Severe
Contribution to NPK removal	Contribution to estimated NPK removal by crop	
	Ideal	0-10%
	Acceptable	10-30%
	Tolerable	30-50%
	Unacceptable	>50%
Microbial contamination	Excess infections per 1000 persons per annum	
	Ideal	<1
	Acceptable	1-3
	Tolerable	3-10
	Unacceptable	>10

Appendix 4.4: The mean nitrogen applied and percentage of time its removal at harvest was within the fitness for use range based on simulation done by the DSS.

Crop	Region	Soil type	Nitrogen							
			Time (%)				Applied (kg ha^{-1})			
			Ideal	Accepta-ble	Tolera-ble	Unaccepta-ble	Ideal	Accepta-ble	Tolera-ble	Unaccepta-ble
Maize	1	Clay	0	0	0	100	0	0	0	262
		Sandy loam	0	0	0	100	0	0	0	270
		Coarse sand	0	0	0	100	0	0	0	376
		Sand	0	0	0	100	0	0	0	339
	2	Clay	0	0	0	100	0	0	0	305
		Sandy loam	0	0	0	100	0	0	0	431
		Coarse sand	0	0	0	100	0	0	0	304
		Sand	0	0	0	100	0	0	0	485
	3	Clay	0	0	0	100	0	0	0	524
		Sandy loam	0	0	0	100	0	0	0	553
		Coarse sand	0	0	0	100	0	0	0	443
		Sand	0	0	0	100	0	0	0	543
	4	Clay	0	0	0	100	0	0	0	483
		Sandy loam	0	0	0	100	0	0	0	501
		Coarse sand	0	0	0	100	0	0	0	423
		Sand	0	0	0	100	0	0	0	518
Swiss chard	1	Clay	0	0	0	100	0	0	0	316
		Sandy loam	0	0	0	100	0	0	0	386
		Coarse sand	0	0	2	98	0	0	169	235
		Sand	0	0	0	100	0	0	0	320
	2	Clay	0	0	0	100	0	0	0	335
		Sandy loam	0	0	0	100	0	0	0	41
		Coarse sand	0	0	0	100	0	0	0	248
		Sand	0	0	0	100	0	0	0	336
	3	Clay	0	0	0	100	0	0	0	375
		Sandy loam	0	0	0	100	0	0	0	458
		Coarse sand	0	0	0	100	0	0	0	275
		Sand	0	0	0	100	0	0	0	370
	4	Clay	0	0	4	96	0	0	187	241
		Sandy loam	0	0	0	100	0	0	0	289
		Coarse sand	0	0	0	100	0	0	0	278
		Sand	0	0	0	100	0	0	0	265
Sorghum	1	Clay	0	0	0	100	0	0	0	234
		Sandy loam	0	0	0	100	0	0	0	239
		Coarse sand	0	0	0	100	0	0	0	226
		Sand	0	0	0	100	0	0	0	354
	2	Clay	0	0	0	100	0	0	0	275
		Sandy loam	0	0	0	100	0	0	0	100
		Coarse sand	0	0	0	100	0	0	0	258
		Sand	0	0	0	100	0	0	0	341
	3	Clay	0	0	0	100	0	0	0	481
		Sandy loam	0	0	0	100	0	0	0	509
		Coarse sand	0	0	0	100	0	0	0	381
		Sand	0	0	0	100	0	0	0	500
	4	Clay	0	0	0	100	0	0	0	459
		Sandy loam	0	0	0	100	0	0	0	501
		Coarse sand	0	0	0	100	0	0	0	476
		Sand	0	0	0	100	0	0	0	497

Appendix 4.5: The mean phosphorus applied and percentage of time its removal at harvest was within the fitness for use range based on simulation done by the DSS.

Crop	Region	Soil type	Phosphorus (P)							
			Time (%)				Applied (kg ha^{-1})			
			Ideal	Accepta-ble	Tolera-ble	Unaccepta-ble	Ideal	Accepta-ble	Tolera-ble	Unaccepta-ble
Maize	1	Clay	0	0	4	96	0	0	28	43
		Sandy loam	0	0	0	100	0	0	0	44
		Coarse sand	0	0	0	100	0	0	0	61
		Sand	0	0	0	100	0	0	0	55
	2	Clay	0	0	0	100	0	0	0	49
		Sandy loam	0	0	0	100	0	0	0	70
		Coarse sand	0	0	0	100	0	0	0	49
		Sand	0	0	0	100	0	0	0	79
	3	Clay	0	0	0	100	0	0	0	85
		Sandy loam	0	0	0	100	0	0	0	90
		Coarse sand	0	0	0	100	0	0	0	72
		Sand	0	0	0	100	0	0	0	88
	4	Clay	0	0	0	100	0	0	0	78
		Sandy loam	0	0	0	100	0	0	0	81
		Coarse sand	0	0	0	100	0	0	0	69
		Sand	0	0	0	100	0	0	0	84
Swiss chard	1	Clay	0	0	0	100	0	0	0	51
		Sandy loam	0	0	0	100	0	0	0	63
		Coarse sand	0	0	0	100	0	0	0	38
		Sand	0	0	0	100	0	0	0	52
	2	Clay	0	0	0	100	0	0	0	54
		Sandy loam	0	0	0	100	0	0	0	67
		Coarse sand	0	0	0	100	0	0	0	40
		Sand	0	0	0	100	0	0	0	55
	3	Clay	0	0	0	100	0	0	0	61
		Sandy loam	0	0	0	100	0	0	0	74
		Coarse sand	0	0	0	100	0	0	0	45
		Sand	0	0	0	100	0	0	0	60
	4	Clay	0	0	0	100	0	0	0	39
		Sandy loam	0	0	0	100	0	0	0	47
		Coarse sand	0	0	0	100	0	0	0	45
		Sand	0	0	0	100	0	0	0	43
Sorghum	1	Clay	0	0	0	100	0	0	0	38
		Sandy loam	0	0	0	100	0	0	0	39
		Coarse sand	0	0	0	100	0	0	0	37
		Sand	0	0	0	100	0	0	0	57
	2	Clay	0	0	0	100	0	0	0	45
		Sandy loam	0	0	0	100	0	0	0	46
		Coarse sand	0	0	0	100	0	0	0	42
		Sand	0	0	0	100	0	0	0	55
	3	Clay	0	0	0	100	0	0	0	78
		Sandy loam	0	0	0	100	0	0	0	83
		Coarse sand	0	0	0	100	0	0	0	94
		Sand	0	0	0	100	0	0	0	81
	4	Clay	0	0	0	100	0	0	0	74
		Sandy loam	0	0	0	100	0	0	0	81
		Coarse sand	0	0	0	100	0	0	0	77
		sand	0	0	0	100	0	0	0	81

Appendix 4.6: The mean potassium applied and percentage of time its removal at harvest was within the fitness for use range based on simulation done by the DSS.

Crop	Region	Soil type	Potassium							
			Time (%)				Applied (kg ha^{-1})			
			Ideal	Acceptable	Tolerable	Unacceptable	Ideal	Acceptable	Tolerable	Unacceptable
Maize	1	Clay	0	0	0	100	0	0	0	65
		Sandy loam	0	0	0	100	0	0	0	67
		Coarse sand	0	0	0	100	0	0	0	93
		Sand	0	0	0	100	0	0	0	84
	2	Clay	0	0	0	100	0	0	0	76
		Sandy loam	0	0	0	100	0	0	0	107
		Coarse sand	0	0	0	100	0	0	0	75
		Sand	0	0	0	100	0	0	0	120
	3	Clay	0	0	0	100	0	0	0	130
		Sandy loam	0	0	0	100	0	0	0	137
		Coarse sand	0	0	0	100	0	0	0	110
		Sand	0	0	0	100	0	0	0	135
	4	Clay	0	0	0	100	0	0	0	120
		Sandy loam	0	0	0	100	0	0	0	124
		Coarse sand	0	0	0	100	0	0	0	105
		sand	0	0	0	100	0	0	0	128
Swiss chard	1	Clay	*	0	0	0	78.3	0	0	0
		Sandy loam	*	0	0	0	95.7	0	0	0
		Coarse sand	*	0	0	0	57.8	0	0	0
		Sand	*	0	0	0	79.2	0	0	0
	2	Clay	*	0	0	0	83.1	0	0	0
		Sandy loam	*	0	0	0	101.6	0	0	0
		Coarse sand	*	0	0	0	61.4	0	0	0
		Sand	*	0	0	0	83.3	0	0	0
	3	Clay	*	0	0	0	92.8	0	0	0
		Sandy loam	*	0	0	0	113.5	0	0	0
		Coarse sand	*	0	0	0	68.1	0	0	0
		Sand	*	0	0	0	91.6	0	0	0
	4	Clay	*	0	0	0	59.2	0	0	0
		Sandy loam	*	0	0	0	71.6	0	0	0
		Coarse sand	*	0	0	0	68.9	0	0	0
		sand	*	0	0	0	65.6	0	0	0
Sorghum	1	Clay	0	0	29	71	0	0	45	63
		Sandy loam	0	0	24	76	0	0	45	64
		Coarse sand	0	0	24	76	0	0	47	59
		Sand	0	0	0	100	0	0	0	88
	2	Clay	0	0	2	98	0	0	46	69
		Sandy loam	0	0	2	98	0	0	50	71
		Coarse sand	0	0	0	100	0	0	0	64
		Sand	0	0	0	100	0	0	0	85
	3	Clay	0	0	0	100	0	0	0	119
		Sandy loam	0	0	0	100	0	0	0	126
		Coarse sand	0	0	0	100	0	0	0	94
		Sand	0	0	0	100	0	0	0	124
	4	Clay	0	0	0	100	0	0	0	114
		Sandy loam	0	0	0	100	0	0	0	124

		Coarse sand	0	0	0	100	0	0	0	118
		sand	0	0	0	100	0	0	0	123

*No parameter

Appendix 6.0: SWB-Sci model description.

Crop model description

The Soil Water Balance (SWB-Sci) model was parameterised to simulate growth and yield for a range of crops, including maize (Jovanovic et al., 2000). The model is a mechanistic, generic and irrigation scheduling model. It makes use of the crop, climate and soil interaction to mechanistically simulate crop growth, salt and nutrient (N and P) balances (Annandale et al., 1999b, Fessehazion et al., 2014, Tesfamariam et al., 2015). The model is comprised of the ClimGen weather unit where parameters such as solar radiation, relative humidity, air temperature, rainfall and wind speed are incorporated. Crop potential evapotranspiration (PET) and Penman-Monteith grass reference evapotranspiration (ETo) are calculated based on weather parameters following algorithms developed by Allen (1998). The soil unit uses PET and ETo to compute actual transpiration and evaporation. The movement of water in multilayers of the soil is simulated by the soil unit of the model following a simple cascading (Campbell and Diaz, 1988) or finite difference approach (Annandale et al., 1999a). Cascading water movement in the soil is simulated after accounting for leaf interception and surface runoff. Separation of soil evaporation from transpiration, according to canopy cover, gives a clear estimate of crop water use (Jovanovic et al., 1999), making it an irrigation scheduling tool that accurately calculates crop water requirements.

Crop growth is simulated following a thermal time approach (Monteith and Moss, 1977). Crop growth is a function of degree day units accumulation starting from emergence (EMDD), flowering (FLDD; completion of the vegetative stage), the transition from vegetative to the reproductive stage (TRDD) and maturity stage (MTDD). Dry matter is accounted for from emergence as a function of unit seed mass. The radiation intercepted by plant canopy (fractional interception) is used for transpiration and contribute to dry matter accumulation is calculated as a function of leaf area index. As the crop continues to grow until maturity, dry matter production is retarded by senesced leaves, which are accounted for by the model. Plant height used to calculate PET is simulated after crop emergence and maximum crop height reaches its maximum during the transition from vegetative to the reproductive stage (Annandale et al., 1999a). Dry matter accumulation is simulated as either radiation or transpiration limited. Transpiration limited dry matter accumulation is calculated as a function of transpiration and dry matter accumulation according to equations by Sinclair et al. (1984). Under conditions limited by radiation, dry matter accumulation is calculated according to equations proposed by Monteith and Moss (1977). The calculations are based on radiation use efficiency, solar radiation for a day, a fractional interception by the canopy and temperature factor for radiation limited growth. The model assumes that after flowering, dry matter accumulation will be towards reproductive sinks. Therefore, harvestable dry matter (HDM) is calculated as dry matter channelled from the stem to grain/reproductive sink. After HDM partitioning, the remaining dry matter is channelled to roots, leaves and then stem. However, the interactive processes in the model allow us to estimate crop yield based on different irrigation management practices.

Model parameterisation

An 18-year climatic data (maximum and minimum relative humidity, air temperature, wind speed, solar radiation and rainfall) obtained from the SASRI was used for scenario analysis of different management practices; irrigation (irrigation vs rainfed) and fertiliser management using different excreta streams (urine, struvite, NUC and LaDePa). The precipitation was added through direct import from the weather data. The irrigation scheduling was simulated allowing 50% allowable depletion level for maize and the approach gave room for rainfall, aiming to manage the rooting zone. Crop growth parameters for modelling maize growth and yield under different management systems have been developed and tested van der Laan (2009). Tesfamariam et al. (2015) evaluated nitrogen management practices in maize (PAN 6966) amended with sewage sludge using the SWB-Sci model. Therefore, the current study will use the existing maize growth and nutrient uptake parameters for simulating scenarios.

Nitrogen and phosphorus are found in various HEDMs, in different forms and concentrations. Therefore, N and P dynamics in the soil vary with contrasting HEDMs and environmental conditions such as rainfall, soil temperature, microbial biomass and cultural practices (Levy et al., 2011). The development of the SWB Sci model included algorithms that can account for such processes and have been tested in a wide range of South African environments (van der Laan, 2009). Furthermore, Ogbazghi et al. (2016) did a scenario analysis on nitrogen mineralisation in soils amended with municipal sludge in different agroecological regions of South Africa using the SWB Sci model. For the current study, we will focus on nitrogen and phosphorus dynamics in soil treated with a combination of human excreta derived materials regarding Vulindlela. The study will look at mineralisation of human excreta derived materials (struvite, NUC and LaDePa), nitrate and orthophosphate fluxes and uptake by maize.

Nitrogen simulation algorithms for the SWB Sci were derived from Cropping Systems Simulation Model (CropSyst) (Stöckle et al., 2003) and P algorithms were derived from Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Muller and Gregory, 2003).

Nitrification in the soil occurs when the soil NO_3^-: NH_4^+ is less than the coded value of 8 and is calculated following Equation 7.3 below:

$$N = NH_4^+[i] - \frac{NO_3^-[i]}{NO_3^-: NH_4^+} * (1 - e^{(-nc*\text{pH function}*\text{soil temperature function})} * nm \quad \text{Equation 7.3.}$$

Whereby N is the nitrified N in the soil layer, nc is the nitrification constant and nm is the nitrification moisture function. The nitrification constant is 0.2.

The nitrification moisture function is the same as the soil water function hence nitrification depends on soil moisture content. Therefore, soil water function is calculated following Equation 7.4 below:

$$\text{Soil water function} = \frac{WFP - WFP_{min}}{WFP_{low} - WFP_{min}} \quad \text{Equation 7.4.}$$

Where: WFP (Water Filled Porosity) = $\frac{\theta}{\theta_s}$. The WFP for zero response on various soil processes is 0.1 (WFPmin), the low threshold value for the maximum response (WFPlow) is 0.5 and the high threshold value for maximum response is 0.7.

The soil water function is equal to 1 when WFP is between WFPlow and WFPhigh. When the WFP is higher than the WFPhigh but ≤ 1, the model calculates the soil water functions following Equation 7.5 below:

$$\text{Soil water function} = WC_{sat} + (1 - WC_{sat}) * \sqrt{\frac{1\text{-}WFP}{1\text{-}WFP_{high}}} \qquad \text{Equation 7.5.}$$

Nitrification is pH-dependent, being high at slightly acidic pH as found by Tarre and Green (2004). Therefore, the SWB Sci calculates soil pH following Equation 7.6 below:

$$\text{pH function} = \frac{\mathbf{pH - pH_{min}}}{\mathbf{pH_{max} - pH_{min}}} \qquad \text{Equation 7.6}$$

Soil P exist in non-labile, labile and solution forms (Shen et al., 2011). Labile P is in close equilibrium with solution P. Solution P is accessible by plant roots and can easily be leached from the soil depending on irrigation management practices and rainfall patterns. In contrast to non-labile P that is permanently adsorbed by soil particles, labile P is loosely held by soil particles. Labile P is therefore easily lost through surface runoff, if irrigation is not well managed, leading to surface water pollution hence it is an important nutrient of consideration in environmentally sustainable agricultural practices (Sharpley et al., 2001).

According to van der Laan (2009), the SWB-Sci model simulates inorganic P following approaches developed by Jones et al. (1984). Movement of inorganic P is a function of soil temperature and water content hence the SWB Sci calculates fluxes following Equation 7.7.

$$\text{Labile active P flux} = 0.6 * MF * e^{(0.115 * \text{soil temperature} - 2.88)} * (\text{labile P - active P} * \frac{PAI}{1\text{-}PAI}) \qquad \text{Equation 7.7}$$

Whereby MF is the moisture function. The value of 0.6 is constant, which was suggested by Vadas et al. (2006) instead of 0.1. If the flux is positive there will be net adsorption and negative value determines net desorption. According to van der Laan (2009), the stable P pool is four times larger than the active P pool hence the movement between the two pools is determined following Equation 7.8.

$$\text{Active stable flux} = \text{P flux coefficient} * (4 * \text{Active P - stable P}) \qquad \text{Equation 7.8}$$

Whereby the P flux coefficient is 0.00076 for calcareous soils and in weathered soils (used during the current study) is determined as per Equation 7.9.

$$\text{P Flux Coefficient} = e(-1.77 \times PAI - 7.05) \qquad \text{Equation 7.9}$$