Vertical hydroponic production of leafy vegetables with human-excreta-derived-materials (HEDMs) from decentralised sanitation technologies

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the University of South Florida through the Pollution Research Group at the University of KwaZulu-Natal, Howard Campus, in South Africa.

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

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DECLARATION: PLAGIARISM

I, Sisekelo Simo Sihlongonyane, declare that:

(i) The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) This dissertation has not been submitted in full or in part for any degree or examination to any other university;

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a) Their words have been re-written but the general information attributed to them has been referenced;

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(v) Where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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Signed: S.S Sihlongonyane

Date: 2021-01-27

LIST OF CONFERENCES AND WEBINARS ATTENDED

- Watershare webinar from WRC and KWR (01 October 2020)
- WRC/SALGA launch of the water technology and innovation forum (28 and 29 September 2020)
- FSM5AfriSan5 conference in Cape Town ICC (18 to 22 February 2019)
- Mile Research Symposium in Durban ICC (6 to 7 June 2019).
- Postgraduate Research and Innovation Symposium in Durban, Westville campus, UKZN (25 October 2019)
- Eco-health International First African Chapter Annual Conference in Durban ICC (13 and 14 November 2018)

ABSTRACT

Hydroponic production of leafy vegetables with human-excreta-derived-materials (HEDMs) extracted by decentralised sanitation technologies is projected to reduce food shortages while improving sanitation services in peri-urban communities, particularly in informal settlements. This study investigated the potential use of HEDMs generated by decentralised sanitation technologies for hydroponic production of leafy crops. HEDMs generated by decentralised sanitation technologies, namely: Anaerobic Baffled Reactor (ABR) and Nutrients, Water and Energy Generator (NEWgenerator) were used as treatments. A vertical hydroponic system called ZipGrow Farm Wall was assembled to conduct horticultural trials at Newlands Mashu Research site in Durban, South Africa. The vertical hydroponic system had eight vertical growing towers. Four vertical growing towers were fertigated with commercial hydroponic fertiliser mix (CHFM) as a control and the other four fertigated with HEDM as a treatment. A literature review was undertaken on open field and hydroponic production of crops with HEDMs. Previous and current studies indicated that nutrients derived from human-excreta have the potential to support the growth of plants even though low yields are obtained in some instance, and faecal pathogen contamination in crops occurs due to fertigation with infected nutrients. Only drip irrigation systems were reported to limit the transfer of faecal pathogens from nutrient source to plants.

The first research study investigated the potential use of anaerobic baffled reactor (ABR) effluent on growth and yield of Swiss chard in a vertical hydroponic system. The results revealed that Swiss chard grown with CHFM performed better than those in ABR effluent and gave a significantly ($p<0.05$) higher plant height and fresh yield. Fresh leaf mass of Swiss chard was reduced in ABR effluent by 78 % when compared to CHFM. Sodium toxicity, ammonium toxicity, aphids and flea beetles reduced the growth and yield of Swiss chard grown with ABR effluent. Amaranthus in planted wetlands of ABR system hosted aphids and flea beetles who moved to defoliate matured Swiss chard leaves grown with ABR effluent as they thought it is a similar crop. In contrast, Swiss chard fertigated with CHFM suffered minimum effects of pest outbreak due to absence of faecal smell and nutrient stress.

The second research study investigated the potential of diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF) on growth, and yield of hydroponically grown non-heading Chinese cabbage. The results revealed there was no significant difference in all determined growth parameters except for fresh yield ($p>0.05$) between plants fertigated by CHFM and

DNP + HF. Fresh leaf mass of non-heading Chinese cabbage leaves was reduced in DNP + HF by 26 % when compared to CHFM. Significant yield decline in non-heading Chinese cabbage grown with DNP + HF was a result of nutrient conditions affecting the uptake and accumulation of nutrients in leaf tissues.

Plant analysis revealed that uptake of macronutrients and micronutrient significantly varied in leaf tissues of non-heading Chinese cabbage between fertigation with CHFM and DNP + HF. Leaf tissues of non-heading Chinese cabbage showed higher levels of N, P, Mg, Mn, Na, Cu, Fe and Al while lower levels of K, Ca and Zn were observed when compared to plants grown with CHFM treatment. The deficiency and toxicity of nutrients in leaf tissues led to interference in photosystem activity of non-heading Chinese cabbage grown with DNP + HF which resulted on decline in final yield. On a positive note, harvested leaves were without faecal coliforms. These findings show that fertigation with ABR effluent and DNP + HF has the potential to support the growth of leafy vegetables in a hydroponic system. However, there is a need for further research to look at other aspects with negatively affected the final yield of crops.

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DEDICATION

This research work is dedicated to supervisors, mentors, colleagues, friends and family members for their prayers for the project to be a success.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 : INTRODUCTION

1.1 The rationale for the research

Poverty and unemployment are one of the main push factors for people to migrate from rural to urban areas to seek job opportunities and a better life (Smit, 1998). Job seekers and those who earn paltry wages construct temporary housing structures in unauthorised vacant land closer to cities. These temporary housing structures have mushroomed and grown to form multiple informal settlements in South African cities (Huchzermeyer, 2006). Informal settlements accommodate about 10 to 20 % of the national population. The number of people living in informal settlements is growing at a higher rate than the construction of new houses aimed to improve their living conditions (Abbott, 2002).

Informal settlements are often overcrowded, lack basic amenities, and in some instances, they are characterised by filthiness (Huchzermeyer, 2006). Most informal settlements are located in marginalised places, such as dumpsites and marshlands, with certain areas lacking necessary sanitation facilities (Wekesa et al., 2011). The provision of onsite sanitation facilities by local municipalities namely; urine diversion dry toilets, ventilated improved pit toilets, and community ablution blocks have improved the level of hygiene in informal settlements (Still et al., 2012).

The usage of some onsite sanitation facilities such as pit latrines and urine diversion dry toilets exposes children to a danger of falling into pits (Mkhize et al., 2017). For example, in South Africa, there have been occasions whereby pupils drown into old pit toilets at schools (Nhamo et al., 2019). Nevertheless, there were no reported cases of drowning in ablution blocks constructed in communities and schools. Community ablution blocks are much safer than other onsite sanitation facilities and have flushing pedestals for transportation of faecal matter to sewer lines connected to centralised wastewater treatment systems (Buckley, 2012; Strande and Brdjanovic, 2014).

The expansion of peri-urban households and community ablution blocks connected to municipality sewer lines has increased the volume of domestic wastewater needed for treatment at centralised wastewater treatment systems. This has led to an increase in pressure on existing centralised wastewater treatment systems which are already faced with challenges of adequately sustaining the operation of wastewater treatment. Henceforth, the establishment of decentralised wastewater treatment systems to ease pressure on centralised wastewater treatment systems (Amoah et al., 2018a). In addition, decentralised wastewater treatment systems are projected to provide wastewater treatment in areas not connected to centralised wastewater treatment systems, especially those at the periphery of municipal boundaries (Massoud et al., 2009).

Nutrient recovery with decentralised wastewater treatment systems is seen as a beneficial way of improving sanitation services in peri-urban areas of developing countries (Gutterer et al., 2009a). Domestic wastewater, either treated or raw contain macronutrients and micronutrients with low concentrations of heavy metals (Pb and Cd), while sodium and chlorine contents are relatively high (Jordán et al., 2008; Yang et al., 2015). A study conducted by Mihelcic et al. (2011) reported that phosphorus present in urine and faeces could account for 22 % of phosphorus needed for global supply. Newly developed decentralised wastewater treatment systems have shown their ability to recover nutrients from domestic wastewater for crop production (Mehta et al., 2015; Otterpohl et al., 2002).

In Durban, South Africa, a decentralised wastewater treatment system called an anaerobic baffled reactor (ABR) was installed for the treatment of domestic wastewater. The anaerobic baffled reactor was designed to treat domestic wastewater from 83 peri-urban households connected to a municipality sewer line (Foxon et al., 2004; Gutterer et al., 2009a; Nasr et al., 2009). In a study conducted using Swiss chard, fertigation with nutrient-rich ABR effluent had a liming effect on acid soils and increased crop growth (Musazura et al., 2015).

The contamination of crops with faecal pathogens has been one of the reasons there is reluctance in the usage of human-excreta derived nutrients. An anaerobic membrane bioreactor sanitation technology has been developed to extract pathogen-free nutrients on sanitation facilities of densely populated areas such as informal settlements (Bair et al., 2015). This technology is referred to as NEWgenerator (nutrients, energy, and water generator), designed to solve sanitation problems for about 2.6 billion people worldwide when mass-produced. The system occupies 6.25 m^2 of space when installed onsite (Peterson, 2017). The NEWgenerator recycles nutrients, electricity, and potable water from domestic wastewater produced by sanitation facilities (Cook, 2016).

The NEWgenerator contains robust, low energy, compact, and flexible state-of-art anaerobic ultrafiltration membrane bioreactor (AnMBR) for treatment of human-excreta into reusable resources. Resilient human pathogens such as Giardia and Ascaris are efficiently inactivated through thermophilic anaerobic digestion (USF, 2015). In India, the NEWgenerator processed useful resources such as hydroponic nutrients from an e-toilet which fed it domestic wastewater. In Durban, South Africa, the NEWgenerator is expected to treat domestic wastewater from a community ablution block in an informal settlement while generating reusable resources (Meketa, 2017a). Calabria et al. (2019a) reported that lettuce grown with nutrients produced by the NEWgenerator showed good crop performance in a vertical hydroponic system in the USA.

The quality of nutrients recovered from human-excreta is dependent on the body weight, total food intake and diet of individuals. A better diet improves the quality and quantity of nutrients present in human excreta. Healthy individuals excrete faecal matter with high-quality nutrients (Rose et al., 2015). Thus food production with human-excreta-derived materials would provide a close loop system whereby people have access to quality food produced with recycling nutrients (Esray, 2001).

1.2 Problem statement

The shortage of arable land in peri-urban areas for subsistent and commercial crop production has urged the shift towards hydroponic crop production. However, hydroponic systems require dissolved nutrients prepared from chemical fertilisers to optimise crop production, which is currently supplied through chemical fertilisers (Gagnon et al., 2010; Magwaza et al., 2020b). The sustainability in supply of chemical fertilisers used in hydroponics is threatened by the depletion of fossil fuels used for their production.

Thus the focus has turned on finding alternative means for the production of fertilisers to meet agricultural needs. Secondly, the supply of potable water used for dissolving and diluting hydroponic fertilisers competes with other sectors of the economy, such as mining and domestic use. Recovering potable water and nutrients from domestic wastewater with off-the-grid decentralised sanitation technologies is argued to be a sustainable solution. Thus there is a continuous development of off-the-grid decentralised sanitation technologies to recycle water and nutrients from sanitation facilities.

Sanitation technologies have proved to produce human-excreta-derived-materials such as treated nutrient-rich domestic wastewater. However, there has been slow progress in testing the suitability of treated nutrient-rich domestic wastewater in hydroponic systems (Magwaza et al., 2020b). Crops grown with treated nutrient-rich domestic wastewater were found to contain faecal pathogens and heavy metals (Akponikpè et al., 2011; Magwaza et al., 2020b; Sharma et al., 2006).

Thus, most consumers are reluctant about the idea of consuming food grown with treated nutrient-rich domestic wastewater. The acceptance of crops hydroponically grown with treated nutrient-rich domestic wastewater solely rely on research studies proving that there is reduced contamination with faecal coliforms and heavy metals. Governments would undoubtedly endorse the reuse of treated nutrient-rich domestic wastewater in addressing food and nutritional insecurity given they pathogen-free, and the concentration of heavy metals is below toxicity levels. This study seeks to generate knowledge on the use of nutrient-rich treated domestic wastewater recovered by off-the-grid sanitation technologies for hydroponic production of common leafy vegetables (Swiss chard and non-heading Chinese cabbage) in South Africa.

1.3 Justification

The reuse of human-excreta-derived-materials produced by sanitation technologies is predicted to support local food production while fostering implications for supporting local wastewater treatment efforts. Agricultural-linked sanitation technologies have shown their ability to safely extract human-excreta-derived-materials from onsite sanitation facilities in peri-urban areas such as informal settlements (Bair et al., 2015).

Incorporation of sanitation technologies and agricultural technologies for crop production is expected to address malnutrition and hunger in poverty-stricken areas such as informal settlements. Human-excreta-derived-materials such as nutrient-rich domestic wastewater contain nutrients and water needed for agricultural use, especially in hydroponic systems. Crops have been successfully grown in hydroponic systems with nutrient-rich domestic wastewater (Butler et al., 1989; Magwaza et al., 2020c).

Zezza and Tasciotti (2010) reported that hydroponic crop production would reduce unemployment and poverty in developing countries. In hydroponics, plants produce crops of superior quality, high yield and allow for rapid harvest (Hussain et al., 2014). The success of previous hydroponic horticultural trials with nutrient-rich ABR effluent (Magwaza et al., 2020a; Magwaza et al., 2020c) and NEWgenerator permeate support advances in further research studies to improve productivity with human-excreta-derived-materials.

1.4 Aim

This study aims to generate knowledge on the use of human-excreta-derived-materials generated by off-the-grid decentralised sanitation technologies for the production of safe, nutritious, and quality horticulture produce using a vertical hydroponic system.

1.5 Objectives

The specific objectives of this study were to:

1. Determine the nutrient composition of commercial hydroponic fertiliser mix and human-excreta-derived-material used as nutrient sources for Swiss chard and non-heading Chinese cabbage growing in a vertical hydroponic system.

2. Compare the effect of commercial hydroponic fertiliser mix and human-excreta-derived-material as nutrient sources on growth and yield of Swiss chard and non-heading Chinese cabbage leafy vegetables in a vertical hydroponic system.

3. Assess the presence of microbial loads in harvested leaves grown with human-excreta-derived-material as nutrient sources in a vertical hydroponic system.

1.6 Outline of the dissertation structure

Literature review and experimental chapters will be written as research papers. The structure is a laid out as follows;

CHAPTER 1: provides the background and significance of the research. The chapter highlights the problems faced with faecal sludge management practices in informal settlements and nutrient recovery from human-excreta in sanitation facilities with decentralised sanitation technologies for agricultural use.

CHAPTER 2: reviews in-depth the depletion of mineral rocks to process chemical fertilisers, nutrient recovery from human-excreta, and application of recovered nutrients in agriculture. This section also covers the implications of using wastewater for open field crop production, hydroponic crop production, health effects on workers, and contamination of crops.

CHAPTER 3: is an experimental chapter reporting on evaluating the feasibility of ABR effluent as a nutrient source for Swiss chard (*Beta vulgaris* subsp. *cicla*) in a vertical hydroponic system.

CHAPTER 4: is also an experimental chapter reporting on evaluating the feasibility of NEWgenerator permeate as a nutrient source for non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system**.**

CHAPTER 5: is the general discussion linking two experimental chapters and concludes the dissertation. The chapters offer insight on challenges experienced, future possibilities, recommendations, and final comments.

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CHAPTER 2 : Crop production with human-excreta-derived-materials in urban and peri-urban areas: A review

Abstract

Global food security remains threatened by the rising costs of chemical fertilisers and persistent drought affecting the supply of fresh water for irrigation of crops. Irrigation of crops with wastewater has been seen as an alternative way for nutrient supply to plants. Peri-urban farmers in some developing countries irrigate their crops with wastewater to supply nutrients in dry months due to a shortage of rainfall. Wastewater contains water and nutrients needed in crop production. Crops grown with wastewater were reported to record high yields while certain crop species recorded low yields. Furthermore, crops raised with wastewater were found to be contaminated with human pathogens and heavy metals. Farmers and workers were reported to develop skin and nail problems afterwards due to constant contact with wastewater. Soils were reported to accumulate high concentrations of sodium and heavy metals due to continuous irrigation with wastewater. As a result, farmers are now encouraged to use hydroponic systems for crop production to limit environmental pollution caused by irrigation with wastewater. Low-cost off-the grid-sanitation technologies have been developed to be installed for onsite treatment and processing of human-excreta into nutrient-rich wastewater for irrigation of crops. This review aims to provide deep insight into the progress made in reusing human-excreta derived nutrients for crop production as a way of reducing food shortages and presenting it as an alternative nutrient source for the near future.

Keywords: Sanitation technologies, human-excreta, nutrient recovery, human-excreta-derived-materials, agriculture, hydroponic systems

2.1 Introduction

The United Nations estimates the global population to reach 8.6 billion in 2030 and 9.8 billion in 2050 (Acedański and Włodarczyk, 2018). In addition, food insecurity and malnutrition continue to affect poverty-stricken communities, especially in developing countries (Godfray et al., 2010). For instance, Sub-Saharan Africa experiences high poverty levels in villages or communities due to low crop yields (Chianu et al., 2012).

Improvement in quantity and quality of crop yields is mostly sustained by fertilisation with chemical fertilisers. Chemical fertilisers are known for their high nutrient content and immediate availability of mineral elements in solution (Chen, 2006; Savci, 2012). Unfortunately, application of high amounts of chemical fertilisers was reported to cause soil deterioration and loss of nutrients in agricultural fields (Wang et al., 2018). The nitrogen in chemical fertilisers was reported to promote the incidence of sap-feeding insects due to its contribution to protein production and insect development (Garratt et al., 2011).

Small-scale and large-scale crop production remains heavily reliant on the fertilisation of plants with chemical fertilisers towards obtaining high yields (Van Averbeke and Yoganathan, 2003). As a result, there is an increase in the rate of mining and depletion of mineral rocks used for the production of chemical fertilisers. Thus, the focus has turned into finding alternative sources of nutrients for crop production in the event of shortages in the supply of chemical fertilisers. The usage of organic fertilisers derived from animal-waste and urban-waste has been foreseen as one of the sustainable and reliable nutrient sources (Case et al., 2017). Application of composted litter and waste allows farmers to recycle nutrients back into the soil and improve soil fertility (Ouédraogo et al., 2001).

The usage of sewer sludge compost in grapevines positively contributed to soil management practices such as a reduction in chemical control of weeds and replacing chemical fertilisers without experiencing loss on vigour and yield (Pinamonti, 1998). Trading of faecal sludge fertiliser was popular in the mid-19 century where it was transported from urbanised towns to farming areas due to urban sprawl. This led to improved sanitation in urban areas (Semiyaga et al., 2015). The approach was abandoned in the 20th century due to; availability of cheaper and safer mineral fertilisers, the presence of nematodes in faecal fertiliser, faecal-oral disease, logistics in the transportation of faecal based fertiliser and reduction in excreta available due to sewered sanitation (Semiyaga et al., 2015).

In the 21st century, there has been an increase in the volume of biosolids generated from the treatment of domestic wastewater in urban areas. Landfills of most municipalities in developing and developed countries are reportedly reaching full capacity due to rising capacity of bio-solids (Cofie et al., 2006). Bio-solids generated from drying beds of centralised wastewater treatments contain nutrients (Tiwari et al., 2017). Thus, recycling nutrients from domestic wastewater allows for the reduction of municipal bio-solids and provides farmers with needed nutrients for crop production (Cofie et al., 2006).

Untreated faecal sludge has been used for agriculture in Tamale, Ghana, as a disposal method (Cofie et al., 2005). Small-holder farmers in peri-urban areas of developing countries have adopted the practice of using wastewater as a nutrient treatment and water supply to support their crops in dry months (Drechsel et al., 2006). Reusing treated wastewater for crop irrigation has been recommended for areas facing water shortages (Pereira et al., 2002).

The reuse of treated wastewater in hydroponic systems showed efficiency in producing commercially valuable plants (Adrover et al., 2013; Oyama et al., 2005). Hydroponic systems are reportedly used for secondary treatment of municipal wastewater and crop production (Boyden and Rababah, 1996; Zheng et al., 2015). The chemical composition of treated wastewater from non-industrial sources which had at least received secondary treatment was reported not to cause adverse effects on plant growth and public health (Adrover et al., 2013).

This review aims to cover depletion of mineral rocks and nutrient recovery from human-excreta sources and reuse of human-excreta derived materials in crop production as an alternative source of nutrients.

2.2 Depletion of potassium and phosphorus rocks

The depletion of mineral rocks used to produce phosphorus and potassium fertilisers remains a major concern to farmers and a threat to global food security. Most farmers rely on chemical fertilisers to meet the nutrient requirements for their crops. For instance, Wang et al. (2018) reported that China used more chemical fertilisers on high-value horticultural crops. Unfortunately, potassium and phosphorus rock mining takes place in a few countries for global supply. Large-scale mining of potassium ores is carried out mainly in; Russia, Canada, Germany, France, Israel, and the USA (al Rawashdeh and Maxwell, 2014; Ciceri et al., 2015). Phosphorus is mined in more than thirty countries, but 90 % of its production is taking place in the USA, Morocco, China, Jordan, and Kazakhstan (Ragheb and Khasawneh, 2010).

Potassium ores are expected to last for 400 years. However, this might change due to over-exploitation to meet the increasing global demand. It is worth mentioning that countries often import more than their needs. For instance, in 2011, Brazil imported 4 357 186 tonnes of K_2O more than 90 % of its current demand. The scarcity of potash reserves has not yet been reported, but there is an impending crisis due to high buying power by farmers in China, India, and Brazil (Ciceri et al., 2015).

Most farmers disregard alternative sources of nutrient supply, namely; animal waste, organic waste and agricultural waste in fear of their adverse effects on crops. Nevertheless, farmers are slowly considering the idea of recycling agricultural waste as part of nutrient recovery and reuse in crop production (Al-Karaki, 2011a). The depletion of fossil fuels used for the production of chemical fertilisers has implored scientists to explore other means of nutrient supply such as recovering nutrients from urban waste which keeps on rising due to rapid urbanisation. Recycling nutrients from human-excreta is projected to solve global sanitation challenges and provide a low-cost source of nutrients to farmers.

2.3 Challenges facing the global sanitation

The World Health Organisation (WHO) and the Water Supply and Sanitation Collaborative Council revealed that 25 % of the developing country's urban residents lack access to sanitation services and up to 82 % for people living in rural areas (Massoud et al., 2009). Household waste collection in many cities is restricted to wealthy neighbourhoods while those living in informal settlements dump waste along roads, illegal sites, and storm-water drain (Cofie et al., 2006). Illegal disposal of faecal matter is encouraged by easy free access to prohibited dumping zones. Other reasons include avoiding; costly long distances travelled to treatment sites, traffic jams, treatment fees, and lack of designated sites for discharge of waste (Murungi and van Dijk, 2014).

In Kampala, Uganda, the transportation costs of each trip to disposal sites, are USD 50 for a 5 to 8 m^3 truck, and more than one trip is needed to empty a sanitation facility every three months per year (Kulabako et al., 2010). This was found to be expensive for people who earn a median monthly income of USD 50 per capita with other family needs to cater for within that income (Montangero et al., 2002). The eThekwini municipality collects faecal sludge from ventilated improved pit (VIP) latrines in informal settlements once every five years (Septien et al., 2018).

The absence of faecal sludge emptying services in informal settlements prompts people to desert full pit toilets who later leak the human excreta to nearby river bodies during flooding by heavy rains in summer. Human-excreta in water tends to hosts and be a vector for waterborne diseases (Maunula et al., 2005). Therefore, nutrient recovery from sanitation facilities reduces the hazard posed by abandoned pit toilets in leaking human excreta to water bodies.

2.4 Recovering nutrients from human-excreta

Vinnerås and Jönsson (2002), reported that a combination of faecal and urine diversion was able to collect 60 % N, 46 % of P and 43 % of K from domestic wastewater. Nutrient distribution in human-excreta accounts for; 10 to 20 % of nitrogen, 20 to 50 % phosphorus and 10 to 20 % potassium in faeces. Urine contains; 80 to 90 % nitrogen, 50 to 65 % of phosphorus, and 50 to 80 % potassium (Niwagaba et al., 2014).

Human-excreta is now processed to form fertilisers and feedstock for the production of biopolymers, biofuels, and other high-value chemicals (Puyol et al., 2017). The recovery of nutrients from human-excreta has previously focused more on source-separated waste produced by households or communities. Various nutrient recovery processes are carried out to extract pathogen-free nutrients in higher concentrations. Nutrients recovered are usually in the form of a liquid and solid fertiliser. These fertilisers are high in nitrogen, phosphorus and potassium content (Harder et al., 2019). The liquid fertiliser products processed from human-excreta are listed below.

2.4.1 Multi-nutrient solutions

Human urine is one of the known useful fertilisers highly rich in nitrogen, containing phosphorus, potassium, and micronutrients. It has shown to be a beneficial liquid fertiliser for aquaculture and a possible input for the production of methylene urea, a slow-release synthetic nitrogen fertiliser. Hydrolysed urine is processed through nitrification and distillation to obtain a concentrated urine-based liquid fertiliser (Harder et al., 2019; Heinonen-Tanski and van Wijk-Sijbesma, 2005).

2.4.2 Macronutrient solutions (Urea – N)

Urea – N is processed from hydrolysed urine under a technique of sorption and desorption from activated carbon then passed through nanofiltration membrane separation. Nanofiltration membrane removes pathogens and organic pollutants. This fertiliser can be used as a feedstock for the production of synthetic fertilisers such as methylene urea (Harder et al., 2019; Pronk et al., 2006).

2.4.3 Macronutrient solutions (Ammonia-N)

A solution rich in ammonium - N is produced by nanofiltration membrane of hydrolysed urine. Urine and treated effluent are air stripped to produce ammonia – N. In addition, sewage sludge undergoes thermal drying and absorption in an acid trap to produce fertilisers such as ammonium sulphate, ammonium borate, and ammonium chloride, ammonium, and ammonium phosphate. Each fertiliser product is solely dependent on the acid trap used during the absorption process. These products are free from pathogens, organic pollutants, and heavy metals. Ammonium nitrate is also a feedstock in the production of synthetic fertilisers (Harder et al., 2019; Horttanainen et al., 2017).

2.4.4 Macronutrient solutions (NK or NPK)

Urine undergoes sorption followed by desorption to recovery NH_4^+ and K^+ separated from Na^+. Hydrothermal processes on wet faecal matter transfer N, P, and K to a liquid residue. In contrast, other nutrients such as calcium, magnesium, zinc, aluminium, and iron are transferred into solid waste (Casadellà et al., 2016; Harder et al., 2019; Lu et al., 2017).

2.4.5 Macronutrient solutions (P)

Solutions rich in phosphorus are extracted from organics or inorganics of sewage. The product obtained is a phosphoric acid that can range from diluted to very pure and concentrated (Egle et al., 2015). The phosphoric acid also serves as a feedstock in the production of synthetic fertilisers. Sorption and desorption of treated effluent can also produce a solution rich in phosphorus, which can be a useful fertiliser, especially in the formation of struvite (Harder et al., 2019; O'Neal and Boyer, 2013; Schaum et al., 2007).

2.5 Wastewater sources in informal settlements

2.5.1 Community ablution blocks

There has been a demand for provision and rendering of better sanitation facilities to curb the transfer of pathogens from hosts to humans (Tumwine et al., 2002). Community ablution blocks are sanitation facilities replacing pit toilets in informal settlements designed to provide urban sanitation services. They are made of a modified shipping container to have showers, toilets and laundry sinks. South African municipalities use them to render better communal and sanitation facilities in informal settlements. Sanitation needs for males and females are separately catered for with different facilities (Crous et al., 2013b).

Community ablution blocks are designed to serve between 50 and 75 households within a radius of 200 m (Roma and Buckley, 2011). They are connected to municipality sewer lines for transportation of human-excreta to centralised wastewater treatment systems. Municipalities employ caretakers to ensure sustainable utilization of the ablution blocks. At night, the facilities are closed to prevent theft and vandalism. The proximity and size of community ablution blocks still fail to fully cater for sanitation needs to all residents compared to those in urban areas (Roma et al., 2010a).

2.6 Problems faced in running centralised wastewater treatment systems

Centralised treatment systems continue to generate municipal biosolids derived from domestic wastewater which are causing an environmental hazard and economic burden (Nahman et al., 2012). The nutrient removal technique practised by centralised wastewater treatment systems (air stripping and chemical precipitation) continues to be a costly process for most municipalities resulting on insufficiently treated effluent due to cutting down of costs in treating wastewater (Odjadjare et al., 2010; Santos and Pires, 2018). Existing centralised wastewater treatment systems are faced with delays in expansion due to; budget restrictions, inadequate funding from the private and public sector (Paraskevas et al., 2002).

2.7 Introduction of decentralised wastewater treatment systems

Small and isolated villages or settlements with low population densities were identified to be suitable in being served by decentralised wastewater treatment systems that are simpler and cost-effective (Butler and MacCormick, 1996; Paraskevas et al., 2002). However, lack of research, poor planning, and development activities in developing countries lead to the selection of inappropriate technologies to suit local conditions. In addition, financial and human resource affordability, and social or cultural acceptability have hindered efforts towards the provision of decentralised wastewater treatment systems (Massoud et al., 2009). However, various decentralised wastewater treatment systems have been launched and being towards nutrient recovery from domestic wastewater in peri-urban areas (Foxon et al., 2004).

2.7.1 Nutrient recovery in wastewater with Algae

Algae is grown in domestic wastewater that has received primary treatment. The microalgae-based technology is considered a low-cost renewable, sustainable, and environment-friendly wastewater treatment process. It can grow in various living conditions and extreme conditions with high salinity, for example, *Dunaliella salina* (Wu et al., 2014). Microalgae are known to be efficient in removing nitrogen, phosphorus, and toxic metals from wastewater under controlled environments, which can be used for the production of biochemical, biofuels, and biofertilisers when produced with concentrated urine (Tuantet et al., 2014).

2.7.2 Nutrient recovery in wastewater with an anaerobic baffled reactor (ABR) system

An off-the-grid sanitation technology called anaerobic baffled reactor (ABR) was developed and constructed to operate without energy input for the biological treatment of domestic wastewater from middle-class households in peri-urban areas. Domestic wastewater passes through a series of anaerobic membrane baffled reactors and filters with microorganisms degrading faecal matter to recover a nutrient-rich treated wastewater (Gutterer et al., 2009a). The nutrient-rich treated wastewater collected after anaerobic filters were reported to support crop production (Nasr et al., 2009; Salukazana et al., 2005). The nutrient-rich wastewater had a liming effect on acid soils and increased Swiss chard growth (Musazura et al., 2015).

2.7.3 Nutrient recovery in wastewater with an anaerobic membrane bioreactor (AnMBR)

A micro or ultrafiltration membrane technology (with pore sizes ranging from 0.3 to 0.4 µm), which allows a membrane to retain microorganisms inside the system (Ince et al., 1997; Judd, 2010). An anaerobic membrane bioreactor (AnMBR) can be a more sustainable wastewater treatment technology than conventional processes because of low demands for energy, nutrients, low sludge production and the potential to produce methane of the anaerobic process (Dong et al., 2016). An anaerobic membrane bioreactor system called a NEWgenerator (nutrients, energy and water generator) had been developed for the treatment of wastewater from public toilets in densely populated slums (Bair et al., 2015). The nutrients extracted are reported suitable for hydroponic production of crops (Calabria et al., 2019b).

2.8 Reuse of wastewater in crop production

There has been an emphasis on the usage of treated wastewater with zero faecal coliforms/100 mL for vegetable crops eaten raw before disinfection especially in the United States of America and the Republic of South Africa (Blumenthal et al., 2000; Jagals and Steyn, 2002). The department of water and sanitation regulates the usage of wastewater for agricultural use in South Africa as a custodian of water resources protecting the environment from pollution.

Table 2.1: South African national wastewater limit values for agricultural use (Blumenthal et al., 2000).

Parameters	**Limits**
pH	5.5 – 9.5
Electrical conductivity	70 – 150 mS/m
Suspended solids	Does not exceed 25 mg/L
Chemical oxygen demand	Does not exceed 75 mg/L
Faecal coliforms	Do not exceed 1000 per 100 mL
Ammonia as nitrogen	Does not exceed 3 mg/L
Nitrate/nitrite as nitrogen	Does not exceed 15 mg/L
Ortho-phosphate as phosphorus	Does not exceed 10 mg/L

2.9 Crop production with wastewater

Wastewater irrigation in the Tula Valley in Mexico supplied 2 400 kg of organic matter, 195 kg of nitrogen, and 81 kg of phosphorus $ha^{-1}.year^{-1}$, leading to a significant increase in crop yields (Jiménez, 2005). Wastewater has some of the critical nutrients required for plant growth (Jordán et al., 2008). Recycling wastewater for irrigation is viewed to increase water resources, provide supplemental nutrients, and protect coastal areas, water resources, and sensitive receiving bodies (Qadir et al., 2010).

Even though the fertiliser value of wastewater is of great importance, periodic monitoring is required to adjust the number of extra fertilisers or, if possible, dilute the wastewater and the acceptable nutrient input on soil with various amounts of treated wastewater (Qadir et al., 2010).

Table 2.2: Nutrients added to the soil through irrigation of crops with treated wastewater (Qadir et al., 2010).

Nutrients	**Concentration (mg/L)**	**Fertiliser contribution (kg/ha)**	
		Irrigation at 3000 m^3/ha	**Irrigation at 5000 m^3/ha**
Nitrogen	16 – 62	48 – 186	80 – 310
Phosphorus	4 – 24	12 – 72	20 – 120
Potassium	2 – 69	6 – 207	10 – 345
Calcium	18 – 208	54 – 624	90 – 1040
Magnesium	9 – 110	27 – 330	45 – 550
Sodium	27 – 182	81 – 546	135 – 910

In Denmark, a vast majority of households apply processed municipal wastewater on agricultural land (Case et al., 2017). In Central, South, and Southeast Asia (Bangladesh, Cambodia, China, India, Indonesia, and Vietnam) wastewater is also used for aquaculture. The farm-level nutrient value of wastewater differs with constituent loads, frequency and amount of application, soil conditions, crop choices, and the cost and availability of alternative nutrient sources (Lazarova and Bahri, 2004; Martijn and Redwood, 2005).

2.10 Effects on soils due to irrigation with wastewater

Irrigation with untreated wastewater increases soil organic matter, nitrogen and concentration of major ions (Tam, 1998). However, excessive provision of nutrients in the soil may have adverse effects, especially phosphorus (PO_4^{3-}) and nitrate, which can be leached into the surface and groundwater, causing eutrophication (Knobeloch et al., 2000; Wu, 1999). Magesan et al. (2000a) reported that an increase in wastewater C: N ratio increases soil microbial biomass, carbohydrate, nematode population while decreasing nitrate leaching with hydraulic conductivity raised to 80 %.

Magesan et al. (2000b) further revealed that the organic and inorganic nutrients in treated effluent that had a high carbon to nitrogen ratio stimulated the soil microorganisms, subsequently decreased the hydraulic activity in the irrigated soil. Wastewater contains organic and inorganic nutrients, with dissolved organic carbon (DOC) being the most common natural nutrient. Organic carbon often influences the bioavailability of nutrients in the water and stimulates the activity of soil microorganisms (Ramirez-Fuentes et al., 2002).

The major disadvantage of using wastewater for irrigation is the accumulation of immobile heavy soils (Abedi-Koupai et al., 2006). Sodium and other forms of salinity are the most persistent in treated wastewater which are often most challenging to remove in wastewater (Toze, 2006). Irrigation of crops with wastewater affects the chemical and physical properties of the soil. Wastewater irrigation increases Mg^{2+} and K^{+} losses in calcareous soils (Jalali et al., 2008).

Soils irrigated with wastewater had a significant decrease in soil pH and an increase in salinity, organic matter content, and cation exchange capacity (Kiziloglu et al., 2008). Antolín et al. (2010) reported that wastewater had a liming effect on acidic soils. Bame et al. (2014), revealed that irrigation with wastewater had residual effects after harvesting on soil for phosphorus and magnesium. In addition, Latare et al. (2014) reported that high application of wastewater caused residual effects and led to a build-up of N, K, S, and Zn contents in the soil after the harvest of wheat.

2.11 Hydroponic production of crops using wastewater

Hydroponic systems limit soils being damaged by salts when applied for the treatment of wastewater and crop production (Haddad and Mizyed, 2011). In some countries, hydroponic systems are used for secondary and tertiary treatment of domestic wastewater (Vaillant et al., 2003). For instance, constructed wetlands in decentralised wastewater treatment systems provide the final treatment of wastewater through nutrient removal by plants (Gutterer et al., 2009b). The wastewater retention time in planted constructed wetlands allows for efficient nutrient removal by plants (Gutterer et al., 2009b).

Plants grown in constructed wetlands are selected mainly based on their ability to acclimatise in local weather conditions quickly, and they require less management to enable efficient treatment of wastewater. In decentralised wastewater systems, reeds are planted on constructed wetlands as they immediately adapt to local climates and grow well in partially treated wastewater loaded with nutrients (Gutterer et al., 2009a). Constructed wetlands resemble open hydroponic systems, but they are designed to discharge nutrient-depleted effluent after final treatment (Gutterer et al., 2009a). In addition, constructed wetlands were found to constitute an efficient and safe alternative to treat and then reuse greenhouse wastewater after showing a 99.99 % removal efficiency of plant pathogens (*Pythium ultimum* and *Fusarium oxysporum*) (Gruyer et al., 2013).

The success of reeds and grasses in nutrient removal of wastewater on constructed wetlands prompted researchers to consider growing useful crops in hydroponics systems. Various hydroponic systems namely; wick system (Haddad and Mizyed, 2011), water culture (Oron, 1994), drip (recovery) (Haddad and Mizyed, 2011), flood and drain (Haddad and Mizyed, 2011), nutrient film technique (Vaillant et al., 2003) and aeroponics (Jurga and Kuźma, 2018) have been used for growing edible crops with wastewater.

Hydroponic systems are now considered as one of the options for decentralised wastewater treatment systems for domestic wastewater and effluent reuse in rural areas, for example, in Palestine. In addition, hydroponic systems have shown to successfully provide tertiary treatment of domestic wastewater while growing edible crops (Haddad and Mizyed, 2011). Crop production with wastewater in hydroponic systems has only been restricted to closed hydroponic systems in order to limit environmental pollution (Truong and Hart, 2001).

In closed hydroponic systems, wastewater is retained in nutrient reservoirs and continuously recirculated in plants with pumps (Jurga and Kuźma, 2018). Haddad and Mizyed (2011) evaluated various hydroponic systems as decentralised wastewater treatment system and reuse for the production of vegetable crops, cut flowers, citrus and olive trees, and herbs. Unfortunately, a hydroponic system was found not suitable for the production of green beans with wastewater (Haddad and Mizyed, 2011).

The application of a vertical recirculating hydroponic system for lettuce production with nitrogen recovered from wastewater produced by an anaerobic membrane bioreactor called NEWgenerator resulted in an 11 % and 19 % increase in fresh and dry mass respectively when compared to the control (Calabria et al., 2019b). The stage of crop development and harvesting frequency affects the treatment of wastewater in a hydroponic system (Zheng et al., 2015). Hydroponics perfectly fit to be used as decentralised wastewater treatment and reuse systems as they are cheaper to construct and much easier to operate (Haddad and Mizyed, 2011).

2.12 Effects of using wastewater on plants

2.12.1 Physiological response

Macro-elements and micro-elements concentrations increases in leaves of plants fertigated with wastewater (Abedi-Koupai et al., 2006). Wastewater application on palak (*Beta vulgaris* var. Allagreen H-1) plants led to a decrease in the rate of photosynthesis, stomatal conductance, and chlorophyll content. In contrast, it increases lipid peroxidation, peroxidase activity, and protein together with proline contents (Singh and Agrawal, 2007). Photosynthesis improved on alfalfa plants under drought conditions due to wastewater application (Antolín et al., 2010).

Fertigation of three vegetable species (*Colocasia esculentum*, *Brassica nigra* and *Raphanus sativus*) with wastewater led to decrease in total chlorophyll and total amino acids levels in plants, and an increase in amounts of soluble sugars, full protein, ascorbic acid, phenol with *B. nigra* the only exception (Gupta et al., 2010). Lower doses of wastewater had a stimulating effect on stomatal conductance in Szarvasi-1 grass (Rév et al., 2017). Odindo et al. (2018) reported that anaerobic baffled reactor (ABR) effluent had a positive effect on the physiological functioning of hydroponically grown tomato plants.

2.12.2 Morphological response

Irrigation of palak with wastewater reduced root length, leaf area, and root biomass (Singh and Agrawal, 2007). Singh and Agrawal (2010), found out that the use of wastewater on mung bean (*Vigna radiata* L. cv. Malviya janpriya (HUM) 6) increased shoot length, leaf area, and biomass at all sewer sludge amendment (SSA) rates (6, 9 and 12 kg/m^2). However, root length increased up to 9 kg/m^2 SSA rates. Lower doses of wastewater had a stimulating effect on root growth in Szarvasi-1 grass. While high doses of wastewater decreased root growth, shoot water content and length, stomatal conductance (Rév et al., 2017).

2.12.3 Yield

Sheikh et al. (1987) reported that salad crops irrigated with treated effluent, which had more concentrations of organic nutrients, produced higher yields compared to similar crops irrigated with groundwater. Application of wastewater produced a higher grain yield due to more number of tillers and higher test weight in both wheat and rice crops (Latare et al., 2014). Bame et al. (2014), found out that above-ground dry matter yields were the highest in maize fertilised with anaerobic baffled reactor (ABR) effluent than other treatments. However, hydroponically grown tomato plants with ABR effluent had reduced yield and required supplementation with chemical fertiliser to meet plant nutrient needs (Magwaza et al., 2020c).

2.12.4 Contamination with human pathogens

Farmers and their families using infected wastewater for irrigation are vulnerable to parasitic worms, protozoa (*Entamoeba histolytica, Giardia intestinalis,* and *Cryptosporidium parvum*), viruses, and bacteria (*Legionella* spp., *Mycobacterium* spp., and *Leptospira*). Skin and nail problems may occur among farmers using infected wastewater (Trang et al., 2007). Contamination of produce with human pathogens occurs through usage of overhead sprinkler irrigation and exposure to pathogens while in storage (Wachtel and Charkowski, 2002) and washing of leafy greens with contaminated water (Mitra et al., 2009; Vojdani et al., 2008). Drip irrigation was reported to limit the transfer of human pathogens to leafy crops upon fertigation with contaminated water (Mitra et al., 2009). However, hydroponically grown tomatoes with anaerobic baffled reactor (ABR) effluent had faecal microbes (Magwaza et al., 2020c).

2.12.5 Heavy metal contamination and toxicity

Leafy vegetables were reported to contain more considerable amounts of heavy metals such as; cadmium than non-leafy species when fertigated with untreated wastewater (Minhas and Samra, 2004). Heavy metal (Cu and Cd) toxicity led to inhibition of growth, transpiration, and chlorophyll biosynthesis in Szarvasi-1 grass grown with wastewater (Rév et al., 2017). A high rate of wastewater application resulted in elevated accumulation of heavy metals in seeds, which restricts the acceptability for human consumption (Singh and Agrawal, 2010). Treated wastewater was found not to produce any harmful effects in barley shoots due to heavy metal accumulation (Adrover et al., 2013). Generally, heavy metal concentrations in plant tissues reflect their levels in irrigation water, and roots are usually more concentrated than foliage.

2.13 Food and Agriculture Organisation (FAO) and World Health Organisation (WHO) standards for the consumption of crops irrigated with treated wastewater

In drip irrigation, the WHO recommends a limit of 1000 faecal coliforms bacteria/100ml for wastewater treatment, and the International Commission on Microbiological Specifications for Foods (ICMSF) recommends $\leq 10^5$ faecal coliforms bacteria/100g fresh weight in vegetables eaten uncooked (Blumenthal et al., 2000).

2.14 Conclusion and future aspects

The projected rise in the global population would lead to an increase in demand for food and treatment of faecal sludge from onsite sanitation facilities. Thus, there has been a push towards recycling water and nutrients from sanitation facilities for reuse in agriculture. Wastewater produced by centralised treatment systems has shown its potential for supporting crop production. Decentralised wastewater treatment systems have been developed to render sanitation services in peri-urban areas and extract nutrient-rich wastewater for crop production. The development of decentralised sanitation technologies with the ability to extract pathogen-free nutrients remains a major priority. Low-cost off-the-grid sanitation technologies have shown their ability to recover pathogen-free nutrients in a pilot-scale or under laboratory experiments. More efforts have to be directed towards large scale nutrient recovery from onsite sanitation facilities.

Crops have been successfully produced in open fields and hydroponic systems with nutrient-rich wastewater. Hydroponic systems are now being suggested and considered for crop production as they reduce environmental contamination and limit the exposure of farmworkers to faecal pathogens when using poorly treated wastewater as a nutrient source. Further research is required for testing nutrient-rich wastewater for crop production on newly established vertical hydroponic systems which are reported to produce high yields within smaller spaces.

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CHAPTER 3 : Evaluating the feasibility of ABR effluent as a nutrient source for Swiss chard (*Beta vulgaris* subsp. *cicla*) production in a vertical hydroponic system

Abstract

Treated domestic wastewater contains nutrients such as nitrogen and phosphorus needed for crop production. For example, effluent from Anaerobic Baffled Reactor (ABR) can be used in hydroponic systems for crop production, particularly in peri-urban areas of developing countries. This study investigated the potential use of ABR effluent on the growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*) in a vertical hydroponic system at Newlands Mashu Research Site, Durban, KwaZulu-Natal, South Africa. Swiss chard seedlings were transplanted in a vertical hydroponic system with eight vertical growing towers. The study was set-up in a completely randomised design with four replicates for each treatment giving a total of eight experimental units. Four vertical growing towers were fertigated with commercial hydroponic fertiliser mix (CHFM) as a control and the other four with ABR effluent as a treatment. After transplanting, plant height, number of leaves with disorders, biomass lost and fresh mass of leaves were measured. Swiss chard grown with CHFM performed better than those in ABR effluent and gave a significantly ($p<0.05$) higher plant height and fresh mass of leaves. The number of leaves with disorders was lower in CHFM treatment than in ABR effluent. Swiss chard fertigated with ABR effluent recorded the highest biomass lost to defoliation by pests. Nitrogen, zinc, and boron content were found to be the limiting elements in ABR effluent to maintain high productivity of Swiss chard. High sodium content (153 mg/L) in ABR effluent had a negative effect on growth of Swiss chard. Thus, the fresh mass of Swiss chard leaves was significantly reduced in ABR effluent by 78 % when compared to fertigation with CHFM. This study demonstrated that ABR effluent has the potential to support the growth of Swiss chard in a vertical hydroponic system but its chemical composition requires supplementation with a chemical fertiliser to maintain high productivity of plants. Adaptation of seedlings to nutrient conditions of ABR effluent before transplanting and replenishing nutrients weekly should be considered as part of further investigation when using ABR effluent as a nutrient source without supplementation with a fertiliser.

Keywords: Swiss chard, ABR effluent, commercial hydroponic fertilisers, hydroponics

3.1 Introduction

Treated domestic wastewater which is a mixture of grey water and black water produced by centralised wastewater systems is used for irrigation of crops in semi-arid rural and peri-urban areas of developing countries (Asano, 1998; Case et al., 2017). Irrigation of crops with treated domestic wastewater is practised to supply nutrients to plants (Obuobie et al., 2006). In, Accra, a majority of peri-urban farmers recorded high yields when using domestic wastewater to irrigate their crops (Drechsel and Keraita, 2014). However, the irrigation of vegetable crops with domestic wastewater is not yet fully embraced by farmers and consumers due to the health risks and perceptions associated with its usage (Saldías et al., 2016).

Farmers and workers in Nam Dinh, Vietnam were reported to develop skin problems due to constant contact with treated domestic wastewater during irrigation (Trang et al., 2007). Vegetable crops grown with domestic wastewater in Malamulele, Limpopo, South Africa were found to contain faecal microbes, and farmers sold their produce in markets for their livelihoods (Gumbo et al., 2010). Decentralised wastewater systems are now being constructed in rural and peri-urban areas for generation of pathogen-free treated domestic wastewater for irrigation of crops in farms and family gardens (Capodaglio, 2017).

In Durban, South Africa, a decentralised wastewater treatment system called an Anaerobic Baffled Reactor was implemented for treating wastewater from peri-urban households, and it recovers nutrient-rich effluent as part of the treatment process (Gutterer et al., 2009a; Musazura, 2014). This system provides biological treatment of raw domestic wastewater through a series of anaerobic baffled reactors (ABR), anaerobic filters and two constructed wetlands. After the anaerobic filters, nutrient-rich effluent undergoes nutrient removal in constructed wetlands (Capodaglio, 2017; Gutterer et al., 2009a).

Previous studies revealed that irrigation with nutrient-rich ABR effluent supported the growth of plants from seedling stage to maturity (Musazura, 2014; Nasr et al., 2009). Swiss chard irrigated with nutrient-rich ABR effluent showed a significantly higher dry mass, fresh mass and leaf area index compared to those irrigated with tap water in pot trials inside a polyethylene tunnel (Musazura, 2014). Magwaza et al. (2020) reported that hydroponically grown tomato plants irrigated with nutrient-rich ABR effluent had the highest harvest index compared to plants irrigated with commercial hydroponic fertiliser mix.

Irrigation with wastewater in hydroponics is regarded as an effective and beneficial way of wastewater reuse (Magwaza et al., 2020b). In addition, hydroponic production of crops with wastewater is seen as a way to meet the demands for the production of high-quality crops while reducing losses of water and nutrients (Haddad and Mizyed, 2011). However, farmers and consumers remain concerned about the accumulation of toxic concentration of micronutrients and pharmaceuticals in edible parts of crops hydroponically grown with domestic wastewater (Herklotz et al., 2010; Madikizela et al., 2018; Sharma et al., 2006). The presence of toxic concentrations of micronutrients and pharmaceuticals in domestic wastewater was reported to cause harmful effects on growth of plants which often leads to reduced yields (Amy-Sagers et al., 2017; Kong et al., 2007).

Swiss chard was successfully produced with nutrient-rich ABR effluent in an open field at Newlands Mashu Research site (Musazura, 2014). However, there is little information on vertical hydroponic production of Swiss chard with nutrient-rich ABR effluent. Therefore, this study investigated the potential use of ABR effluent on the growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*) in a vertical hydroponic system inside a polyethylene tunnel at Newlands Mashu research site.

3.2 Materials and Methods

3.2.1 Site location

The research site is located at 71 John Dory Road, Newlands-Mashu, Durban, KwaZulu-Natal, South Africa (29^{o} 46' 25.648' S; 30^{o} 58' 28.329' E). This site was built by the BORDA Bremen Overseas Research and Development Association (BORDA) and its global partners for the introduction of a decentralised wastewater treatment system focusing on providing sanitation amenities to disadvantaged communities (Gutterer et al., 2009b). Currently, the site provides biological treatment of raw domestic wastewater from 84 low-to-middle income households connected to a sewer system (Musazura, 2014).

Raw domestic wastewater undergoes treatment by anaerobic microorganisms breaking down faecal matter in the settling chamber before flowing by gravity flow to three parallel anaerobic baffled reactor trains which have compartments. Train 1 and train 2 consist of seven compartments, while train 3 has four compartments. The first three compartments in train 3 are double in size while the last compartment is equal to the size of the other trains. After anaerobic baffled reactor trains, there are anaerobic filters to filter floating particles in partially treated effluent before further treatment in planted wetlands. The partially treated effluent released after anaerobic filters is usually rich in nutrients. A pump was used to draw partially treated nutrient-rich effluent into a 5 000 L tank to store for agricultural trials inside a polyethylene tunnel (Foxon et al., 2004; Magwaza et al., 2020c).

3.2.2 Hydroponic system

A vertical hydroponic system called a ZipGrow Farm Wall^{TM} (ZipGrow Inc., Ontario, Canada) was assembled inside the polyethylene tunnel (refer to appendix 6). The vertical hydroponic system was internally modified to have two units merged in one system. Each unit had its drip line, four vertical growing towers and a nutrient reservoir with a submersible pump (pump head = 4.0 m and flow-rate = 6 200 L/h) for transportation of nutrients in a continuous recirculation method. Each vertical growing tower had two folding supporting growing inorganic media to hold plants. The supporting inorganic medium was made of fibrous, thermos-polypropylene with a white strip inside to channel the flow of nutrients from drippers to the plant roots (Calabria et al., 2019a). The system has two troughs (top and bottom) for holding vertical growing towers. The top trough has a drip line to supply nutrients into vertical growing towers, and the bottom trough collects nutrient solutions drained from vertical growing towers to return into reservoirs.

The vertical hydroponic had the following dimensions; 2.0 m (width) × 2.6 m (height); area required was 5.3 m^2. Vertical growing towers are spaced by 0.0038 m (3.8 cm) apart.

3.2.3 Experimental set-up in the vertical hydroponic system

The vertical hydroponic system had eight vertical growing towers. Four vertical growing towers fertigated with commercial hydroponic fertiliser mix (CHFM) and the other four vertical growing towers fertigated with anaerobic baffled reactor (ABR) effluent. The study was set-up in a completely randomised design with four replicates for each treatment giving a total of eight experimental units.

Table 3.1: Layout of experimental design in hydroponic system.

Commercial hydroponic fertiliser mix	ABR effluent
VGT 1	VGT 5
VGT 3	VGT 2
VGT 6	VGT 4
VGT 7	VGT 8

3.2.4 Preparation of nutrient feeds

3.2.5 Municipality tap water

Municipality tap water used for preparation of commercial hydroponic fertiliser mix was used without correcting its pH with an acid.

3.2.5.1 Commercial hydroponic fertiliser mix

Commercial hydroponic fertilisers were purchased from Hygrotech Pty. Ltd. Pietermaritzburg, South Africa. A 45 L nutrient solution of commercial hydroponic fertiliser mix was prepared by dissolving 22.5 grams of HYGROPONIC TM fertiliser mix (Nitrogen (N) – 68 g/kg; Phosphate (P) – 42 g/kg; Potassium (K) – 208 g/kg; Magnesium (Mg) – 30 g/kg; Sulphur (S) – 64 g/kg; Iron (Fe) – 1254 mg/kg; Copper (Cu) – 22 mg/kg; Zinc (Zn) – 149 mg/kg; Manganese (Mn) – 299 mg/kg; Boron (B) – 373 mg/kg and Molybdenum (Mo) – 37 mg/kg) and 11.25 grams of calcium nitrate (Nitrogen (N) – 117 g/kg and Calcium (Ca) – 166 g/kg). The HYGROPONIC TM fertiliser mix and calcium nitrate were separately dissolved in tap water in their respective measuring beakers in order to avoid precipitation of calcium nitrate. A 22.5 L HYGROPONIC TM fertiliser mix solution and 22.5 L calcium nitrate solution was then mixed to form the 45 L nutrient solution of commercial hydroponic fertiliser mix to use for fertigation of plants.

3.2.5.2 ABR effluent

ABR effluent was collected from the 5000 L tank (storing nutrients for crop trials) next to the polyethylene tunnel with 20 L sterile containers. A 45 L volume of ABR effluent was used as the final feed solution for irrigation of plants.

3.2.6 Flow-rate of drippers

The flow-rate was fixed at 3.6 L/h in all drippers with microjet valves in order to maintain uniformity in fertigation of plants in vertical growing towers. The flow-rate was adapted from who used it for fertigation of lettuce with diluted synthetic NEWgenerator permeate in a vertical hydroponic system.

3.2.7 Planting date, planting method and operation of vertical hydroponic system

Swiss chard (*Beta vulgaris* subsp. *cicla*) seedlings that were four weeks old were bought from Tropical nursery, Durban, South Africa. Swiss chard seedlings were planted in the vertical hydroponic system on 15 August 2018. The seedlings were transplanted in the morning (09h00 to 10h00) by placing onto a white strip in a slanting position 15 mm apart inside the supporting medium of the vertical growing towers. The supporting medium was folded and inserted inside the vertical growing tower after transplanting. Each fold had five transplants, and the vertical growing towers were designed to carry two folds. Therefore, ten seedlings were transplanted in each vertical growing tower, and there were 40 plants per treatment which made up a total of 80 Swiss chard transplants cultivated into the vertical hydroponic system. Power was then turned on after cultivation to begin irrigation of plants by submersible pumps continuously recirculating nutrients around in roots. Nutrient sources were replenished every two weeks of recirculation until end of eight week study period.

3.2.8 Data collection and harvesting date

Data was collected after a week upon transplanting and every week until harvesting phase for plant height, the number of leaves with disorders (misshaped leaves) and the total biomass lost in each treatment to determine the effect of nutrient sources on Swiss chard grown in a vertical hydroponic system. Above ground biomass losses in plants was accounted for pruned leaves which had died (green leaves turning brown) due to effects of leaves shading each other caused by delayed harvesting. In addition, leaves which died due after infection with Swiss chard pests and diseases were also recorded as part of above ground biomass loss in plants. Biomass lost per plant was determined through weighing dead matter of Swiss chard on an analytical balance (RADWAG, PS 4500.RS, Poland). Swiss chard leaves were harvested once only on 15 October 2018 at the end of the study period. The study lasted for eight weeks. Fresh leaf mass per plant was determined through weighing fresh matter of

Swiss chard (leaf fresh mass) on an analytical balance (RADWAG, PS 4500.RS, Poland) after harvesting.

3.2.9 Data analysis

The collected data for growth parameters were subjected to statistical analysis using GenStat version 17th Edition (VSN International, Hemel Hempstead, UK). Analysis of variance (ANOVA) was performed for evaluating the effects of nutrient solutions on crop development. Treatment means separated using Fisher's Least Significant Difference (LSD) test at 5 % level of significance.

3.3 Results

3.4 Nutrient analysis

Nutrient analysis results indicated that the municipality tap water used for preparation of CHFM had a neutral water pH (7.6). The pH of CHFM was slightly acidic (6.4) and ABR effluent was neutral (7.0). Nitrogen in a fresh solution of CHFM was mostly available in nitrate form while ABR effluent had ammonium as the predominant form of nitrogen. The electrical conductivity in a fresh solution of CHFM was higher than of ABR effluent. CHFM had a higher concentration of Nitrogen (N), Potassium (K), Magnesium (Mg), Calcium (Ca), Iron (Fe), Manganese (Mn), Zinc (Zn) and Boron (B) than ABR effluent. Only concentrations of copper (Cu), molybdenum (Mo) and sodium (Na) were lower in CHFM than in ABR effluent (Table 3.2).

Table 3.2: Chemical composition of municipality tap water and nutrient sources used for crop production.

Parameters	UNITS	Municipality tap water	CHFM	ABR effluent
DO	mg/L	-	8.7	2.1
EC	mS/m	17.6	102	95.3
pH	-	7.6	6.4	7
NH_4-N/NO_3-N	-	-	18:82	100:0
NH_4-N	mg/L	<0.10	10.7	77.4
NO_3-N	mg/L	0.6	48	0.3
Nitrogen	mg/L	1.3	121	80
Phosphorus	mg/L	0.01	22	17.1
Potassium	mg/L	3.51	108	22
Magnesium	mg/L	2.2	23	9.3
Calcium	mg/L	6.8	78	21
Sulphur	mg/L	0.73	39	27
Iron	mg/L	0.11	0.45	0.13
Manganese	mg/L	bdl	0.12	0.02
Zinc	mg/L	0.84	0.09	bdl
Boron	mg/L	0.06	0.18	bdl
Copper	mg/L	0.06	bdl	0.02
Molybdenum	mg/L	bdl	bdl	0.55
Sodium	mg/L	3.53	16.5	153
Cadmium	mg/L	0.01	bdl	bdl
Chromium	mg/L	bdl	bdl	bdl
Nickel	mg/L	0.16	bdl	bdl
Lead	mg/L	bdl	bdl	bdl

CHFM, Commercial hydroponic fertiliser mix; ABR effluent, treated wastewater from an Anaerobic Baffled Reactor system; DO, dissolved oxygen; EC, electrical conductivity; NH_4-N, ammonium nitrogen; NO_3-N, nitrate nitrogen; bdl, below detection level; dash, units not available; Detection limit: Zinc, 0.02 mg/L; Boron, 0.02 mg/L; Copper, 0.02 mg/L; Molybdenum, 0.11 mg/L; Cadmium, 0.02 mg/L; Chromium, 0.02 mg/L; Nickel, 0.02 mg/L; Lead, 0.02 mg/L.

3.4.1 Effect of nutrient sources on growth and biomass production in hydroponically grown Swiss chard

Swiss chard grown with ABR effluent reported a significantly low growth and yield compared to treatment with commercial hydroponic fertiliser mix. The plant height of Swiss chard grown with CHFM (21.8 cm) was significantly higher than of plants treated with ABR effluent (18.2 cm). The number of leaves with disorders per plant and biomass lost per plant was higher in Swiss chard treated with ABR effluent compared to treatment with CHFM. Swiss chard treated with ABR effluent produced a significantly lower fresh mass of leaves (2.88 g) compared to treatment with CHFM with a mass of 16.07 g (Table 3.3 and Table 3.4).

Table 3.3: Analysis of variance showing mean squares and significant test of plant growth and yield of hydroponically grown Swiss chard treated with different nutrient sources (CHFM and ABR effluent).

Source of variation	DF	Plant height	Leaves with disorders	Biomass lost	Fresh leaf mass
Nutrient source	1	212.90*	31.687ns	60.50ns	348.17**
Residual	6	43.76	6.126	51.14	5.69
Total	7				

CHFM, commercial hydroponic fertiliser mix; ABR effluent, treated wastewater from an Anaerobic Baffled Reactor system. * Significant at $p<0.05$; **Significant at $p<0.001$; NS, non-significant; DF, degrees of freedom.

Table 3.4: Effect of nutrient sources on plant growth and yield of hydroponically grown Swiss chard. The two nutrient sources used were; commercial hydroponic fertiliser mix (CHFM) and Anaerobic Baffled Reactor (ABR) effluent.

Nutrient source	Plant height (cm/plant)	Leaves with disorders/plant	Biomass lost (g/plant)	Fresh leaf mass (g/plant)
CHFM	21.8	0.79	10.0	16.07
ABR effluent	18.2	2.42	15.40	2.88
P-value	<0.05	<0.05	0.319	<0.001
LSD	3.31	1.44	12.37	4.13

CHFM, commercial hydroponic fertiliser mix; ABR effluent, treated wastewater from an Anaerobic Baffled Reactor system.

3.4.2 Biomass lost to pests and diseases

Figure 3.1: Appearance of Swiss chard leaves showing symptoms of; spinach leaf miner (A), aphids (B), powdery mildew (C) and flea beetles (D) infection three weeks after transplanting.

3.4.3 Fresh yield

The fresh mass of leaves per plant harvested at the end of the study showed that Swiss chard grown with CHFM produced a significantly higher fresh yield than plants treated with ABR effluent (Table 3.4).

3.5 Discussion

This study investigated the potential use of ABR effluent on the growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*) in a vertical hydroponic system at Newlands Mashu Research Site, Durban, KwaZulu-Natal, South Africa. Nutrient-rich ABR effluent has been reported as a good source of nitrogen and phosphorus for growth of plants (Foxon et al., 2004; Nasr et al., 2009).

Treated wastewater such as ABR effluent which has received at least secondary treatment is without heavy metals and does not affect plant growth (Adrover et al., 2013). Musazura (2014) reported that growth parameters and yield of Swiss chard showed no significant difference between irrigation with tap water + fertilisers and ABR effluent on an open field. However, in this study, Swiss chard grown with CHFM performed better than those in ABR effluent and gave a significantly ($p<0.05$) higher plant height and fresh mash of leaves (Table 3.3).

The stunted growth in Swiss chard grown with ABR effluent was related to its reduced nutrient supply lower than CHFM and the low dissolved oxygen content which contributed in a reduction in nutrient uptake (Schröder and Lieth, 2002). The dissolved oxygen in ABR effluent was 1.3 mg/L compared to 8.7 mg/L present in prepared nutrient solution of CHFM (Table 3.2). Brechner et al. (1996) reported that leafy vegetables required at least 4 mg/L of dissolved oxygen to grow satisfactorily in hydroponics. Deficiency of dissolved oxygen affects root formation and plant growth (Schröder and Lieth, 2002; Suyantohadi et al., 2010). The effects of dissolved oxygen deficiency were observed in poor root development in Swiss chard grown with ABR effluent. There was an absence of roots hairs in Swiss chard grown with ABR effluent whilst roots hairs developed in plants of CHFM treatment (Appendix 12).

Sodium content in ABR effluent also affected the growth of Swiss chard, as it was approximately five times the concentration found in CHFM (Table 3.2). Swiss chard which belongs to the beet family requires sodium as a beneficial nutrient source when it is less than 36.8 mg/L (Kronzucker et al., 2013). Toxicity of sodium in wastewater is reported to adversely affect plant growth as it increases exchangeable sodium ions on the exchange complex at the expense of Ca^{2+}, Mg^{2+} and K^+ (Jalali et al., 2008). In addition, higher amounts of Na^+ inactivates and affect metabolic processes in plants (Sudhir and Murthy, 2004). The K and Ca content was low in ABR effluent which had adverse effects on mitigating the damage of Na^+ in plant tissues of Swiss chard (Adrover et al., 2013; Tester and Davenport, 2003).

Nitrogen supply had a major effect on the growth of Swiss chard fertigated by ABR effluent as it was mainly available as ammonium (Nasr et al., 2009). Feeding leafy vegetables such as Swiss chard with nutrient solutions rich in ammonium was reported to cause ammonium toxicity resulting in stunted growth, foliar chlorosis and stunted roots (Santamaria et al., 1999). A proper combination of ammonium and nitrates was recommended for good growth of vegetable crops (Liu et al., 2017; Song et al., 2017).

The ammonium to nitrate ratio in a nitrogen fertiliser plays a considerable role in the growth of vegetable crops in hydroponic systems. A ratio of 25:75 is mostly suggested and considered suitable for high productivity of leafy vegetables (Song et al., 2017). The ammonium to nitrate ratio was 18:82 in CHFM with nitrates as the dominant form of nitrogen. In contrast, ABR effluent had a ratio of 100:0 with ammonium the dominating form of nitrogen. Hydroponic solutions were reported to enhance good growth of leafy vegetables when nitrates are the dominating form of nitrogen (Song et al., 2017).

Ammonium has a stimulating effect on plant growth and development when it is not a significant source of nitrogen (Savvas et al., 2006). Swiss chard grown with ABR effluent suffered negative effects of ammonium being a dominating form of nitrogen in a nutrient solution which resulted in reduced growth and crop productivity (Savvas et al., 2006; Song et al., 2017). Furthermore, the availability of nitrogen in nutrient sources favoured Swiss chard grown with CHFM than ABR effluent. CHFM had a nitrogen content of 121 mg/L compared to ABR effluent which had 80 mg/L. Leafy vegetables such as Swiss chard require at least 100 mg/L of nitrogen to enhance good growth (Hopper et al., 1997).

Therefore, Swiss chard grown with CHFM had better growth due to adequate supply of nitrogen, zinc and boron as compared to those of ABR effluent. Reduced supply of boron and zinc results in stunted growth, malformations of leaves and yield reduction in leafy vegetables (Eaton, 1940; Hajiboland and Amirazad, 2010). Toxicity of molybdenum in ABR effluent affected the growth of Swiss chard too. The growth of young pea plants was inhibited by the toxicity of molybdenum (Kevresan et al., 2001).

Molybdenum and ammonium toxicity inhibits the activity of nitrate reductase needed for the assimilation of nitrates in green plants resulting in disorders (Kaiser et al., 2005; Kevresan et al., 2001). Swiss chard grown with ABR effluent had a higher number of leaves with disorders (misshaped leaves) which was an indication of nutrient stress and a pest problem (Table 3.4). The outbreak of Swiss chard pests (aphids and flea beetles) contributed to stunted growth and distortion of leaves. Initially, there was effective chemical control of pests with an agricultural disinfectant called sporekill (Appendix 10), However, it was not an insecticide even though pests were successfully controlled in Swiss chard fertigated by CHFM. On the other hand, the shortcomings of sporekill was observed in its failure to control persistent pest infection in Swiss chard fertigated with ABR effluent, which can be attributed to various factors.

Thus, Swiss chard pests later developed resistance to chemical control on plants mainly fertigated with ABR effluent. Matured Swiss chard leaves were defoliated by aphids and flea beetles which are common pests affecting leafy vegetables (Mou, 2005). The outbreak of pests was propelled by the presence of *Amaranthus mangostanus* L. plants (weeds) growing in planted wetlands of the ABR system, which was the breeding site of aphids and flea beetles.

Aphids and flea beetles were reported to move from nearby weeds to leafy vegetables where they cause defoliation (Brandenberger et al., 2016). The total biomass lost to pests in CHFM, and ABR effluent showed no significant difference (Table 3.3). However, the biomass lost in Swiss chard grown with ABR effluent (15.4 g) was higher than the one in CHFM treatment (10.0 g). The resistance of aphids and flea beetles to chemical control was associated with the presence of faecal smell in Swiss chard fertigated with ABR effluent, which continuously attracted pests from weeds growing in planted wetland of ABR system which was closer to experimental area. Farmers stopped using human-excreta derived fertilisers at the end of 19th century due to the presence of faecal smell and availability of safer mineral fertilisers (Semiyaga et al., 2015).

The absence of faecal smell in Swiss chard grown with CHFM resulted in fewer leaves defoliated by pests than plants grown with ABR effluent. As a result, the fresh mass of Swiss chard leaves obtained at the end of the study was significantly high in plants grown with CHFM than those raised with ABR effluent. The reduction in crop productivity through fertigation with treated wastewater such as ABR effluent was associated with lower nutrient supply and high sodium content when compared to treatment with commercial nutrient solutions (Adrover et al., 2013; Magwaza et al., 2020c).

3.6 Conclusions and future aspects

Swiss chard grown with CHFM performed better and produced a significantly higher yield than ABR effluent. The low yield obtained in Swiss chard grown with ABR effluent when compared to treatment with CHFM was attributed to several factors combined which were inferior nutrient concentration, high sodium content and vulnerability to pests attracted by faecal smell present in wastewater. Commercial hydroponic fertiliser mix (CHFM) had a higher nutrient supply than Anaerobic Baffled Reactor (ABR) effluent. High sodium content in ABR effluent negatively affected the ability of Swiss chard plants to maintain high productivity. Swiss chard fertigated with ABR effluent recorded the highest biomass lost to defoliation by pests. Pests were attracted by faecal smell remaining in plants after fertigation with ABR effluent as they thought it was Amaranthus which hosted aphids and flea beetles in planted wetlands of ABR system located next to experimental site. Further research is required whereby ABR effluent is supplemented with a chemical fertiliser to have the same concentration of nutrients to those of commercial hydroponic fertiliser mix. Adaptation of seedlings to nutrient conditions of ABR effluent before transplanting and replenishing nutrients weekly should be considered as part of further investigation when using ABR effluent as a nutrient source without supplementation with a fertiliser. Frequent harvest of matured leaves is suggested as the older leaves suppress the growth of new leaves, thus resulting in production of lower yield than expected.

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CHAPTER 4 : Evaluating the feasibility of NEWgenerator permeate as a nutrient source for non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) production in a vertical hydroponic system

Abstract

Shortages of agricultural land in informal settlements of South Africa have resulted in studies of finding alternative ways of food production. An ultrafiltration anaerobic membrane system called NEWgenerator (Nutrients, Energy and Water generator) has been developed to extract a pathogen-free nutrient-rich permeate from public toilets to use for food production in a vertical hydroponic system. However, the nutrient-rich permeate required supplementation with a commercial fertiliser since it was deficient in micronutrients. This study investigated the potential use of diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF) on the growth and yield of non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system at Newlands Mashu research site, Durban, KwaZulu-Natal, South Africa. Non-heading Chinese cabbage seedlings were transplanted in a vertical hydroponic system with eight vertical growing towers. Four vertical growing towers were fertigated with CHFM (commercial hydroponic fertiliser mix) and the other four with DNP + HF. The number of leaves per plant, fresh leaf mass, dry leaf mass, root length and mineral content in tissues were measured to determine the effect of nutrient sources on non-heading Chinese cabbage grown in a vertical hydroponic system. The results revealed there was no significant difference ($p>0.05$) in all determined growth parameters except for yield parameters (fresh leaf mass and dry leaf mass) between plants fertigated by CHFM and DNP + HF. Fresh mass of non-heading Chinese cabbage leaves was significantly reduced in DNP + HF by 26 % when compared to CHFM treatment. On a positive note, the harvested leaves from both nutrient sources were without faecal coliforms. This work demonstrated that diluted NEWgenerator permeate has the potential to support the growth of leafy vegetables in a vertical hydroponic system, but there is a need to daily monitor and maintain the pH of nutrient source as its instability resulted in reduction on final yield.

Keywords: Hydroponics, commercial fertilisers, human-excreta derived materials

4.1 Introduction

Municipalities in major cities of South Africa are on a drive to roll out better sanitation services to people living at informal settlements through the construction of community ablution blocks (Crous et al., 2013a; Roma et al., 2010b). Community ablution blocks are flushing shared water and sanitation facilities which provide sanitation services to people living at informal settlements (Crous et al., 2013b). These sanitation facilities are connected to local sewer lines for transportation of human waste to centralised wastewater treatment systems (Roma et al., 2010b). Decentralised wastewater treatment systems are now being piloted for the introduction of off-the-grid biological treatment of wastewater in peri-urban areas aimed to reduce the volume of domestic wastewater treated in centralised wastewater treatment systems (Amoah et al., 2018b; Massoud et al., 2009). Newly developed decentralised wastewater treatment systems have shown their ability to process domestic wastewater into reusable products such as plant nutrients (Mehta et al., 2015).

Recently, efforts have been directed towards the development of sanitation technologies with the ability to extract pathogen-free nutrients from domestic wastewater (Evans et al., 2013). One of those sanitation technologies is called a NEWgenerator (Nutrients, Energy, Water generator) designed to provide wastewater treatment in informal settlements (Bair et al., 2015). The NEWgenerator processes domestic wastewater from public toilets with an anaerobic membrane bioreactor system to produce potable water, biogas and nutrient-rich treated wastewater (Bair et al., 2016; Meketa, 2017b). The nutrient-rich treated wastewater is reported suitable for hydroponic production of leafy vegetables. It can contribute towards reducing food shortages in informal settlements while creating economic opportunities for people through selling the surplus to urban markets (Bair et al., 2015).

Treated wastewater has been considered a useful source of water to produce barley fodder under hydroponics systems (Al-Ajmi et al., 2009; Al-Karaki, 2011b). Hydroponic production of Szarvasi-1 energy with treated wastewater showed that it is a good source of nutrients for high biomass non-food crops given it has a low heavy metal content (Rév et al., 2017). Adrover et al. (2013), recommended that treated wastewater must be supplemented with fertilisers as nitrogen and iron were the major limiting nutrients in the growth of barley in a hydroponic system. Nitrogen was found to be less than 50 mg/L, and Iron was below detection level in treated wastewater. Barley requires more than 100 mg/L of nitrogen in nutrient solutions for normal growth of plants (Hopper et al., 1997).

Hydroponically grown tomato plants with anaerobic baffled reactor (ABR) effluent supplemented by commercial hydroponic fertilisers showed better growth, biomass gains and higher mineral accumulation in shoots than those grown with commercial hydroponic fertilisers (Magwaza et al., 2020c). In some instances, hydroponic systems are also used for secondary treatment of wastewater through the production of crops (Haddad and Mizyed, 2011). Spinach grown for 21 days with diluted urine in a hydroponic system showed comparable growth to those raised with a commercial nutrient solution. The waste solution discarded at the end of the experiment met Singapore discharge standards to watercourses. The discharge standards met were; chemical oxygen demand (<30 mg/L), total soluble solids (<10 mg/L), nitrates (< 4.5 mg/Land total phosphorus (<0.76 mg/L) (Yang et al., 2015).

Previous studies have shown that fertigation of vegetable crops with wastewater have both positive and negative effects on plants. Some crops were reported to produce good yields, for example, Swiss chard (Musazura, 2014). In contrast, other crops were found to experience a decline in yield; for example, Black mustard (Gupta et al., 2010). The physiological response of crops produced using wastewater differs amongst species due to their differences in their genetic make-up. Thus, further research is required in understanding the implications of growing local leafy vegetables with nutrients derived from domestic wastewater in a closed hydroponic system.

Amaranth and non-heading Chinese cabbage were successfully grown in a closed hydroponic system with commercial hydroponic fertilisers (Maboko and Du Plooy, 2019). Calabria et al. (2019a) reported that lettuce grown for 14 days with diluted synthetic NEWgenerator permeate in a vertical hydroponic system showed a higher average fresh mass than the control. This study investigated the potential use of diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF) on the growth of Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system.

4.2 Materials and Methods

4.2.1 Research sites

4.2.1.1 Nutrient extraction research site

This research site is located in Thandanani informal settlement (29.7835^o S, 31.0206^o E), Durban, KwaZulu-Natal, South Africa. An off-the-grid decentralised wastewater treatment system (refer to appendix 3) was installed to treat human excreta from toilets of a male community ablution block which is used daily by people living in the informal settlement. The sanitation technology is an anaerobic ultrafiltration membrane bioreactor system referred to as NEWgenerator^{TM} (the University of South Florida, Tampa, USA) with the ability to process domestic wastewater into nutrient-rich wastewater, potable water and biogas (Bair et al., 2015).

4.2.1.2 Agricultural research site

The research site is located at 71 John Dory Road, Newlands-Mashu, Durban, KwaZulu-Natal, South Africa (29^o 46' 25.648' S; 30^o 58' 28.329' E). This site was built by the BORDA Bremen Overseas Research and Development Association (BORDA) and its global partners for the introduction of a decentralised wastewater treatment system focusing on providing sanitation amenities to disadvantage communities (Gutterer et al., 2009b). Currently, the site provides biological treatment of raw domestic wastewater from 84 low-to-middle income households connected to a sewer system (Musazura, 2014).

Raw domestic wastewater undergoes treatment by anaerobic microorganisms breaking down faecal matter in the settling chamber before flowing by gravity flow to three parallel anaerobic baffled reactor trains which have compartments. Train 1 and train 2 consist of seven compartments, while train 3 has four compartments. The first three compartments in train 3 are double in size while the last compartment is equal to the size of the other trains. After anaerobic baffled reactor trains, there are anaerobic filters to filter floating particles in partially treated effluent before further treatment in planted wetlands (Magwaza et al., 2020).

4.2.2 Hydroponic system

A vertical hydroponic system called a ZipGrow Farm Wall^{TM} (ZipGrow Inc., Ontario, Canada) was assembled inside the polyethylene tunnel (refer to appendix 6). The vertical hydroponic system was internally modified to have two units merged in one system. Each unit had its drip line, four vertical growing towers and a nutrient reservoir with a submersible pump (pump head = 4.0 m and flow-rate = 6 200 L/h) for transportation of nutrients in a continuous recirculation method. Each vertical growing tower had two folding supporting growing media to hold plants. The supporting inorganic medium was made of fibrous, thermos-polypropylene with a white strip inside to channel the flow of nutrients from drippers to the plant roots (Calabria et al., 2019a). The system has two troughs (top and bottom) for holding vertical growing towers. The top trough has a drip line to supply nutrients into vertical growing towers, and the bottom trough collects nutrient solutions drained from vertical growing towers to return into reservoirs.

The vertical hydroponic had the following dimensions; 2.0 m (width) × 2.6 m (height); area required was 5.3 m^2. Vertical growing towers are spaced by 0.0038 m (3.8 cm) apart.

4.2.3 Experimental set-up in the vertical hydroponic system

The vertical hydroponic system had eight vertical growing towers. Four vertical growing towers were fertigated with commercial hydroponic fertiliser mix (CHFM), and the other four vertical growing towers were fertigated with diluted NEWgenerator (nutrients, water and energy generator) permeate + hydroponic fertiliser (DNP + HF). The study was set-up in a completely randomised design with four replicates for each treatment giving a total of eight experimental units.

Table 4.1: Layout of experimental design.

CHFM	**DNP + HF**
VGT 1	VGT 5
VGT 3	VGT 2
VGT 6	VGT 4
VGT 7	VGT 8

VGT, Vertical growing tower.

4.2.4 Preparation of nutrient feeds

4.2.4.1 Municipality tap water

Municipality tap water used for preparation of commercial hydroponic fertiliser mix and diluting NEWgenerator permeate was used without correcting its pH with an acid.

4.2.4.2 Commercial hydroponic fertiliser mix

Commercial hydroponic fertilisers were purchased from Hygrotech Pty. Ltd. Pietermaritzburg, South Africa. A 45 L nutrient solution of commercial hydroponic fertiliser mix was prepared by dissolving 22.5 grams of HYGROPONIC ^{TM} fertiliser mix (Nitrogen (N) – 68 g/kg; Phosphate (P) – 42 g/kg; Potassium (K) – 208 g/kg; Magnesium (Mg) – 30 g/kg; Sulphur (S) – 64 g/kg; Iron (Fe) – 1254 mg/kg; Copper (Cu) – 22 mg/kg; Zinc (Zn) – 149 mg/kg; Manganese (Mn) – 299 mg/kg; Boron (B) – 373 mg/kg and Molybdenum (Mo) – 37 mg/kg) and 11.25 grams of calcium nitrate (Nitrogen (N) – 117 g/kg and Calcium (Ca) – 166 g/kg). The HYGROPONIC ^{TM} fertiliser mix and calcium nitrate were separately dissolved in tap water in their respective measuring beakers in order to avoid precipitation of calcium nitrate. A 22.5 L HYGROPONIC ^{TM} fertiliser mix solution and 22.5 L calcium nitrate solution was then mixed to form the 45 L nutrient solution of commercial hydroponic fertiliser mix to use for fertigation of plants.

4.2.4.3 Diluted NEWgenerator permeate + hydroponic fertiliser

NEWgenerator permeate was collected with sterile containers from Thandanani informal settlements and transferred to Newlands Mashu research site. The NEWgenerator required dilution before usage at it was highly concentrated in macronutrients but deficient with micro-nutrients. The permeate was diluted at a dilution ratio of 1:9 with tap water (five litres of NEWgenerator permeate was diluted with 40 litres of municipality tap water) to make a volume of 45 L as a nutrient feed. Thereafter, 7.5 g of HYGROPONIC^{TM} fertiliser mix (Nitrogen (N) – 68 g/kg; Phosphate (P) – 42 g/kg; Potassium (K) – 208 g/kg; Magnesium (Mg) – 30 g/kg; Sulphur (S) – 64 g/kg; Iron (Fe) – 1254 mg/kg; Copper (Cu) – 22 mg/kg; Zinc (Zn) – 149 mg/kg; Manganese (Mn) – 299 mg/kg; Boron (B) – 373 mg/kg and Molybdenum (Mo) – 37 mg/kg) was then added to the nutrient feed towards addressing micronutrient deficiencies in the final feed solution for fertigation of plants.

4.2.5 Nutrient analysis

Samples of nutrient sources were taken before (freshly prepared new solution) and at the end (waste solution) of crop production for nutrient analysis at Talbot Laboratories, Pietermaritzburg, KwaZulu-Natal, South Africa.

4.2.6 Flow-rate of drippers

The flow-rate was fixed at 3.6 L/h in all drippers with microjet valves in order to maintain uniformity in fertigation of plants in vertical growing towers. The flow-rate was adapted from Calabria et al. (2019a) who used it for fertigation of lettuce with diluted synthetic NEWgenerator permeate in a vertical hydroponic system.

4.2.7 Planting date, planting method and operation of vertical hydroponic system

Non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) seedlings were four weeks old that were bought from Sunshine seedlings in Pietermaritzburg, South Africa. Planting of seedlings in the vertical hydroponic system took place on 17 May 2019. The seedlings were transplanted in the morning (09h00 to 10h00) by placing onto a white strip in a slanting position 15 mm apart inside the supporting medium of the vertical growing towers. The supporting medium was folded and inserted inside the vertical growing tower after transplanting. Each fold had five transplants, and the vertical growing towers were designed to carry two folds.

Therefore, ten seedlings were transplanted in each vertical growing tower, and there were 40 plants per treatment which made up a total of 80 non-heading Chinese cabbage transplants cultivated into the vertical hydroponic system. Power was then turned on after cultivation to begin irrigation of plants by submersible pumps continuously recirculating nutrients around in roots. A pH meter was used to monitor the pH value of nutrient solutions from the beginning of fertigation until the end of trial period.

4.2.8 Data collection and harvesting date

The number of leaves per plant, root length, fresh leaf mass and dry leaf mass were measured to determine the effect of nutrient sources on non-heading Chinese cabbage grown in a vertical hydroponic system. Hoboware data loggers (Onset Computer Corporation, Bourne, USA) were installed and used to measure the micro-climate around the vertical hydroponic system inside the polythene tunnel. The average growing conditions (night/day) were: temperature (33.1/15.6; ^{o} C), relative humidity (77.6/77.1; %), active photosynthetic radiation (29.8/18.6; µmol/m^{2}s^{1}), solar radiation (31.3/0.6; W/m^{2}) and dew point temperature (28.7/11.6; ^{o} C). Non-heading Chinese cabbage leaves were harvested once only on 03 July 2019 at the end of the study period. The fresh leaf mass and fresh root per plant was determined through weighing on an analytical balance (RADWAG, PS 4500.RS, Poland) after harvesting.

4.2.9 Plant tissue analysis

Samples of freshly harvested leaves were taken from each treatment for blending with deionised water. The blended solutions were taken for faecal coliform analysis at Talbot Laboratories, Pietermaritzburg, KwaZulu-Natal, South Africa. The remaining fresh leaves and roots (washed off potting soil) were dried in an oven at 60 ^{o} C for 48 hours. The dried plant material (leaves and roots) of each treatment was replicated three times for macronutrients and micronutrients analysis at the Soil and Plant Laboratory, CEDERA (Department of Agriculture and Rural Development), Pietermaritzburg, KwaZulu-Natal, South Africa.

4.2.10 Data analysis

The collected data for growth parameters and elements accumulated in plant tissues were subjected to statistical analysis using GenStat version 17th Edition (VSN International, Hemel Hempstead, UK). Analysis of variance (ANOVA) was used to determine the effect of nutrient solutions on crop development and nutrients accumulated in plant tissues. Treatment means were separated using Fisher's Least Significant Difference (LSD) test at 5 % level of significance.

4.3 Results

4.3.1 Nutrient analysis

Dilution of high strength NEWgenerator permeate in order to supplement deficient micronutrients (Manganese (Mn) and zinc (Zn)) resulted in decline macronutrients (Nitrogen (N), Phosphorus (P), Potassium (K) and Calcium (Ca)) in DNP + HF (Table 4.2 and Table

4.3). However, K, Mg, Ca, and S contents in high strength NEWgenerator permeate were lower than the concentration of these nutrients in CHFM before dilution (Table 4.2). Mg and S contents increased in DNP + HF when compared to the concentration of these nutrients in NEWgenerator permeate due to supplementation with chemical fertiliser (Table 4.2 and Table 4.3). However, Mg and S content in DNP + HF remained low when compared to the concentration of these nutrients in CHFM (Table 4.3).

DNP + HF had a very low dissolved oxygen content compared to CHFM. Ammonium was the predominant form of N in DNP + HF while in CHFM, most of N was in nitrate form. DNP + HF had a lower N, K, Ca, S, Fe, Mn, Zn, and B content than CHFM. In contrast, Mg, P and Na content were higher in DNP + HF than in CHFM. Magnesium, boron, copper, and sodium contents increased in waste solution of CHFM while the waste solution of DNP + HF recorded an increase in nitrates, phosphorus, magnesium, manganese, zinc, boron, copper and sodium (Table 4.3).

The pH was alkaline in DNP + HF and neutral in CHFM (Table 4.4). After five days of transplanting, the pH dropped to fluctuate to highly acidic conditions in DNP + HF while it fluctuated in slightly acidic conditions in CHFM (Table 4.4).

Table 4.2: Chemical composition of municipality tap water and NEWgenerator permeate before dilution.

Elements (mg/L)	Units	Municipality tap water	NEWgenerator permeate
Faecal coliforms	CFU/mL	0	0
DO	mg/L	-	4.1
EC	mS/m	17.6	228
pH	-	7.6	7.1
NH_4-N	mg/L	<0.10	210
NO_3-N	mg/L	0.6	0
Nitrogen	mg/L	1.3	282.3
Phosphorus	mg/L	0.01	67
Potassium	mg/L	3.51	70
Magnesium	mg/L	2.2	10.4
Calcium	mg/L	6.8	38
Sulphur	mg/L	0.73	12
Iron	mg/L	0.11	0.16
Manganese	mg/L	bdl	bdl
Zinc	mg/L	0.84	bdl
Boron	mg/L	0.06	0.07
Copper	mg/L	0.06	0.08
Molybdenum	mg/L	bdl	bdl
Aluminium	mg/L	3.53	bdl
Sodium	mg/L	0.01	87
Cadmium	mg/L	bdl	bdl
Chromium	mg/L	0.16	bdl
Nickel	mg/L	bdl	bdl
Lead	mg/L	bdl	bdl

CHFM, Commercial hydroponic fertiliser mix; NEWgenerator permeate, treated wastewater from NEWgenerator system; DO, dissolved oxygen; EC, electrical conductivity; NH_4-N, ammonium nitrogen; NO_3-N, nitrate nitrogen; bdl, below detection level; dash, units not available; Detection limit: Manganese, 0.02 mg/L; Zinc, 0.02 mg/L; Aluminium, 0.02 mg/L; Molybdenum, 0.11 mg/L; Cadmium, 0.02 mg/L; Chromium, 0.02 mg/L; Nickel, 0.02 mg/L; Lead, 0.02 mg/L.

Table 4.3: Chemical composition of nutrient sources used for fertigation (fresh solution) of plants and discarded at the end of study (waste solution).

Elements	Units	CHFM		DNP + HF	
		F.S.	W.S.	F.S.	W.S.
DO	mg/L	5.8	7.1	1.3	8.1
EC	mS/m	91.4	56.3	82.3	60.4
pH	N.A.	7.8	6.3	8.2	4.7
NH_4-N	mg/L	10.7	1.6	45	0
NO_3-N	mg/L	48	26.2	12.2	20.9
Nitrogen	mg/L	77	39	66	53
Phosphorus	mg/L	19.1	15.7	29.5	33
Potassium	mg/L	104	12.9	57	22
Magnesium	mg/L	24	28	26	27
Calcium	mg/L	70	38	22	48
Sulphur	mg/L	38	35	19	11
Iron	mg/L	0.27	0.13	0.1	0.11
Manganese	mg/L	0.41	0.02	0.08	0.18
Aluminium	mg/L	<0.02	<0.02	<0.02	0.04
Zinc	mg/L	0.12	0.11	0.04	0.13
Boron	mg/L	0.16	1.7	0.1	1.74
Copper	mg/L	0.03	0.38	0.05	0.13
Molybdenum	mg/L	<0.11	<0.11	<0.11	<0.11
Sodium	mg/L	23	37	33	37
Cadmium	mg/L	bdl	bdl	bdl	bdl
Chromium	mg/L	bdl	bdl	bdl	bdl
Nickel	mg/L	bdl	bdl	bdl	bdl
Lead	mg/L	bdl	bdl	bdl	bdl

CHFM, Commercial hydroponic fertiliser mix; DNP + HF, diluted NEWgenerator permeate + hydroponic fertiliser; FS, fresh solution for fertigation; W.S., waste solution for discharge; DO, dissolved oxygen; EC, electrical conductivity; NH_4-N, ammonium nitrogen; NO_3-N, nitrate nitrogen; bdl, below detection level; dash, units not available; Detection limit: Aluminium, 0.02 mg/L; Molybdenum, 0.11 mg/L; Cadmium, 0.02 mg/L; Chromium, 0.02 mg/L; Nickel, 0.02 mg/L; Lead, 0.02 mg/L.

Table 4.4: The electrical conductivity and pH of nutrient sources during crop production.

	CHFM		**DNP + HF**	
Days after planting	EC (mS/m)	pH	EC (mS/m)	pH
0	91.4	7.8	82.3	8.2
1	90.8	7.6	77.9	7.8
3	89.5	6.2	72.3	5.3
5	96.3	5.8	77.1	4.8
8	97.6	5.5	79.1	4.9
9	96.5	5.2	79.6	4.7
10	95.6	5.4	77.3	4.8
11	87.7	5.4	78.4	4.6
13	78.0	5.9	74.6	4.6
14	71.3	6.1	70.0	4.3
15	65.9	6.3	65.8	4.6
17	56.3	6.3	60.4	4.7

CHFM, commercial hydroponic fertiliser mix; DNP + HF, diluted NEWgenerator permeate + hydroponic fertiliser; EC, electrical conductivity.

4.3.1 Effect of nutrient sources on growth and biomass production in hydroponically grown non-heading Chinese cabbage

The number of leaves per plant (9.0) showed no significant difference in non-heading Chinese cabbage plants between fertigation with diluted NEWgenerator permeate + hydroponic fertilizer and chemical hydroponic fertilizer mix. Non-heading Chinese cabbage treated with DNP + HF produced a significantly lower fresh leaf mass (12.11 g) and dry leaf mass (1.21 g) compared to treatment with CHFM with a mass of 16.34 g and 1.47 g respectively (Table 4.5 and Table 4.6).

Table 4.5: Analysis of variance showing mean squares and significant test of plant growth and yield of hydroponically grown non-heading Chinese cabbage treated with different nutrient sources (CHFM and DNP +HF).

Source of variation	DF	Number of leaves/plant	FLM	DLM	Root length
Nutrient source	1	0.00ns	35.66*	0.134*	1.051ns
Residual	6	4.130	5.69	0.0170	
Total	7				

CHFM, commercial hydroponic fertiliser mix; DNP + HF, diluted NEWgenerator permeate + hydroponic fertiliser; FLM, fresh leaf mass; DLM, dry leaf mass; * Significant at $p<0.05$; NS, non-significant; DF, degrees of freedom.

Table 4.6: Effect of nutrient sources on plant growth and yield of hydroponically grown non-heading Chinese cabbage. The two nutrient sources used were, commercial hydroponic fertiliser mix (CHFM) and diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF).

Nutrient source	Number of leaves/plant	FLM(g/plant)	DLM(g/plant)	Root length(cm/plant)
CHFM	9.0	16.34	1.47	6.5
DNP + HF	9.0	12.12	1.21	5.8
P-value	1.00	<0.01	<0.05	0.23
LSD	1.181	2.283	0.226	1.315

CHFM, commercial hydroponic fertiliser mix; DNP + HF, diluted NEWgenerator permeate + hydroponic fertiliser. FLM, fresh shoot mass; SDM, dry leaf mass; LSD 0.05.

4.3.2 Mineral content in leaves and roots

Mineral content in leaves was statistically significantly different ($p<0.05$) between nutrient sources. Only Na content in leaves and N in roots showed no significant difference between nutrient sources. Leaves of non-heading Chinese cabbage grown with CHFM had higher K, Ca and Zn content and a lower N, P, Mg, Na, Mn, Fe and Cu content than those of non-heading Chinese cabbage grown with DNP + HF. Similar results were found in roots except for N and Na content (Table 4.7).

Table 4.7: Mineral content in plant tissues of non-heading Chinese cabbage expressed as g/kg.

	N	**P**	**K**	**Ca**	**Mg**	**Na**	**Zn**	**Mn**	**Fe**	**Cu**	**Al**
Nutrient sources (Leaves)											
CHFM	56.8	8.4	93.1	25	7.3	5.2	0.18	0.074	0.15	0.029	0.12
DNP + HF	59.6	9.5	68.3	17.8	8.3	5.3	0.13	0.101	0.24	0.030	0.16
P-value	< 0.05	<0.001	<0.001	<0.001	<0.001	0.43	<0.001	<0.001	<0.001	<0.001	<0.01
LSD	1.80	0.195	0.979	0.321	0.207	0.333	0.0028	0.00016	0.0055	0.00028	0.0055
Nutrient sources (roots)											
CHFM	22.5	5.8	14.8	15	8.5	2.1	0.17	0.14	4.1	0.24	2.5
DNP + HF	22.3	6.2	10.9	11.1	9.7	1.6	0.12	0.16	5.8	0.32	3.0
P-value	0.79	<0.001	<0.001	<0.001	<0.001	0.11	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	1.95	0.096	0.207	0.293	0.185	0.63	0.0044	0.0044	0.133	0.0049	0.064

CHFM, Commercial hydroponic fertiliser mix; DNP + HF, diluted NEWgenerator permeate + hydroponic fertiliser; LSD 0.05.

4.4 Discussion

This study investigated the potential use of diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF) on the growth and yield of non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system at Newlands Mashu research site, Durban, KwaZulu-Natal, South Africa. The growth response of non-heading Chinese cabbage ((*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system showed significant difference between nutrient sources for fresh leaf mass and dry leaf mass.

Biological nitrification of ammonium-nitrogen in DNP + HF during the 17-day growing period was found to enhance good growth in non-heading Chinese cabbage plants such that the number of leaves and root length was comparable to treatment with CHFM. Nutrient recirculation periods of more than 14 days in diluted NEWgenerator permeate were recommended towards stimulating enough nitrate-nitrogen for plant uptake in order to enhance good growth in hydroponic systems (Calabria et al., 2019a).

Fertigation with CHFM produced significantly higher biomass than treatment with DNP + HF. However, growth parameters (number of leaves per plant and root length) of non-heading Chinese cabbage were statistically not different between nutrient treatments in the vertical hydroponic system. The high biomass produced by CHFM was a result of higher nutrient supply and slight acid-pH levels during fertigation which supplied adequate concentrations of elements needed for plant growth. Water pH of CHFM fluctuated between 5 and 6.5 during crop production (Table 4.3).

The small biomass produced by DNP + HF was associated with reduced nutrient supply lower than CHM and very low water pH (4.0 – 5.0) during fertigation in the second week which reduced the availability of some elements due to precipitation. Leafy vegetables such as non-heading Chinese cabbage requires nutrient sources to have a water pH ranging from 5.5 – 6.5 during crop production (Maboko and Du Plooy, 2019). The very low water pH in DNP + HF resulted in an increase in the availability of micronutrients such as Fe which led to toxic levels in hydroponic solution. It is worth mentioning that N, K, S and Ca contents were lower in DNP + HF than in CHFM before fertigation of plants (Table 4.3).

Nitrogen supply had a significant effect on leaf's growth than on root's growth. The N content in roots showed no significant difference, but it statistically differed in leaves of non-heading Chinese cabbage treated with DNP + HF when compared to treatment with CHFM. When nutrients are limited as in the treatment with DNP + HF growth of roots is stimulated than the growth of leaves (Adrover et al., 2013).

The highest of N content was detected in the leaves of non-heading Chinese cabbage treated with DNP + HF although there was a low supply of the element in the solution. The lower content of N in CHFM treatment was attributed to the luxury supply of the element which contributes little to crop productivity and nitrates being dominating form of nitrogen which often results in a decline in total N in plant tissues (Brix et al., 2002; Maneejantra et al., 2016). Nitrogen content increases in plant tissues which are fed ammonium as a predominant form of nitrogen than nitrates in acidic conditions (Brix et al., 2002; Güsewell, 2004).

Nitrogen toxicity leads to stunted growth and reduction in yield when ammonium is the dominating source of nitrogen (Goyal and Huffaker, 1984). Ammonium has a limiting effect on the uptake of nitrates by plants (Hochmuth et al., 2004). Song et al. (2017) reported that nutrient uptake and plant biomass of non-heading (flowering) Chinese cabbage was reduced when the nutrient solution had 75 % as ammonium-nitrogen. DPN + HF had 79 % as ammonium-nitrogen in a nutrient solution which resulted in smaller biomass of non-heading Chinese cabbage.

Besides N, the N-source significantly affected tissue concentration of P, Mg, Na, Fe, Mn and Cu which all higher in non-heading Chinese cabbage plants predominately fed ammonium as a nitrogen source in DNP + HF than in CHFM. In contrast, the influence of ammonium content resulted in lower contents of Zn, Ca and K in both leaves and roots of plants grown with DNP + HF than those of CHFM treatment. High ammonium content increases acidity in nutrient solutions and becomes stressful to plants in very acidic conditions (Brix et al., 2002).

Ammonium was reported to have an inhibiting effect on the absorption of calcium resulting in the deficiency of the macronutrient in plant tissues (Fageria, 2001). Calcium deficiency was found to cause a significant decline in crop yields (Hara and Sonoda, 1981). The deficiency of calcium can be further be attributed to its low content in DNP + HF during fertigation (Table 4.3). However, the availability of Ca was reduced by the very strong acid conditions due to precipitation with P, Al and Mn (Trejo-Téllez and Gómez-Merino, 2012). Waste solutions of DNP + HF had a higher Ca content, which was released by the absorption of P into plant tissues (Table 4.2). Ca precipitated with phosphates at pH 8.4 in a fresh solution of DNP + HF, thus having a lower content than the waste solution (Penn and Camberato, 2019; Trejo-Téllez and Gómez-Merino, 2012).

High P content in leaves of DNP + HF treatment can be associated to a lower N: P ratio and higher supply of P in hydroponic solution which can lead to toxic effects in plant tissues (Güsewell, 2004). The critical level of P concentration between sufficient and toxicity was suggested to be 8.0 g/kg (0.8 %) in plants. Phosphorus toxicity was observed in plants when tissues have their content level between the range of 9.0 to 18 g/kg (Jones Jr and Analysis, 1998). Therefore, leaf tissues of plants fertigated with DNP + HF had accumulated toxic level of P (9.5 g/kg) as it was within the range of toxicity. The excess phosphorus concentration in leaf tissues of non-heading Chinese cabbage grown with DNP + HF resulted in zinc deficiency. Phosphorus toxicity induces zinc deficiency which results in a reduction in yields of crops (Gianquinto et al., 2000).

The surplus concentration of P in the root zone was reported to cause reduced plant growth and uptake of Zn (Gianquinto et al., 2000; Hochmuth et al., 2004). The waste solution of DNP + HF recorded an increase in Zn concentration which was liberated by the uptake of P as it was precipitated at alkaline pH in the fresh solution and indicated a reduced uptake of the element compared to plants treated with CHFM (Table 4.3). In addition, the availability of Zn to plants was limited in very strong acidic conditions as P content increased in waste solution resulting in precipitation of Zn (Table 4.3).

Zinc deficiency is also caused by iron toxicity which occurred in plants treated with DNP + HF (Hägnesten, 2006). Zinc deficiency was found to cause stunted growth in cabbage plants due to a drastic decrease in leaf surface area and the number of leaves (Hajiboland and Amirazad, 2010). Furthermore, zinc deficiency may induce boron toxicity which often leads to a reduction in yield (Cartwright et al., 1984; Singh et al., 1990).

The magnesium content in shoots and roots of non-heading Chinese cabbage treated with DNP + HF was significantly higher than of CHFM treatment. Fresh solution of DNP + HF had a higher magnesium content than in CHFM (Table 4.3). Plants require magnesium content in plant tissues to range between 2.5 to 3.5 g/kg (0.25 to 0.35 %) in dry matter content (Jones Jr and Analysis, 1998; Przybysz et al., 2016).

In our study magnesium content in dry matter of non-heading Chinese cabbage was beyond the optimum range needed by plants. Significantly higher dry matter content in plants grown with DNP + HF treatment resulted in magnesium toxicity effects. Magnesium toxicity has a depressive effect on the uptake of K and Ca, which were found deficient in plant tissues (Fageria, 2001). K and Ca are responsible for translocation of nutrients, activation of enzymes, and their deficiency results in reduced yields (Fageria, 2001; Hara and Sonoda, 1981). The waste solution of DNP + HF recorded an increase in Mg content (Table 4.3). Absorption of nutrients by plants in a closed hydroponic system was found to result in an increase in Ca and Mg content (Trejo-Téllez and Gómez-Merino, 2012).

Iron toxicity is mostly commonly associated with highly acidic soil or hydroponic nutrient environments. This was observed in the study as the pH of DNP + HF fluctuated within highly acidic range during the second week of fertigation resulting in plant tissues accumulating toxic concentrations of iron (Table 4.7). Iron content was 0.1 mg/L in fresh solution of DNP + HF, less than the required range (0.5 – 3.0 mg/L) for growth of plants. However, when iron is in low concentration in the medium (nutrient solution) it can accumulate in high concentrations in leaf tissues (Twyman, 1951). Iron toxicity in leaf tissues was created by manganese toxicity in shoots of plants (El-Jaoual and Cox, 1998).

At low levels of iron, manganese was reported to accumulate in higher concentrations in leaf tissues (Twyman, 1951). Manganese toxicity in plants grown with DPN + HF resulted in leaf tissues having a higher copper content. However, manganese was reported to reduce copper toxicity in plants (El-Jaoual and Cox, 1998). Toxic concentrations of copper affect a plant's capacity to absorb and translocate other nutrients (Fageria, 2001). In addition, high amounts of copper inhibit plant growth, induces chlorophyll degradation and interferes with photosystem activity resulting in depressive effects on yield (Rouphael et al., 2008; Xiong and Wang, 2005).

Aluminium content in leaves and roots of plants treated with DNP + HF was significantly higher than of CHFM treatment. Aluminium toxicity causes a low rate of water and nutrient uptake, which results in shorter roots, decrease in leaf growth and biomass accumulation

(Amist et al., 2017; Panda et al., 2009). The aluminium content increased in the waste solution of DNP + HF as it formed precipitates with phosphorus under very acidic conditions (Penn and Camberato, 2019). Roots had significantly higher aluminium content than shoots (Table 4.5). As a result, there was reduced uptake of K and Ca into plant tissues due to aluminium toxicity in roots (Rengel, 1992).

The K and Ca deficiency failed to mitigate the effects of Na damage in plant tissues as there was reduced uptake of their concentration (Kader and Lindberg, 2010; Liu and Zhu, 1998; Tester and Davenport, 2003). Roots and shoots of DNP + HF treatment had relatively higher sodium content and lower levels of K and Ca than of CHFM. Thus the concentration of Na resulted in reduced growth due to the toxicity of Na^+ (Tester and Davenport, 2003).

Heavy metals contents of nutrient sources were all below critical levels to induce toxicity in non-heading Chinese cabbage. Faecal coliforms were absent in harvested leaves as DNP + HF was without faecal coliforms too. However, researchers have edged consumers to properly cook or disinfect edible parts of vegetable crops raised with treated wastewater before eating (Akponikpè et al., 2011).

4.5 Conclusion and future aspects

This study demonstrated that diluted NEWgenerator permeate + hydroponic fertiliser can support the growth of non-heading Chinese cabbage in a vertical hydroponic system. Plants grown with diluted NEWgenerator permeate + hydroponic fertiliser showed comparable growth (number of leaves and root length) to those of commercial hydroponic fertiliser mix. The smaller biomass produced by DNP + HF was associated to its reduced nutrient supply lower than of CHFM and very low water pH (fluctuating within 4.0 and 5.0) during the second week of fertigation which reduced the availability of some elements in solution. Further research is required whereby commercial hydroponic fertiliser mix and diluted NEWgenerator permeate have the same concentration of nutrients before fertigation and the pH of nutrient sources is maintained within the range needed by plants for absorption of nutrients.

4.6 Acknowledgements

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CHAPTER 5 : GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This study investigated the potential use of human-excreta derived materials in a vertical hydroponic system for production of leaf vegetables to be consumed by people living in peri-urban areas especially those found in informal settlements of South Africa. Food poverty, malnutrition, unemployment and poor sanitation services has been one of the major challenges facing people living in informal settlements. The provision of improved sanitation facilities such as community ablution blocks and recovering nutrients from human-excreta with sanitation technologies for reuse in subsistence or commercial hydroponic farming has been projected as one of the sustainable solutions towards addressing challenges faced by people living in informal settlement. This chapter is a wrap-up of the entire study and will highlight major findings, discuss and make conclusions and suggestions for future research studies on the reuse of human-excreta derived materials in a vertical hydroponic system.

5.1 General discussion

This study investigated the potential use of human-excreta derived materials (HEDMs) on the growth and yield of leafy vegetables produced in a vertical hydroponic system inside a polyethene tunnel at Newlands Mashu research site, Durban, South Africa. When conducting studies involving hydroponic systems it is important to consider external factors and the composition of nutrient sources especially; pH, electrical conductivity and dissolved oxygen as they play a significant role in nutrient uptake. This is because the external factors and composition of nutrient sources may have an influence on the results and conclusions of the study. Therefore external factors and nutrient composition of nutrient sources were taken into consideration when highlighting major findings in determining the effect of HEDMs on the production of leafy vegetables in a vertical hydroponic system.

The first research study investigated the potential use of Anaerobic Baffled Reactor (ABR) effluent on the growth and yield of Swiss chard (*Beta vulgaris* subsp. *cicla*) in a vertical hydroponic system (Chapter 3). The results revealed that Swiss chard grown with commercial hydroponic fertiliser mix (CHFM) performed better than those in ABR effluent and gave a significantly ($p<0.05$) higher plant height and fresh shoot mass. Nutrient composition of nutrient sources suggested that ABR effluent was insufficient to support the growth of Swiss chard in a vertical hydroponic system. ABR effluent had a lower supply of N, P, K, Mg, Ca, S, Fe, Mn, Zn and B but had a higher content of Cu, Mo and Na when compared to the concentration of these nutrients in CHFM. In addition, nitrogen content in ABR effluent was less than 100 mg/L the minimum requirement for growth of Swiss chard (Hopper et al., 1997). Similar results were obtained by Magwaza et al. (2020c) who reported that low concentrations of N, P, K, Ca and Zn in ABR effluent led to reduced growth and yield in hydroponically grown tomato plants compared to those grown with commercial hydroponic fertiliser mixture. Adrover et al. (2013) highlighted that low concentrations of N and Fe in treated wastewater limited high productivity of barley in a hydroponic system when compared to fertigation with a commercial nutrient solution.

Yield reduction in Swiss chard grown with ABR effluent was mainly associated with a higher number of fully matured leaves being defoliated by aphids and flea beetles before harvesting. Aphids and flea beetles were from nearby weeds (*Amaranthus mangostanus* L.) which grew in planted wetlands of ABR system five meters away from experimental area. They were attracted by faecal smell remaining in Swiss chard after fertigation with ABR effluent. Nutrient stress caused by high sodium and ammonium contents in ABR effluent affected defensive mechanism of Swiss chard to pest infection. It was observed that effective chemical control of aphids and flea beetles in Swiss chard grown with CHFM was mainly due to absence of nutrient stress and faecal smell in plants.

The results of this study are in disagreement with Musazura (2014) who reported that growth parameters and yield of Swiss chard showed no significant difference between irrigation with tap water + fertilisers and ABR effluent on soil trials. In their study, there was an absence of pests which had a significant effect on the final yield in our study. In addition, the soil fertility influenced the outcome of the study as it was already fertile before fertigation with ABR effluent. It is worth mentioning that in their study, ABR effluent had concentrations of all macronutrients and micronutrients significantly lower than of tap water + fertilisers solution. Therefore, the initial soil fertility played a major role in the results obtained in their study.

The presence of faecal pathogens in nutrient-rich ABR effluent is the only limiting factor for growing leafy vegetables to be consumed raw (Foxon et al., 2004). Magwaza et al. (2020) reported that hydroponically grown tomato plants irrigated with nutrient-rich ABR effluent had a high microbial load compared to plants irrigated with commercial hydroponic fertiliser mix. Only leafy vegetables to be consumed after cooking such as Swiss chard can be grown with ABR effluent. Cooking was reported to destroy faecal pathogens left in leafy vegetables after disinfecting them (Hillers et al., 2003).

The second research study conducted in chapter 4 which investigated the potential use of diluted NEWgenerator permeate + hydroponic fertiliser (DNP + HF) on the growth and yield of non-heading Chinese cabbage (*Brassica rapa* L. subsp. *chinensis* (Halnelt)) in a vertical hydroponic system. The results revealed that non-heading Chinese cabbage grown with CHFM and DNP + HF showed no significant difference for growth parameters (number of shoots per plant and length of roots), but significantly varied in shoot fresh mass and shoot dry mass. The smaller biomass produced by DNP + HF was associated to its reduced nutrient supply lower than of CHFM and very low water pH of nutrient source (4.0 – 5.0) during the second week of fertigation which reduced the availability of some elements in solution.

The dominance of ammonium as a nitrogen source in DNP + HF resulted in an increase in acidity levels as hydrogen ions were released during nutrient uptake causing a decrease in pH of nutrient source (Table 4.4). Maboko and Du Plooy (2019) maintained the pH of CHFM within range of 5.8 to 6.1 in order to enhance good growth of non-heading Chinese cabbage in a hydroponic system. In our study non-heading Chinese cabbage grown with CHFM produced a significantly higher yield as pH value fluctuated within 5.3 – 6.3 during fertigation. On the other hand, the pH value of DNP + HF fluctuated within 4.0 – 5.0 during fertigation, which affected biomass production.

Plant tissue analysis conducted in non-heading Chinese cabbage revealed that the pH value of DNP + HF had a significant impact on uptake of macronutrients and micronutrients. The reduction in yield was associated with leaf tissues having Zn deficiency, Ca deficiency, K deficiency, P toxicity, Mn toxicity, Cu toxicity and Fe toxicity when compared to shoots of CHFM treatment. On a positive note, non-heading Chinese cabbage of DNP + HF treatment was without faecal coliforms which reduced the risk of developing human infectious pathogens associated with the consumption of crops grown with nutrients derived from human-excreta.

5.2 CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH STUDIES

Commercial hydroponic fertiliser mix had a higher nutrient supply than human-excreta derived materials (ABR effluent and DNP + HF) used as treatments. Swiss chard grown with CHFM had a significant higher plant height and yield than of ABR effluent in a vertical hydroponic system. Non-heading Chinese cabbage grown with CHFM and DNP + HF showed no significant difference for growth parameters (number of shoots per plant and length of roots), but significantly varied in shoot fresh mass and shoot dry mass. This is because the uptake of macronutrients and micronutrients in non-heading Chinese cabbage significantly varied between fertigation with CHFM and DNP +HF.

The pH of nutrient sources dropped during fertigation of plants which affected nutrient uptake and biomass production. There was a significant effect in biomass production with DNP + HF due to the pH value fluctuating below the range of 5.5 – 6.5 required for production of non-heading Chinese cabbage. CHFM produced a significantly higher biomass as the pH value fluctuated within the range normally needed by non-heading Chinese cabbage for absorption of nutrients in adequate amounts.

ABR effluent and DNP + HF showed their potential to support the growth of Swiss chard and non-heading Chinese cabbage respectively, although there was significant decline in final yield. It was observed that their limitations in biomass production were mainly associated with their chemical composition (high sodium content, very low dissolved oxygen content and high ammonium content) which required plants to be adapted to their nutrient conditions before transplanting. In addition, ABR effluent and DNP + HF required different nutrient management practices from the one normally used when feeding plants with a commercial hydroponic fertiliser mix as nutrient source.

When using ABR effluent as a nutrient source it is advisable to replenish it weekly instead of every fortnight in order to maintain adequate supply of nutrients. When using DNP + HF as a nutrient source, it advisable to daily monitor and maintain the pH value to be within the range need by selected crop. Tap water must be considered to maintain the pH of human-excreta derived materials (ABR effluent and DNP + HF) as it would be replacing water lost in nutrient sources through evaporation and evapotranspiration. Addition of tap water to maintain pH would also reduce acidity levels in nutrient sources caused by increase in hydrogen ions released by high ammonium content during nutrient uptake.

Future studies must consider adapting seedlings of leafy vegetable to nutrient conditions of ABR effluent and diluted NEWgenerator permeate before transplanting into hydroponic system. Leafy vegetable weeds growing in the planted wetland of the ABR system have to be removed as they are a host and breeding site of pests. NEWgenerator permeate must be diluted to have the same concentration of nutrients to those of commercial hydroponic fertiliser mix before fertigation of plants in order to determine if the differences in nutrients played a significant role in reduction of yield in our study.

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APPENDICES

Appendix 1: Sanitation technology called Anaerobic Baffled Reactor (ABR) system treating domestic wastewater from connected sewer households for discharge to water bodies.

Appendix 2: Nutrient-rich effluent generated from middle-class households by ABR system.

Appendix 3: Sanitation technology called NEWgenerator connected to a blue community ablution block for recovery of hydroponic nutrients, biogas and potable water.

Appendix 4: NEWgenerator permeates generated from a community ablution block by sanitation technology called NEWgenerator.

Appendix 5: Merck instruments for nutrient analysis of samples for treatments.

Appendix 6: Inside the polyethene tunnel used for conducting horticultural trials.

Appendix 7: U30 HOBO data loggers with sensors placed onto the vertical hydroponic system collecting weather conditions.

Appendix 8: Transplanting technique of seedlings to grow inside vertical towers.

Appendix 9: Vertical growing towers transplanted with Swiss chard seedlings

Appendix 10: Plant sanitiser called Sporekill, and a garden spray used to control diseases in Swiss chard plants during first research study.

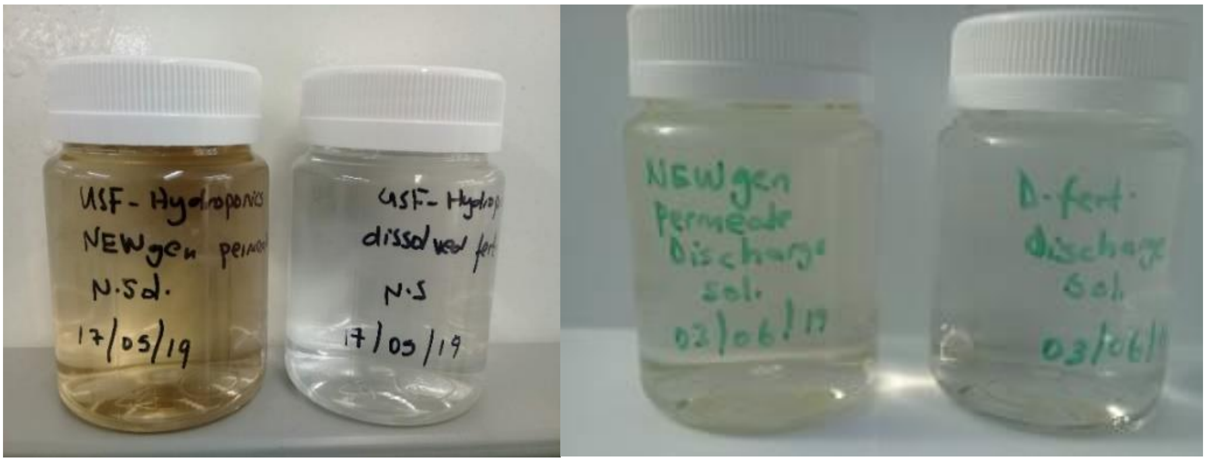
Appendix 11: Yield of Swiss chard grown by commercial hydroponic fertilisers in a yellow 25 L bucket and yield of Swiss chard grown with ABR effluent in a 10 L black bucket after 56 days of crop production.

Appendix 12: Appearance of Swiss chard roots fertigated by commercial hydroponic fertiliser mix (A) and anaerobic baffled reactor (B) effluent at harvesting phase.

Swiss chard grown with CHFM had roots developing roots hairs (marked) on the growing media while there were no root hairs in Swiss chard fertigated with ABR effluent.

Appendix 13: Internal tunnel micro-climate around the vertical hydroponic system during non-heading Chinese cabbage production.

Time	**Duration**	**Solar Radiation, W/m²**	**PAR, µmol/m²s¹**	**Temp, °C**	**RH, %**	**DewPt, °C**
0	Night	0.6	18.7	20.317	70.4	14.8
	Day	35.6	31.2	33.521	78.6	29.3
1	Night	0.6	18.7	18.604	77.3	14.6
	Day	35.6	33.7	35.985	78.9	31.8
2	Night	0.6	21.2	15.652	79.3	12.1
	Day	35.6	33.7	41.239	77.9	36.6
3	Night	0.6	21.2	14.553	76	10.4
	Day	35.6	33.7	41.152	75.2	35.9
4	Night	0.6	21.2	20.269	72.2	15.1
	Day	4.4	6.2	21.27	60.5	13.3
5	Night	0.6	1.2	17.249	68.7	11.5
	Day	39.4	33.7	34.545	68.1	27.8
6	Night	0.6	18.7	14.577	79.4	11.1
	Day	11.9	28.7	30.571	81.7	27.1
7	Night	0.6	8.7	17.653	78.5	13.9
	Day	34.4	28.7	33.835	79.3	29.8
8	Night	0.6	16.2	16.082	80.8	12.8
	Day	33.1	28.7	31.357	81.7	27.9
9	Night	0.6	16.2	15.963	82.7	13
	Day	33.1	28.7	36.389	81.2	32.7
10	Night	0.6	16.2	13.81	76.7	9.8
	Day	33.1	28.7	33.131	79.2	29.1
11	Night	0.6	16.2	16.32	77.9	12.5
	Day	45.6	16.2	26.646	83.9	23.7
12	Night	0.6	21.2	15.294	75.6	11
	Day	34.4	36.2	29.84	81.1	26.3
13	Night	0.6	21.2	13.329	76.7	9.3
	Day	14.4	33.7	29.065	78.2	24.9
14	Night	0.6	16.2	11.71	80.3	8.4
	Day	33.1	33.7	33.914	80.7	30.2
15	Night	0.6	18.7	11.662	78.2	8
	Day	34.4	33.7	32.381	80.4	28.6
16	Night	0.6	21.2	12.654	78	8.9
	Day	34.4	33.7	35.422	76.4	30.7
17	Night	0.6	21.2	14.768	78.2	11
	Day	30.6	33.7	31.868	77	27.4



Appendix 14: Nutrient solutions before and after 17-day recirculations in non-heading Chinese cabbage plants. Key: dissolved fertiliser – Commercial hydroponic fertiliser mix and NEWgen permeate – Diluted NEWgenerator permeate + hydroponic fertiliser.

Appendix 15: Yield of non-Chinese cabbage after 17 days of crop production in a vertical hydroponic system. D.F. – Dissolved fertilizers (commercial hydroponic fertiliser mix) and W.W. – Wastewater (diluted NEWgenerator permeate + hydroponic fertiliser).