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ASSESSING THE VALUE OF FERTILISERS DERIVED FROM CONTAINER-BASED SANITATION SYSTEMS

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ABSTRACT

It is estimated that 61% of the world population lacks access to safely managed sanitation and that in low-income countries (LICs) only 6.7% of the population is connected to a sewerage network. Container-based sanitation (CBS) systems have shown great potential for increasing access to sanitation in densely populated urban slums given that they do not require permanent infrastructures. Resource recovery is usually an essential part of CBS systems to provide sustainable faecal sludge management. Transforming human excreta into fertilisers creates value from faecal sludge while producing an organic soil amendment, addressing both sanitation and soil fertility challenges. Soil amendments made from organic residues are however known to be difficult to market profitably. This thesis therefore investigated the properties of human excreta derived fertilisers (HEDF) and the opportunities and challenges to their commercialisation in LIC.

Nutrient characterisation of composts, anaerobic digestate and vermicompost from two CBS ventures showed significant differences in nutrient content between these three HEDF types. Pathogen and heavy metal analyses demonstrated that there is no pollution threat from HEDF when produced according to WHO guidelines. Field and glasshouse crop trials demonstrated the positive effect HEDF can have on crops and soil health. These benefits however do not currently translate into their commercial value. A case study approach was used to identify barriers and enabling conditions faced by two CBS organisations that successfully produce and sell HEDF. The low market value of compost prevented both organisations from recovering treatment costs from HEDF sales. One major barrier to wider adoption of HEDF use was the lack of regulations or certifications specific to this type of fertiliser. Perception challenges exist because of the potentially harmful components human excreta contain such as pathogens and heavy metals. It is therefore essential to create a way of proving or guaranteeing the quality and safety of HEDF products. The value of quality-assuring schemes for HEDF became evident when applying the Biosolids Assurance Scheme from the UK to HEDF, which helped identify a contamination issue in one of the treatment sites considered.

Para la Agüe, que siempre fue mi fan número uno

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TABLE OF CONTENTS

LIST OF FIGURES

APPENDICES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABP	Australian Biosolids Partnership
AD	Anaerobic Digestion
ANOVA	Analysis of Variance
BoP	Bottom of the Pyramid
BAS	Biosolids Assurance Scheme
C	Compost
C^{HEDF}	Compost derived from HEDF
CA	Company A
CB	Company B
$C^{HEDF}+I$	Compost derived from HEDF and chemical fertiliser
CBS	Container-Based Sanitation
CEC	Cation Exchange Capacity
CNRE	Centre National de Recherches en Environnement (National Center for Environment Research, Madagascar)
D^{HEDF}	Digestate derived from HEFD
DINEPA	Direction Nationale de l’Eau Potable et de l’Assainissement (National Directorate for Water Supply and Sanitation, Haiti)
EU	European Union
FAO	Food and Agriculture Organisation
FS	Faecal Sludge
FSM	Faecal Sludge Management
GAP	Good Agricultural Practices
GBP	British Pound (£)
Global GAP	Global Good Agricultural Practices
HACCP	Hazards Analysis and Critical Control Points
HEDF	Human Excreta Derived Fertiliser
IDB	Inter-American Development Bank
I	Mineral (inorganic) fertiliser
ISO	International Organisation for Standardisation
KEBS	Kenya Bureau of Standards
KEPHIS	Kenya Plant Health Inspectorate
LIC	Low-Income Country

LMIC	Low and Middle-Income Country
LRI	Laboratoire Radio Isotopes
MSW	Municipal Solid Waste
NBP	National Biosolids Partnership
NGO	Non-Governmental organisation
NPK	Compound fertiliser containing nitrogen, phosphorus and potassium.
NUE	Nutrient Use Efficiency
OSS	On-Site Sanitation
p	probability
PPCPs	Pharmaceuticals and Personal Care Products
PPP	Public-Private Partnership
R&D	Research and Development
ReVAQ	Ren växtnäring från avlopp (Pure Plant Nutrients from Sewage, Sweden)
SAI Platform	Sustainable Agriculture Initiative Platform
SDG	Sustainable Development Goals
SME	Small and Medium Enterprise
SSA	Sub-Saharan Africa
SWM	Solid Waste Management
UK	United Kingdom
UN	United Nations
US	United States (of America)
UNICEF	United Nations Children's Fund
USD	United States Dollar ($)
USEPA	United States Environmental Protection Agency
V	Vermicompost
V^{HEDF}	Vermicompost derived from HEDF
V^{HEDF}+I	Vermicompost derived from HEDF and chemical fertiliser
WHO	World Health Organisation
WTP	Willingness To Pay

NOTATIONS

B	Boron
C	Carbon
Ca	Calcium
Cb	Cobalt
Cd	Cadmium
Cl	Chlorine
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
Fe	Iron
g	Gram
H	Hydrogen
ha	Hectare
Hg	Mercury
K	Potassium
kg	Kilogram
L	Litre
m	Meter
Mg	Magnesium
mg	Milligram
Mn	Manganese
Mo	Molybdenum
mS	Millisiemens
N	Nitrogen
Ni	Nickel
$N\text{-}NH_4$	Ammonium
$N\text{-}NO_3$	Nitrate
P	Phosphorus
Pb	Lead
S	Sulphur
Zn	Zinc

1 INTRODUCTION

1.1 Research background

Access to safe water, appropriate sanitation and sustainable food production are some of the greatest challenges we are currently faced with to provide sustainable futures worldwide for the 9 billion people that are predicted to populate the Earth by 2050. The Sustainable Development Goals (SDGs) outline some of these challenges and set targets to be reached in coming years (UN, 2015). Target 6.2 aims to “achieve access to adequate and equitable sanitation and hygiene for all”, which is ambitious given that 2.3 billion people lacked access to basic sanitation and 61% of the world population did not have access to safely managed sanitation in 2015 (WHO/UNICEF, 2015). A step change in the sanitation sector is required to achieve this target, especially in the area of adequate Faecal Sludge Management (FSM) (Hueso, 2016). In addition, Target 2.3 of the SDGs aims to double the productivity of smallholder farmers by facilitating their access to inputs and markets and Target 15.3 aims to combat desertification and restore degraded soils. Achieving food security and environmental health are two key issues countries of Sub-Saharan Africa (SSA) are facing and need to address urgently to ensure the wellbeing of their populations and facilitate economic growth (Rosemarin *et al.*, 2008). Nutrient depletion in Africa is a known phenomenon due to the agricultural practices and lack of fertiliser use in the area (Cofie *et al.*, 2009; Wanzala and Groot, 2013). The agricultural productivity of Africa is very low, with 65% of the workforce being employed in the agricultural sector but represents only 32% of its GDP. It is also the region in the world that uses the least fertiliser quantities, about 8 kg.ha^{-1} per annum which is less than one tenth of the world average (Chauvin *et al.*, 2012). This trend needs to be shifted to increase the agricultural output of the area and allow food production to meet the requirements of an ever-increasing population. Henao and Baanante (1999) highlight the importance of using organic fertilisers (such as compost, farm yard manure or sludge) along with other farming practices to reduce the need for chemical fertilisers and preserve soil health.

Globally it is estimated that two out of five people are connected to a sewage network whereas about 80% of sanitation access in urban areas in SSA is provided through on-site sanitation (OSS) technologies (Kariuki *et al.*, 2003). It is estimated that in cities of low-income countries (LICs) only 22% of OSS are safely managed (Blackett *et al.*, 2014). In order to establish long-lasting FSM solutions it is essential to find a combination of collection, treatment and excreta disposal that is appropriate for the local conditions and financially sustainable. Many innovative sanitation initiatives have been created and a wide range of treatment options and end products have been proposed and trialled: end products can range from soil amendments, fuel pellets, cement, animal feed or bioenergy (Strauss, 2000; Cofie *et al.*, 2005; Dominguez *et al.*, 2006; Kargbo, 2010; Nguyen, 2010; Rodriguez *et al.*, 2011; Kengne *et al.*, 2014). It has been recognised that for sanitation services for the poorest to be commercially viable for private companies, resource recovery is essential to generate revenues from FS-derived products since cross-subsidies are unlikely to be economically viable (Murray *et al.*, 2011). One type of product that can be obtained from excreta is Human Excreta-Derived Fertiliser (HEDF), such as compost, vermicompost and digestate.

HEDF in this context is defined as a fertiliser derived from ‘fresh’ source-separated human excreta, as opposed to excreta that have been mixed with household and industrial wastewater streams resulting in sewage sludge. HEDF originates from excreta that have been stored for less than one month, unlike excreta from pit latrines, which have accumulated in pits for several months or years. The distinction between fertilisers originating from fresh and stored excreta was made because it has been shown that the properties of human sludge change over time (Niwagaba *et al.*, 2014). HEDF can originate from faeces or urine alone or a mixture of faeces and urine.

The value of HEDF lies in its fertilising and soil conditioning properties: it contains essential plant nutrients but it is also made up of organic matter that improves soil health by increasing its water retaining capacity, reducing erosion and building structure (Guzha *et al.*, 2005). Reuse of human excreta as a fertiliser could therefore be an attractive solution to both the sanitation crisis and the nutrient depletion of soils in SSA. This nutrient recycling opportunity has been traditionally realised in some areas (eg: China, Thailand, Vietnam) and recognised as an attractive solution to the sanitation issue by professionals in the sector (Heinonen-Tanski and van Wijk-Sijbesma, 2005; Bracken *et al.*, 2009; Koné *et al.*, 2009; Winker *et al.*, 2009; Sharma *et al.*, 2017). Scientific research has extensively been carried out on the effects of animal manures (pig, poultry, cow) (Atiyeh *et al.*, 1999, 2000, 2001; Gutiérrez-Miceli *et al.*, 2007; Lazcano *et al.*, 2009; Doan *et al.*, 2013, 2015; Alfa *et al.*, 2014) but less so on human derived excreta and those that do focus on the effect of a single type of fertilising product on crops (Guzha *et al.*, 2005; Adamtey *et al.*, 2010; Rodríguez-Canché *et al.*, 2010; Owamah *et al.*, 2014).

One type of sanitation ventures that is promising for densely populated urban areas and that typically include resource recovery are Container-Based Sanitation (CBS) systems (Andersson *et al.*, 2017). These systems are relatively new with innovative business models and usually integrate recovery of resources (Tilmans *et al*., 2015). This research proposes to investigate the fertiliser value of HEDF from CBS organisations by comparing their nutrient content and effect on soil and crops. The fertilisers tested on crops came from the project sponsor's pilot system in Madagascar, Loowatt, consisting of a dry toilet with a biodegradable sealing and excreta storage with an associated excreta treatment process. The excreta treatment system is a staged process: anaerobic digestion followed by composting and finally vermicomposting, which yields three HEDFs : anaerobic digestate (D^{HEDF}), compost (C^{HEDF}) and vermicompost (V^{HEDF}). These three fertilisers are derived from one another, which allowed investigating the evolution of nutrients from one treatment stage to the next, constituting a novel aspect of this research. These HEDFs were also compared with those from two other CBS organisations, Sanergy in Kenya and SOIL in Haiti.

Another knowledge gap that will be addressed in this project is exploring the challenges related to their commercialisation at a large scale. Although the positive effects of organic fertilisers on soil have been proven (Sanchez-

Monedero *et al.*, 2004; Basso *et al.*, 2005, Monaco *et al.*, 2008; Odlare *et al.*, 2008; Akanni *et al.* 2011), compost has often been reported to be hard to market profitably in developing countries because of the often low willingness to pay of customers for excreta-derived products (Danso *et al.*, 2002). Many sanitation ventures find themselves in a situation where the local market conditions are unfavourable for compost marketing and the final product has to be given away or sold at a loss. This project therefore also seeks to evaluate the parameters that make fertiliser desirable for farmers, identify the barriers and enabling factors for commercialising HEDFs in different contexts and propose solutions to these.

1.2 **Research aims and objectives**

The aim of this project was to investigate and compare the agronomic as well as the economic potential of HEDFs. The resulting objectives are as follows:

1. Characterise the nutrient content of three different types of HEDFs, namely pasteurised D^{HEDF} from anaerobic digestion of toilet excreta, C^{HEDF} and V^{HEDF} from AD digestate and straw.

2. Demonstrate fertiliser potential and human health safety aspects of the use of HEDFs.

3. Identify the barriers and enabling conditions to the widespread use of HEDF.

4. Investigate the potential role of certification and self-regulation for enabling the widespread commercialisation of HEDFs.

1.3 **Research methodology**

This thesis aimed to characterise the value of HEDF both for soil and crops as well as evaluate their commercial value. Multiple methodologies were applied to address the research objectives given the range of disciplines, challenges and stakeholders involved in and influencing the production and sale of fertilisers made from human excreta. An overall transdisciplinary framework was chosen for this research, which is most appropriate for research focussed on tackling a contemporary problem most often involving non-academic stakeholders and aiming to create an impact or change (Lang *et al.*, 2012). The term transdisciplinary in itself however has been the subject of debates, with some arguing that interdisciplinary and transdisciplinary research are interchangeable and others strictly separating them as two positively different research approaches (Lawrence, 2010). However as Lyall *et al.* (2015) suggest, the two terms are often used interchangeably in certain contexts and they show that in the UK research community inter- and transdisciplinarity are commonly interchanged. The Research Councils for instance more and more frequently encourage collaboration of researchers with external stakeholders and research that aims to create an impact. These two features fit well with the definition of transdisciplinary, but the term is seldom used by UK Research Council. In fact, part of this project was funded by a 'Knowledge Exchange Innovation Internship' grant from the Natural Environment Research Council (grant NE/P012760/1), which called for collaboration with industry and for impactful research but with no mention of transdisciplinary research in the call for proposal. This research was transdisciplinary in that it dealt with a 'real world' problem, involving mostly non-academic stakeholders and research objectives were addressed by integrating findings from a range of disciplines, mainly soil and crop science and social sciences.

The boundaries of this research were determined by applying soft systems analysis principles (Checkland, 2000). Soft system methodology was appropriate for this research since it is concerned with analysing 'real world' issues and finding ways to improve them. It is especially well suited for multidimensional issues that are seen as 'messy situations' and are hard to define. The developers of the SSM define an application of the methodology *"to create a process of learning your way through problematical situations"* (Checkland and Poulter, 2010). This methodology encourages the researcher to assess the different dimensions of a given issue in a dynamic and iterative process. This iterative approach was particularly useful in helping define and shape the direction of this research, which changed and integrated new topics and issues as the research progressed. Soft systems analysis encourages the creation of ‘rich pictures’ to *“capture, informally, the main entities, structures and viewpoints in the situation, the processes going on, the current recognized issues and any potential ones”* (Checkland and Poulter, 2010). Developing a ‘rich picture’ during this research was useful for identifying the different dimensions of the topic considered here and the interconnections between different stakeholders involved in the production, commercialisation and regulation of HEDF. The rich picture in Figure 1-1 illustrates the researcher’s understanding of the problem and interactions considered in this research surrounding the commercialisation of HEDF. This rich picture evolved during the research and was a valuable tool for the researcher to organise ideas and concepts as well as identifying stakeholders to consider when addressing the research objectives. (A larger scale version of this picture is provided in Appendix A).

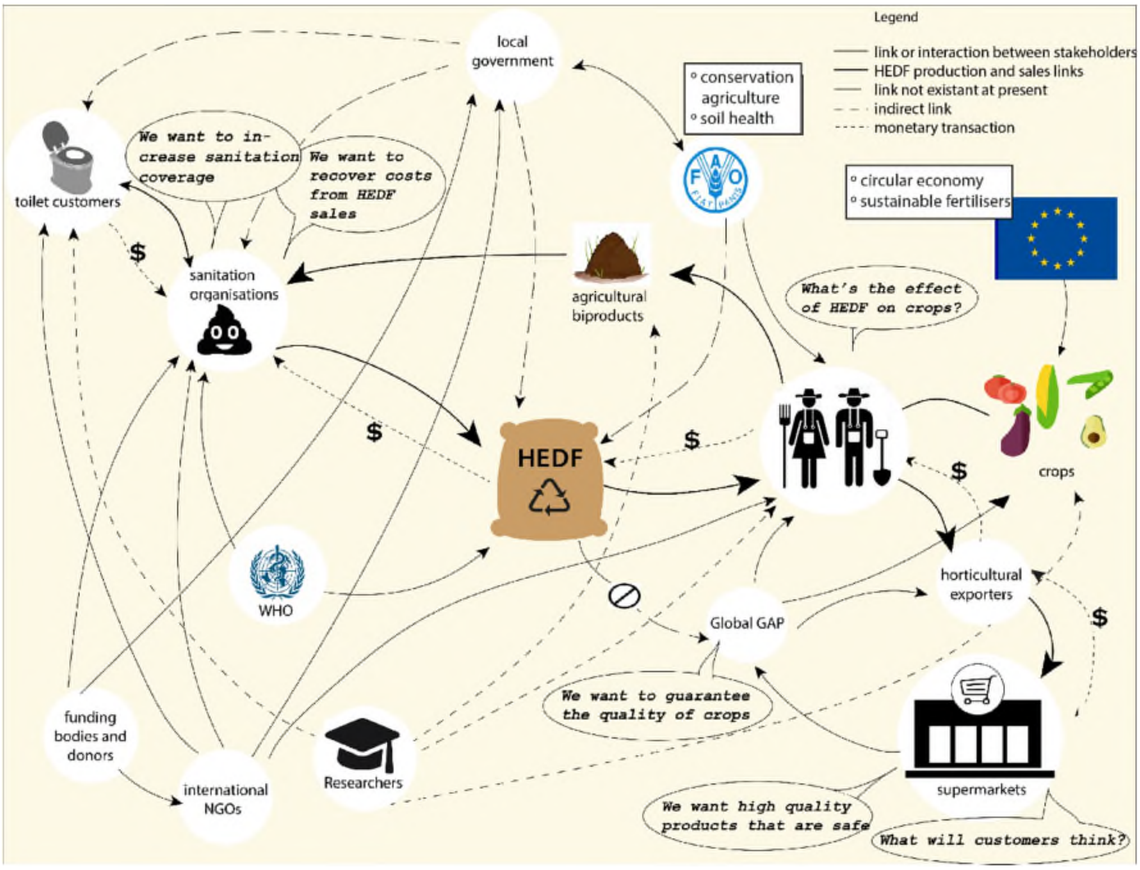

Figure 1-1 Rich picture of the problem situation regarding the commercialisation of fertilisers derived from human excreta

A scientific experimental design was followed for the crop trials, both in the field in Madagascar and in the glasshouse at Cranfield. Both crop trials were designed to test and compare the effect of different fertilisers, hence control plots were put in place in both experiments and treatments applied according to complete random block design. Different fertiliser rates were applied to test for concentration effects and each treatment was triplicated to facilitate robust statistical analysis.

HEDF and farm soil samples to characterise HEDF properties and their effect on soils were taken applying composite sampling methods, which are particularly suited for obtaining representative soil samples and for maintaining realistic analytical testing time and costs (Patil, 2002). In the case of HEDF sampling, three subsamples were collected at different points of a batch during one sampling event and analysed as a single sample. When sampling soils from farms, a minimum of seven soil sub-samples were taken across a given field by walking a W shape along the length of the field, to collect representative samples of the whole area considered.

Results of quantitative data were statistically analysed using the statistical software Statistica (Statsoft, 2011). The details of the analyses applied are defined in more detail for each experiment in the articles presented in the following chapters of the thesis.

A qualitative research approach was chosen for the other research activities realised to evaluate the opportunities and barriers to HEDF commercialisation. Stakeholder analyses were carried out in the form of interviews, which were recorded and subsequently transcribed and coded using the software NVivo (QSR International, 2015). Further details on qualitative methodologies is provided in the relevant chapters that follow.

1.4 **Thesis structure**

This thesis is presented as a series of chapters formatted as articles for publication in peer-reviewed journals, which have either been published, submitted for review or are in preparation for review. All the papers were written by the lead author, Berta Moya and co-authored and edited by Dr Alison Parker and Dr Ruben Sakrabani. The paper presented in Chapter 4 had one additional author, Baptiste Mesa, who provided the detailed fertiliser characteristics for that article. All the experimental and field work described in the articles was carried out by the lead author. The overall thesis outline is presented in Figure 1-2.

The thesis is structured as follows:

- Chapter 1 introduces the research topic and the approaches taken to tackle it.

- Chapter 2 presents a literature review to set the context of the research and identify the research gaps that were addressed in this research (this section of the thesis will not be submitted for publication).

- Chapter 3 evaluates the characteristics of HEDF from two different CBS organisations, their variability, safety and compliance with international regulations by following the Biosolids Assurance Standard originally developed for biosolids in the UK (Paper 1, in preparation to be submitted to Scientific reports *Moya, B., Parker, A. Sakrabani, R., 'Characterising fertilisers derived from human excreta: trends in pathogens, heavy metal and nutrient content in two Sub-Saharan African nations''*). Overall these experiments showed that safe fertilisers can be produced from human excreta if the right conditions and hygiene precautions are in place. Applying the testing schedule of an assurance scheme proved valuable for identifying contamination and product quality issues.

- Chapter 4 analyses the quality of HEDF and evaluate their acceptability within the local market where they are produced. (Paper 2, published in

Waste Biomass and Valorization, *Moya, B., Parker, A., Sakrabani, R. and Mesa, B. (2017) 'Evaluating the Efficacy of Fertilisers Derived from Human Excreta in Agriculture and Their Perception in Antananarivo, Madagascar', Waste and Biomass Valorization. pp. 1–12*. https://doi.org/10.1007/s12649-017-0113-9). Antananarivo (Madagascar) was the field site for the crop trial and three different HEDF were used to grow maize: D^{HEDF}, C^{HEDF} and V^{HEDF}, each derived from the previous one. A series of interviews were also carried out with farmers of the peri-urban area of Antananarivo, which highlighted the importance of characterising the market, identifying users' perceived needs and developing a product responding to these. Chapter 4 was, in part, presented at the 5th Dry Toilet conference in Finland in August 2015.

- Chapter 5 reports the results from a glasshouse crop trial carried out with HEDF in summer 2015. C^{HEDF} and V^{HEDF} were imported from Loowatt's production plant in Madagascar and used to grow maize in pots under controlled conditions in Cranfield. (Paper 3, submitted to Archives of Agronomy and Soil Science, *Effect of compost and vermicompost derived from human excreta on the growth of maize: evidence from a glasshouse pot experiment*). This experiment allowed more detailed investigation of the effect of HEDF on soil and crops and highlighted the chemical differences between C^{HEDF} and V^{HEDF} and their different effect on soil and crops. This experiment also highlighted the benefits of mixing chemical and organic fertilisers to combine their benefits obtaining fast plant growth and improving soil health. Chapter 5 was, in part, presented at SanCoP 18 in September 2016 in the UK and at the IWA FSM4 conference in India in February 2017.

- Chapter 6 explores the factors that enable or hinder the commercialisation of HEDF through two case studies of CBS ventures that produce soil amendments. Case studies were developed with SOIL in Port au Prince and Cap Haitian, Haiti, and with Sanergy in Nairobi, Kenya where stakeholder analyses were carried out. (Paper 4, in preparation for submission to Waste Management, *Moya, B, Parker, A., Sakrabani, R*., *Fertilisers from container-based sanitation systems: assessing enabling conditions and barriers to their commercialisation in Haiti and Kenya*). Both companies were selling their full C^{HEDF} production but neither recovered transport and treatment costs from sales. The case studies highlighted the need for institutional involvement to incentivise the sale and use of HEDF locally and create clear policies on HEDF to increase the economic viability of CBS ventures and HEDF sales.

- Chapter 7 explores the challenges related to the adoption of HEDF by farmers involved in horticultural crop exports in Kenya (Paper 5, submitted to Food Policy, *Moya, B., Parker, A., Sakrabani, R., Challenges to the use of fertilisers derived from human excreta for agriculture: the case of vegetable exports from Kenya to Europe and international certifications).* The stakeholder analysis carried out revealed the major impact that international agricultural certifications have on determining farming practices for farmers exporting crops. The opposition of these agricultural standards to the use of materials derived from sewage sludge is a major barrier for the wider adoption of HEDF in Kenya. Soil analyses from fields treated with HEDF were also carried out and did not show an increase in heavy metal or pathogen concentration as a result of HEDF application. In the discussion it is suggested that a certification scheme specific to HEDF similar to those developed for biosolids in other countries could help increase the acceptability of this type of fertilisers.

- Chapter 8 presents the overall discussion of the thesis, presenting the key findings and their implications for the Sanitation Sector.

- Chapter 9 finalises the thesis with the key conclusions of the research.

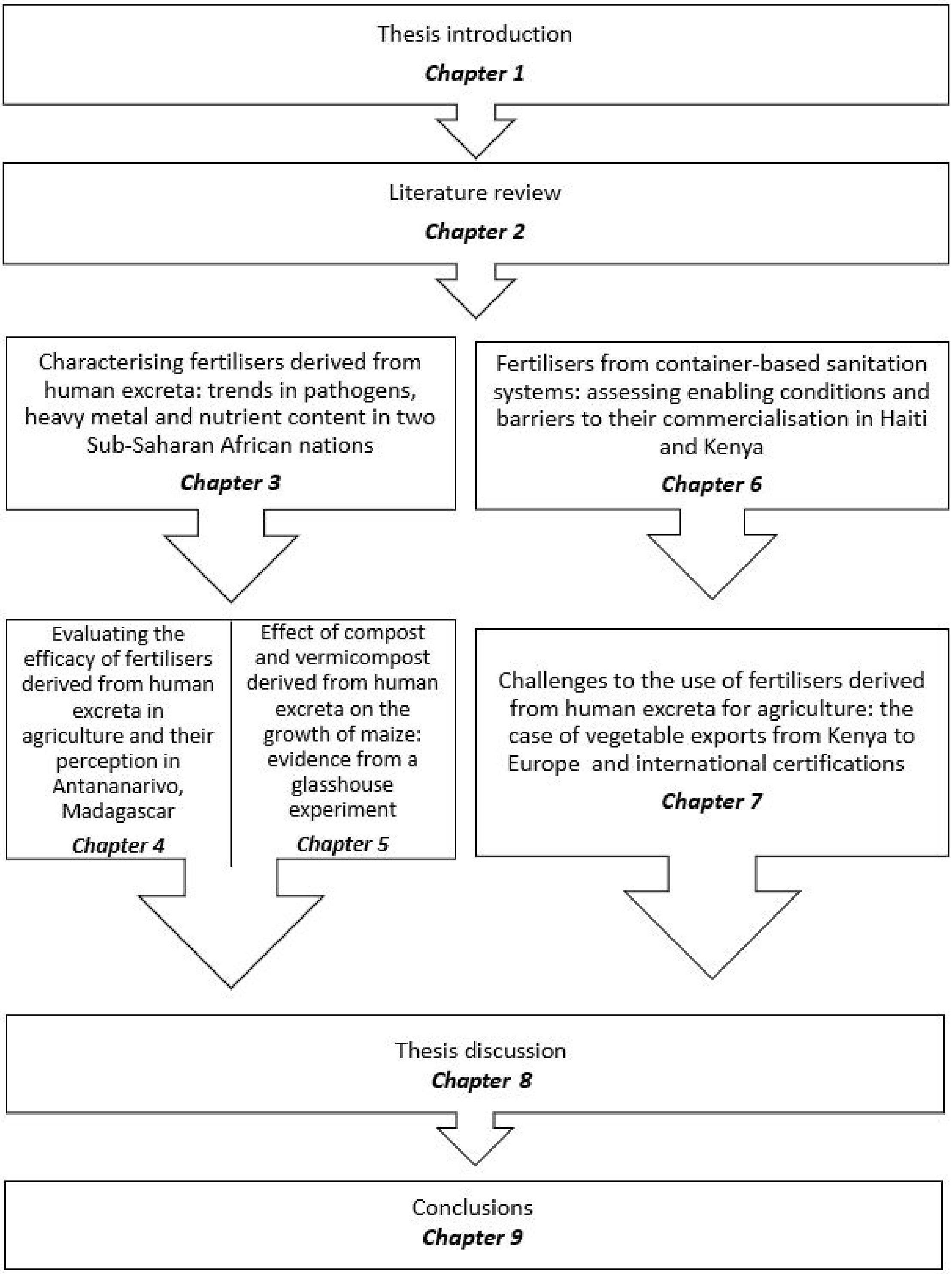

Figure 1-2 Flow diagram of thesis content and structure

2 LITERATURE REVIEW

A global effort from national and international institutions involving both the public and private sectors alike is pushing towards reaching a solution to sanitation issues in low and middle-income countries (LMIC). Universal toilet coverage and structures for safe handling and disposal of human excreta need to be established to reach a sustainable sanitation solution. A major challenge that sanitation ventures in LIC often face is that the revenue from selling toilet infrastructure and waste collection is not sufficient to obtain a self-sustaining business. Most sanitation enterprises therefore count on generating revenue from treating faecal waste by creating a marketable end-product. Given the high nutrient content of human waste, it can be reused in agriculture as a soil amendment; a practice which has been common in countries like China and Japan for centuries (Heinonen-Tanski & van Wijk-Sijbesma, 2005). Many enterprises therefore opt for producing fertilisers from the human excreta they collect and treat, aiming to sell it to local farmers. In order to market these fertilisers however, their properties and effect on soil and crops first need to be characterised and the potential effect of pathogens and metals on human and environmental health need to be addressed. This project sets forth to investigate both the agronomic and commercial value of three HEDF based on a case study of Loowatt, a sanitation SME currently installing toilets and producing fertilisers in Antananarivo, the capital of Madagascar. The following sections introduce the topic and review the relevant corresponding literature.

2.1 The global sanitation situation

Approximately 2.3 billion people worldwide lack access to improved sanitation, “a facility that hygienically separates human excreta from human contact” (UNICEF and WHO, 2017). Lack of access to adequate water, sanitation and hygiene is related to 4% of the deaths worldwide (Pruss *et al.*, 2002). The target for sanitation in the sustainable development goals (SDG) aims to “achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations” (UN, 2015). In contrast to the millennium development goal for sanitation, which only aimed to increasing access to ‘improved’ sanitation, one of the indicators of target 6.2 of the SDG is the percentage of population using safely managed sanitation services, which is “the population using a sanitation facility that is not shared with other household, and where excreta are disposed of in situ or treated off-site” (UNICEF and WHO, 2017). This implies that sanitation coverage will need to be provided to an additional 5.6 billion people by 2030 (Mara and Evans, 2017). There is an added emphasis on improving FSM practices, which has been reflected in the surge in research and projects related to FSM in recent years. The biannual FSM conference for instance started with a few FSM specialists meeting in 2011 and has now grown as an international conference attracting over a thousand sanitation practitioners and researchers. FSM is particularly a challenge in urban settings of LICs where the majority of sanitation provision is through OSS that require emptying. It is estimated that in cities of LIC, almost two thirds of sanitation is provided through OSS and safe sludge management is only provided to 22% of those systems (Blackett *et al.*, 2014). Peal *et al.* (2014) developed an analytical tool for assessing FSM in cities and none of the 12 cities in LMIC that they assessed managed all the faecal sludge (FS) of the city safely. The fraction of safely managed faecal sludge in the 12 cities considered was lowest in Phnom Penh, Cambodia (0%) and Dhaka, Bangladesh (2%) and highest in Palu, Indonesia (86%) and Dumaguete, Philippines (92%).

Sludge management from OSS presents challenges especially in densely populated urban areas because of space and resource limitations. OSS is traditionally provided by pit latrines but emptying these systems is particularly problematic in urban slums where vehicle access is often challenging or impossible (Parkinson and Quader, 2008). It has been recognised that alternative systems are required and initiatives such as the Reinvent the toilet challenge from Bill and Melinda Gates foundation have fostered a surge in innovation in OSS provision (Gates Foundation, 2011; Kone, 2012, Graf *et al.*, 2014). CBS is an alternative OSS sanitation system that has been gaining interest in recent years. These systems do not require any permanent infrastructure: sanitation is provided through mobile toilets where excreta are concealed in sealable containers, which are collected periodically. The sanitation organisations providing CBS systems most often cover the full sanitation value chain with resource recovery from excreta often forming part of the treatment solution (Tilmans *et al.*, 2015). Interest in these systems is growing and it is recognised that they will form part of sanitation solutions in cities if the sanitation target of the SDGs is to be reached (Mara and Evans, 2017).

Resource recovery from FS presents many opportunities: energy, water or nutrients can be harnessed from sludge and value can be created (Diener *et al.*, 2014; Rao *et al.*, 2017). Generating value from sludge also creates incentives for achieving sustainable and circular economy solutions in sanitation (Andersson *et al.*, 2016; Toilet Board Coalition, 2017). Nutrient recovery from FS in particular can provide a great channel for recycling nutrients back to soil.

2.2 Global nutrient management challenges

Global challenges are also faced with nutrient management to meet the food demands of the increasing world population. Several issues need to be tackled to ensure sustainable agricultural systems are achieved. Nutrient cycles and the challenges to maintain them are presented in the following sub-sections.

2.2.1 Nutrient cycles and plant nutrient uptake mechanisms

Plants interact with soil through the oxygen, carbon, phosphorus and nitrogen cycles. Through these cycles plants obtain the 16 nutrients they need to live and grow. These nutrients are classified in 4 categories: structural nutrients, primary macronutrients, secondary macronutrients and micronutrients (Table 2-1), relating to the quantities in which plants require these nutrients. Three macronutrients are obtained from air and water: oxygen, carbon dioxide and hydrogen, the rest of nutrients are obtained from the soil. Nitrogen can be obtained from air through the action of bacteria as well as from soil.

Structural nutrients	Primary macronutrients	Secondary macronutrients	Micronutrients
Hydrogen (H)	Nitrogen (N)	Calcium (Ca)	Zinc (Zn)
Oxygen (O)	Phosphorus (P)	Magnesium (Mg)	Iron (Fe)
Carbon (C)	Potassium (K)	Sulphur (S)	Manganese (Mn)
			Chlorine (Cl)
			Copper (Cu)
			Boron (B)
			Molybdenum (Mo)

Table 2-1 Plant nutrients extracted from air, water and soil (in blue are elements extracted from air and water, in green elements extracted from soil and fertilisers) Nitrogen can be extracted both from soil and air

Nutrient supply from soil to roots is a dynamic process involving a range of interactions between plant roots, soil biota, air, water and minerals. Plant roots absorb nutrients from the soil solution: plants are capable of taking up nutrients only if they are present in solution (inorganic or mineral form). Nitrogen is taken up as nitrate (NO_3^-) or ammonia (NH_4^+) or is provided indirectly through N fixation by bacteria. Phosphorus is taken up as $H_2PO_4^-$, potassium as K^+, Calcium as Ca^{2+}, Mg as Mg^{2+} and sulphur as SO_4^{2-} (**Error! Reference source not found.**).

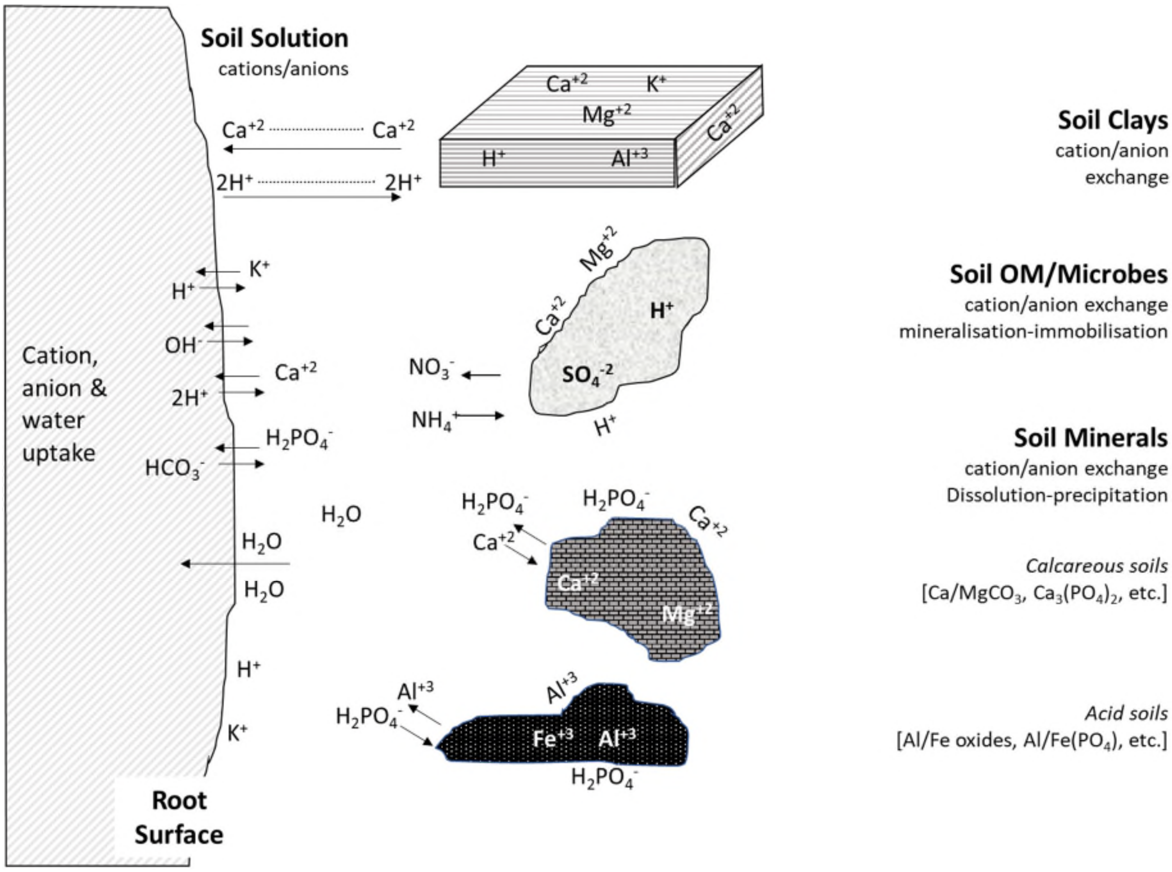

Figure 2-2 Ionic exchanges at the surfaces of roots, organic matter and minerals (from Havlin et al. (2014))

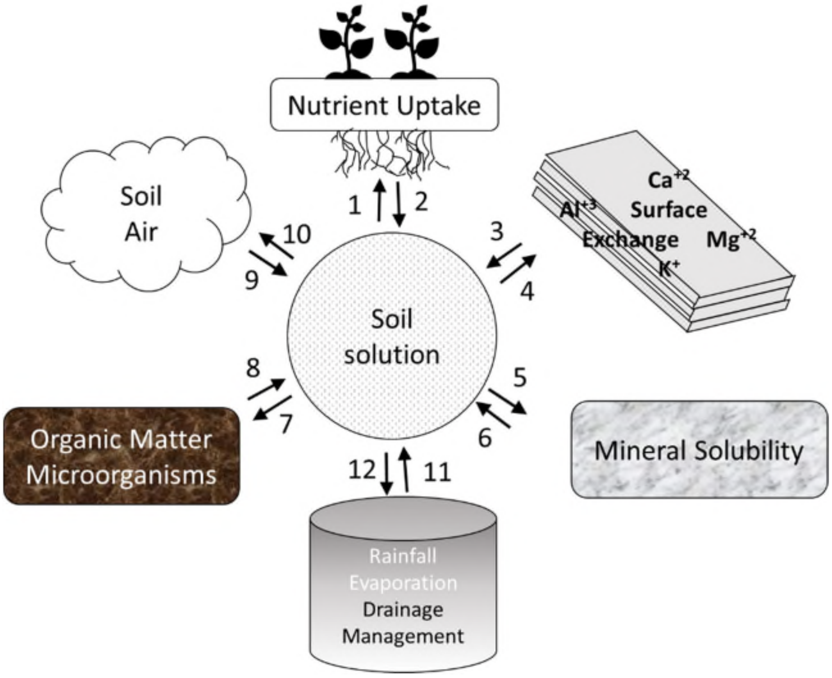

Figure 2-3 Interactions between soil components (from Havlin *et al.* (2014))

Figure 2-3 illustrates the interactions that occur between the different soil components. The numbers in the figure represent reactions between the components and the soil solution. Reactions 1 and 2 are the processes in which plants obtain nutrients from soil. When absorbing nutrients roots release small quantities of H ions (both in anion and cation form), through this process they maintain the aqueous solution electrically neutral, but this can also change the pH of the rhizosphere which affects the availability of nutrients (Havlin *et al.*, 2014). Plant nutrient availability is dependent on the concentration of nutrients in solution but mostly on the ability of the soil to maintain the concentration of nutrients in solution. The process of maintaining soil nutrient concentration is called the soil buffer capacity and requires the release of adsorbed nutrients present in organic matter or minerals (reactions 5, 6, 7 and 8). When a soil system is not able to meet crop demands for nutrients by supplying enough exchangeable nutrients from its mineral and organic reserves, nutrient deficiency occurs in the plant and external supply of nutrients is needed. Water also plays an important role in regulating the concentration of nutrients and contributing in the dissolution of aggregates and salts.

Certain minerals in soil can have an effect on nutrient availability. Fe for instance is known to influence phosphorus availability in acidic soils, it can immobilise phosphorus by precipitation (reaction 4) but these can also become desorbed from the surface of clay minerals to become available in the soil solution again (reaction 5). Organic matter is made up of microorganisms which degrade plant matter and, in the process, can absorb ions from the soil solution (nutrient immobilisation, reaction 7). When these microorganisms die, these nutrients are released back into the soil solution and become available to plants again (reaction 8). Microorganisms can represent a significant reserve of nutrients in soil and are also necessary for completing crucial biological nutrient cycles in the soil system such as nitrogen fixation from air and P solubilization. The presence of organic matter is also essential for supporting the presence of bacterial populations that contribute to nutrient cycles and have beneficial effects on plant roots such as providing antibiotics for increased plant resistance (Zhang *et al.*, 2005).

Organic matter in soil is naturally replenished in soil via the cycle of growth and decay of plant materials. This cycle is broken in soils used for agriculture since plant materials are removed at harvest and it is therefore essential to replenish soil organic matter after crop harvest to maintain a healthy soil system that can support plant growth (Yadav and Malanson, 2007). Chemical fertilisers only supply nutrients in soluble form to plants, they do not contribute to organic matter addition to soil. Fertilisers derived from organic residues can however have the advantage of providing organic matter to soil, depending on the treatment processes applied to the residues.

2.2.2 Soil degradation and low use of fertilisers in LICs

Achieving food security is a major issue for many low-income countries, especially in SSA where agricultural practices and lack of fertiliser use are leading to a nutrient depletion of soils and land degradation (Cofie *et al.*, 2009; Wanzala and Groot, 2013). Africa has not benefited from the ‘Green Revolution’ like Asia or Latin America and the productivity of land remains very low: with 65% of the workforce being employed in the agricultural sector, it represents only 32% of its GDP (Wanzala and Groot, 2013). This trend needs to be shifted to increase the agricultural output of the area and allow food production to meet the requirements of an increasing population. Low land productivity in SSA is partly due to low nutrient availability in soil; it is estimated that 75% of soils in SSA are nutrient deficient (Toenniessen *et al.*, 2008). SSA is also the region of the world that uses the least fertiliser quantities, about 8 kg.ha^{-1} which is less than one tenth of the world average, mainly because they are not affordable to most farmers in the region (Smaling *et al.,* 2006; Chauvin *et al.,* 2012). The price of chemical fertilisers is actually much higher in Africa than in Europe because of transport costs (Jayne *et al.*, 2003). Sanchez (2002) gives the example of one metric tonne of urea which is between 3 to 5 times more expensive in Africa than in Europe depending on the distance of the country from a port. Agricultural intensification and expansion however is a major cause of land degradation in SSA (Tully *et al.*,

2015) so measures to increase land productivity must ensure soil health preservation to prevent further degradation.

When soil is used for agriculture the natural nutrient cycle is broken; during crop harvest the nutrients contained in the plants are removed instead of being returned to soil through the natural degradation path. It is therefore essential to replenish soils with nutrients when they are being used for agricultural purposes to prevent loss of soil fertility. Organic matter replenishment through the use of organic amendments such as such as compost, farm yard manure or sludge are essential for preserving soil health and can reduce the need for chemical fertilisers (Bationo *et al.*, 2007). The addition of nutrients must also be controlled to prevent nutrient losses and environmental pollution. A case study from the Bihar region in India for instance showed that about 70% of N that was applied to agricultural land was lost to the environment (Tirado *et al.*, 2012).

2.2.3 Finite resources of phosphorus

Nutrients provided by chemical fertilisers are most often produced from mineral sources. The three main components of fertilisers are the three macronutrients: Nitrogen, Phosphorus and Potassium (NPK). N is provided through ammonia obtained from N gas through an energy-intensive process, P is mined from phosphate rock and K is precipitated from salts. P reserves especially raise a concern because it is a limited resource and phosphate rock reserves are fast depleting. There is a debate regarding how long phosphorus reserves will last and when ‘peak phosphorus’ will be reached but there is no doubt that the amount of rock phosphate is finite (Steen, 1998). Cordell *et al*. (2009) predict that peak phosphorus will be reached around 2030 and show that with current consumption rates, the demand of phosphorus will increase between 50-100% by 2050 to meet increased global food demand. Another challenge with phosphate rock reserves is that they are concentrated in a handful of countries and in geopolitically sensitive areas (main sources are in Morocco, China and the US) (Rosemarin *et al.*, 2008). Finding alternative sources to phosphate rock as our primary source of fertiliser will become a necessity in coming years and recycling human excreta into soil as fertiliser is an attractive solution to this, especially in congested and resource-restricted urban areas. Human excreta are a valuable source of phosphorus since adults excrete almost 100% of the phosphorus eaten, with the highest concentration in the urine fraction (Drangert, 1998). Production of struvite (magnesium ammonium phosphate) from urine is attracting interest as phosphorus recovery method and to generate value from urine by producing phosphate fertilisers (Tilley *et al.*, 2009; Etter *et al.*, 2011). With ever increasing urban populations, it can be argued that excreta are the largest source of phosphorus in cities (Jonsson *et al.*, 2004; Cordell *et al.,* 2009). It is estimated that if all urine and faeces were collected and their phosphorus harvested, it could account for 22% of the global phosphorus demand (Mihelcic *et al.,* 2011). The composition of organic fertilisers is directly related to the organic matter it originates from and to the treatment process the material has undergone (Fuchs *et al.*, 2008), there is therefore a need to investigate the potential fertiliser products that can be obtained from organic materials such as human excreta and evaluate their quality.

2.2.4 Fertilising products that can be obtained from organic residues

A range of fertilising products can be produced from organic residues, including digestate, compost and vermicompost, which were the focus of this research. The production mechanisms and the properties of each of these soil amendments are detailed in the following sections.

Digestate

The anaerobic digestion process

Anaerobic digestion is a microbial degradation process made up of a succession of stages involving different bacteria in an environment free of oxygen. Some of the bacteria involved in the process are methane-producing bacteria (Pfeffer, 1980). The resulting product is biogas, a methane-rich gas which can be used in similar ways to natural gas. Digestate is the other product of the process, which contains all the nutrients present in the raw material before digestion and therefore constitutes a valuable fertiliser. Nutrients are broken down from the original organic matter through the chain of reactions that occur during anaerobic digestion, the components of the initial organic material become degraded into their building block basic components (Pfeffer, 1980). Nutrients end up in their most soluble form at the end of the digestion process, readily available for plants.

Nutrient content of digestate

During the digestion process no nutrients are lost, only the chemical form they are present in changes (Möller and Müller, 2012; Loria and Sawyer, 2005) compared the nutrient content of raw and digested swine manure these were found to be statistically identical and their long-term effect on soil was found to also be identical (Loria and Sawyer, 2005).

The process of anaerobic digestion reduces the concentration of organic N because it becomes mineralised in the digestion process. Kirchmann and Witter (1992) compared the ammonium content of fresh, aerobically and anaerobically decomposed animal manure and found that only anaerobically digested waste contained more than half of N in the form of ammonia, the most readily available form for plants. Digestate can therefore behave in similar ways to chemical fertilisers because the nutrients are in their most soluble and chemically available form. Furthermore Morris and Lathwell (2004) reported that the application of digestate yielded better growth of maize than chemical fertiliser in the early stage of crop growth.

Nutrients are present in mineral form after anaerobic digestion so it is hypothesised that this type of amendment is more susceptible to nutrient leaching than other organic amendments (Nkoa 2014). Chantigny *et al.* (2008) concurred with this hypothesis after growing maize on plots treated with swine manure digestate and plots treated chemical fertilisers and obtaining similar corn grain yields and grains with similar N and P content on all plots. Ammonia can easily volatilise if not stored in a closed environment, storage conditions and application rates for digestate therefore need to be carefully controlled to avoid N losses; it is even recommended to apply digestate in several doses to avoid nutrient leaching in soil (Smith *et al.*, 2014). The origin of anaerobic digestate substrates also directly affects the composition of the digestate obtained and so there is a higher risk of heavy metal contamination from digestate use than chemical fertilisers (Nkoa, 2014). There are few studies that have been carried out on the fertiliser value of digestates and as Möller and Müller (2012) point out, more detailed investigations are required to characterise the nutrient content of digestates with different feedstocks and their effect on soil.

Compost

- Overview of the composting process

Composting is an aerobic degradation process; it is a spontaneous microbial exothermic process involving a wide range of microorganisms and small invertebrates. The process consists of 4 successive stages that yield carbon dioxide, water and a humus-like material rich in organic matter which constitutes a valuable soil amendment. The temperature during the composting process initially rises rapidly and spontaneously through the microbial activity of the bacteria consuming the readily degradable material such as sugars and protein. Thermophilic microorganisms then become predominant once the temperature in the pile has reached between 50-70°C degrading more complex materials such as fats, lignin and cellulosic materials. A reduction in temperature then takes place giving rise to a recolonization of the medium by mesophilic organisms and further degradation and stabilisation of the organic matter (Diaz *et al.,* 2011). During these successive stages organic compounds are oxidised, nutrients are released and immobilised and new compounds are synthesized through microbial action (Insam and de Bertoldi, 2007).

- Compost operating parameters

Several operating parameters need to be controlled for an optimal composting process, namely pH, Carbon to Nitrogen ratio (C/N), moisture and porosity. One of the main factors contributing to the efficiency of composting is the C/N of the initial organic material; the initial balance of C and N concentration in material prior composting should be between 20 and 30 in order to provide the appropriate ratio of nutrients to the composting microorganisms during their growth. pH should be maintained between 6 and 7.5 to maintain a good operating environment for microbes and prevent N volatilisation which occurs if the pH is above 7.5 (Diaz *et al.,* 2011). Moisture is needed for bacterial growth and an optimal range is between 40 and 60% by weight; excess moisture inhibits oxygen transfer and anaerobic conditions can develop as a result inhibiting the composting process. Porosity in the composting pile is important for ensuring good aeration and oxygen transfer and the free pore space should ideally be between 35 and 50% (Bernal *et al.,* 2009).

- Compost nutrient content

The qualities of compost as a soil conditioner are known, its application leads to an increase in the organic matter and nutrients are provided through slow and gradual release (Insam and de Bertoldi, 2007). The latent nutrient benefits of compost are sometimes seen as a drawback by farmers, especially in poorer countries where farmers expect to see fast results from their investment. Several researchers therefore recommend enriching compost with chemical fertilisers providing additional nutrients in order to optimise crop yields after compost application (Adamtey *et al.*, 2009; Useni *et al.*, 2013).

One of the advantages of compost application is that nutrients are present in organic forms and therefore less prone to leaching. Maynard (1993) found that nitrate leaching to ground water occurred with compost applications (average 3.4 $mg.L^{-1}$ nitrate concentration in water) but nitrate concentrations in ground water were higher beneath control plots fertilised with chemical fertilisers (4.2 $mg.L^{-1}$), concentrations of groundwater nitrate remained under the regulatory limits with both treatments. Basso and Ritchie (2005) however reported higher mean annual nitrate leaching from plots treated with compost (35 kg NO_3–N ha^{-1} in alfalfa–maize and 30 kg NO_3–N ha^{-1} in maize–alfalfa) than those treated with chemical fertilisers (33 kg NO_3–N ha^{-1} in alfalfa–maize and 25 kg NO_3–N ha^{-1} in maize–alfalfa) in a 6 year experiment growing maize and alfalfa in rotation.

Compost production and application to soil has also been used as a measure for soil carbon sequestration in the context of climate change mitigation. Increases in soil carbon concentration have been measured after repeated applications of compost over several years (Eghball, 2002; Monaco *et al.*, 2008; Kukal, Rehana-Rasool and Benbi, 2009; Sodhi *et al.,* 2009). There is however evidence of greenhouse gas emissions (carbon dioxide and nitrous oxide) during composting, which could counteract the climate change mitigation benefits of compost application (Hao *et al.,* 2004).

Vermicompost

- Vermicompost process overview

The first commercial application of vermicomposting was developed in the UK in 1982 and has now spread worldwide for transformation of a wide range of organic materials using several species of earthworms (Edwards *et al.,* 2011). Vermicomposting is a degradation process with similarities to composting, which utilises earthworms, usually *Eisenia Fetida,* to degrade organic matter. Organic matter is digested jointly by worms and microorganisms and produce vermicompost, a humic-like substance with finer structure than compost. The microorganisms biochemically degrade the organic matter but the worms are instrumental in aerating and fragmenting the substrate and therefore increase microbial activity (Edwards *et al.,* 2011). Unlike compost, vermicompost occurs at ambient temperature, although these need to be close to mesophilic (10- 32^{o}C) for worm optimal worm activity and survival (Edwards *et al.,* 2011). Stabilised vermicompost should have a pH ranging between 5.5 and 8, moisture between 30 to 50%, organic matter content be greater than 20-25%, and C/N ratio below 20. Nutrient contents of vermicompost depend on their parent material but as an indication, Total N can range from 0.1 to 4%, NH_4-N should not exceed 10% of Total N, and P concentrations higher than 0.5% are desirable (Edwards *et al.,* 2011). Vermicompost is said to have advantages over compost, such as heavy metal reduction through assimilation by the worms (Atiyeh *et al.*, 2000; Pereira *et al.*, 2014). Nutrients are more readily available for plants in vermicompost because the process achieves a higher degree of mineralisation; it has been shown for instance to have a higher concentration of nitrates than compost (Atiyeh *et al.*, 2000; Sinha *et al.*, 2010).

- Effect of vermicomposting on soil and crops

Several studies have shown the beneficial effects of vermicompost on the productivity of several crops such as tomato (Atiyeh *et al.*, 2001; Gutiérrez-Miceli *et al.*, 2007), aubergine (Gandhi and Sundari, 2012), rice (Kale *et al.*, 1992) and pepper (Rodríguez-Canché *et al.*, 2010). Atiyeh *et al.* (2000) however found that excess application of vermicompost lead to reduced yields and growth of tomato plants and Roberts *et al.* (2007) reported that the addition of vermicompost to soil did not significantly increase fruit number, weight or yield of tomatoes. Arancon and Edwards (2011) produced vermicomposts from a range of organic materials (paper waste, cow manure, food waste) and tested their effect on a range of crops (tomatoes, strawberries, grapes and peppers) and showed yields from plots treated with vermicomposts were higher than those treated with chemical fertilisers but they also showed that the properties of vermicompost depend on the parent material and their effect varies depending on the crop type. It has also been shown that vermicompost can have disease preventing properties for crops through the action of bacteria and funghi present in vermicompost as well as promoting the microbial activity in the soil (Szczech, 1999; Masciandaro *et al.*, 2000; Gutiérrez-Miceli *et al.*, 2007). Sinha et al (2010) also claim that the lower operating temperatures of vermicomposting prevent ammonia volatilisation and hence allow for lower N losses and lower emissions of Nitrous oxide (a much more powerful greenhouse gas than carbon dioxide) than during the composting process. Frederickson and Howell (2003) however found that vermicomposting systems had the capacity to emit high levels of nitrous oxides, which were comparable to those from other waste processing methods. Nigussie *et al.* (2016) combined composting and vermicomposting and showed that the addition of a vermicomposting stage significantly reduced N losses and greenhouse gases emissions from composting. Worm feeding ratio during vermicomposting was also shown to have an impact the NO_2 emissions during treatment, higher feeding ratios lead to higher nitrous oxide emissions (Nigussie *et al.*, 2017)

2.3 The potential of fertiliser production from human excreta

A wide range of end products can be obtained from human excreta depending on the treatment applied on FS. These include direct products such as fertilisers, biofuel and building materials as well as products indirectly derived from excreta such as fish and plants, protein material (Kengne, *et al.,* 2014). The processes to produce organic fertilisers include anaerobic digestion, composting and vermicomposting.

2.3.1 Risks associated with human excreta reuse

Pathogens

Human excreta contain high concentrations of microorganisms (10^{11}-10^{13} microorganisms per gram of faecal material) and are a vector of a wide range of disease-causing pathogens (Schonning and Stenstroem, 2004). Most pathogens are contained in the faeces fraction of human excreta and some of these pathogens are highly resistant, they can survive for many months in soil (e.g. Ascaris eggs) (Feachem *et al.*, 1983; Schonning and Stenstroem, 2004) as shown in Table 2-1. The survival of pathogens in soil depends on several factors such as the temperature, moisture content of the soil, soil type, vegetation present, exposure to UV as well as the method by which it was introduced (Jacobsen and Bech, 2012).

Table 2-2 **Estimated survival times of pathogens during storage of faeces and in soil in days unless otherwise stated (norm. = normally) (from Schonning and Stenstrom, 2004)**

Microorganism	**Faeces and sludge 20-30°C (Feachem *et al., 1983)***	**Faeces T_{90} ~20°C**	**Soil 20-30°C (Feachem *et al., 1983)***	**Soil T_{90} ~20°C**	**Soil absolute max[i] / normal max**
Bacteria					1 year/ 2 months
Faecal coliforms	<90 norm. <50	15-35 (*E.coli*)	<70 norm. <20	15-70 (*E.coli)*	
Salmonella	<60 norm. <30	10-50	<70 norm. <20	15-35	
Viruses	<100 norm. <20	Rotavirus: 20-100 Hepatitis A: 20-50	<100 norm. <20	Rotavirus: 5-30 Hepatitis A: 10-50	1 year/ 3 months
Protozoa (*Entamoeba*)	<30 norm. <15[ii]	Giardia: 5-20 *Cryptosporidium:* 20-120	<20 norm. <10[ii]	Giardia: 5-20 *Cryptosporidium:* 30-400	?/2 months
Helminths (egg)	Several months	50-200 (*Ascaris)*	Several months	15-100 (*Ascaris)*	7 years/ 2 years

[i] Absolute maximum for survival is possible during unusual circumstances such as at constantly low temperature or in well-protected conditions

[ii] Data are missing for *Giardia* and *Cryptosporidium*; their cysts and oocysts might survive longer than the time given here for protozoa

All pathogens are sensitive to temperature; pathogens become deactivated and therefore harmless to human health above a certain temperature, variable between different microorganisms. Feachem *et al*. (1983) showed that there is a link between the temperature, time of exposure and pathogen deactivation and they developed correlations for most human pathogens present in waste water and human excreta, as illustrated in Figure 2-4. Pathogens can be inactivated by a short exposure to high temperatures but they will also be deactivated if they are subjected to lower temperatures for a longer period of time.

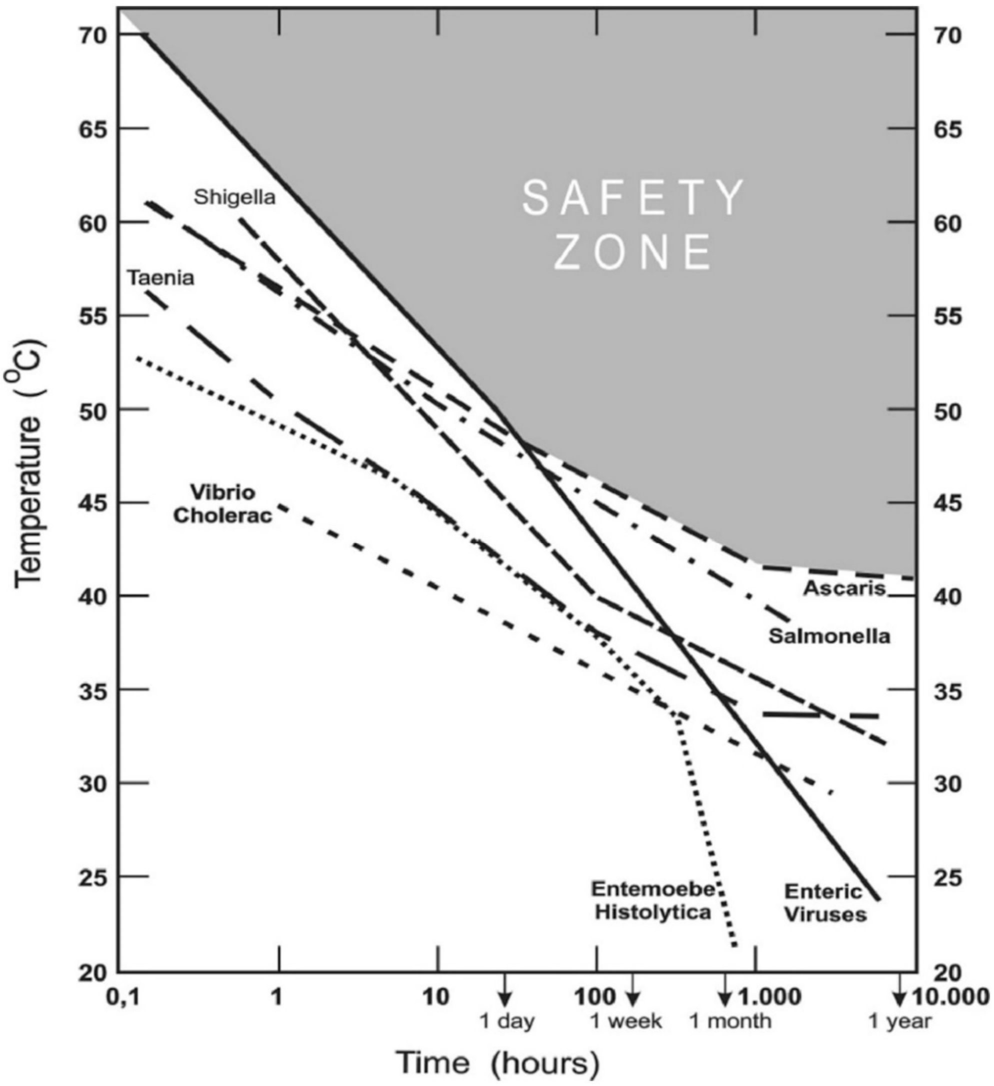

Figure 2-4 The "safety zone diagram" (Feachem *et al.*, 1983)

Pathogen deactivation must be achieved by treatment before released to the environment to avoid risks of contamination and preserve human health. Pathogens can be removed by biological, physical or chemical means. The level of pathogen reduction required depends on the end use that will be given to the FS with the highest level of removal required when FS is to be used in agriculture for horticultural crops (Kengne *et al.,* 2014). It is also essential that the treatment process chosen is carried out accurately and until completion otherwise pathogen inactivation cannot be guaranteed. Germer *et al*. (2010) for instance show the importance of appropriate management of a composting process; an opened composting pile with material with an unbalanced C/N did not reach temperatures high enough for pathogen inactivation (<55°C) whereas a pile with a balanced mix of initial materials and additional insulation reached temperatures above 55°C for 2 weeks which ensured pathogen inactivation.

Measuring pathogen content of wastes, the use of indicator organisms

Testing for the presence of all pathogenic organisms to ensure satisfactory removal would be too time-consuming and expensive in practice given the wide range of microorganisms present. Instead certain organisms have been selected as indicator microorganisms, and their presence and concentration is representative of the pathogenic population present in the waste. Indicator microorganisms of pathogenic faecal contamination must meet certain criteria: they have to be exclusively of faecal origin, be present in greater numbers than the pathogens of concern, be removed from faecal matter or wastewater in similar ways to pathogenic organisms and have clear and reliable ways of detection and enumeration (Mara, 2004).

In practice the indicator organisms of faecal material are coliform bacteria, helminths as well as bacteriophage as indicators of viruses. Coliform bacteria are pervasive in faeces and originate from the intestinal tract, their presence is therefore an indication of faecal contamination. There are tests that have been developed for the detection of total coliforms, faecal coliforms and *E.coli*, the latter having traditionally been used as the principal indicator of faecal contamination. There are however issues with this indicator since other bacteria from the *Escherichia* genus can grow in the environment and sometimes can interfere with tests (Niwagaba *et al.,* 2014). There is evidence that *E.coli* can be naturally present in the environment in tropical climates (Fujioka *et al.*, 1998a; Byappanahalli and Fujioka, 2004) and it is therefore argued that alternative indicator organisms are required. *Clostridium perfringens* can survive in water longer than other resistant enteric microorganisms and is therefore considered a suitable alternative indicator of faecal contamination (Medema *et al.,* 1997; Sidhu and Toze, 2009).

Pathogens in FS are also present as viruses, protozoa and helminths. Aside from coliforms, the most common indicators of pathogen reduction are helminths given their high resistance and prevalence in LMIC. The helminth most commonly used as an indicator is *Ascaris lumbricoides* because of the persistence and resistance to inactivation of its eggs. Ascaris eggs are the most resistant to treatment given their ability to survive in many environments and at a wide range of temperatures so a preferred method of measuring helminth inactivation is to determine the viability of the eggs present. Their detection involves the coproscopic method which applies a series of sedimentation, flotation, centrifugation and microscopic analyses (Moodley *et al.* 2008), making this detection method difficult to carry out in resource-limited environments.

Guidelines exist for the quality of treated human excreta required before their reuse, providing protocols for governments and organisations to follow worldwide and ensure reuse of excreta is realised in a safe manner (WHO, 2006). These guidelines however have limitations in certain environments and the pathogen limits set out by the WHO are not applicable worldwide. Limits for *E.coli, Salmonella* and helminth ova are set in the WHO guidelines for safe reuse of excreta. However, in tropical countries for instance coliforms are sometimes already present in soil from other sources than human faeces and are able to colonise the soil making them ineffective indicator organisms of faecal contamination. Fujioka *et al*. (1998) found that coliforms which are recommended as indicators of faecal contamination by the United States Environmental Protection Agency (USEPA) are naturally present in soil in Hawaii and Guam and their presence cannot therefore automatically be linked to faecal contamination. Forslund *et al*. (2012) grew tomatoes by drip irrigation using wastewater and when measuring *E. coli* concentrations they found a weak correlation between *E. coli* concentrations in wastewater and soil and no correlation between concentrations in wastewater and on tomatoes. According to the WHO guidelines, the practices used in the experiment were unsafe because of *E.coli* concentrations in the irrigation water above the recommended limits but their results show that the tomatoes obtained were safe for human consumption. This example showed limitations in the guidelines and the authors therefore called for a revision and improvement of the pathogen limits set by the WHO guidelines (Forslund *et al.*, 2012).

The WHO guidelines establish pathogen concentration limits for the reuse of excreta but there are no unified standard methods for the detection of pathogens in treated wastes, which is another challenge for demonstrating the safety of soil amendments derived from human waste and comparing them between different case studies. Sidhu and Toze (2009) highlight the need for standardised detection methods for pathogens in addition to standardised pathogen concentration limits in order to allow for comparable results between studies. The experiments carried out in this project used ISO standards for pathogen detection when available (ISO4832, 2006; ISO6579, 2012; ISO7937, 2004; ISO16649-2, 2001) or the most accepted detection methods in the sanitation sector when ISO standards did not exist (Moodley *et al.*, 2008).

Heavy metals

Heavy metals are components present in sewage sludge that cause major concern because of their environmental pollution potential. Certain heavy metals such as Cd can enter the food chain through soil hence regulations set limits for final concentrations allowed in soil amendments derived from sludge. Heavy metals present in sewage sludge from centralised wastewater treatment plants originate mostly from industrial wastewaters and urban runoff (Sharma *et al.*, 2017). Source-separated human excreta are unlikely to contain high concentrations of heavy metals besides those needed for functioning the human body. Cu, Cr, Ni and Zn are all essential elements for maintaining human health and are present in human excreta but are not in concentrations harmful to humans (BNF, 2018; Vinnerås *et al.*, 2006). Vinnerås *et al.*, (2006) characterised the sources of heavy metals from building blocks in Sweden that used urine-diverting toilets and found that grey water had significantly higher concentrations of heavy metals than urine and faeces. It is however not uncommon to find discarded solid wastes in OSS systems, especially in pit latrines with deep vaults (Niwagaba *et al.,* 2014; Odey *et al.*, 2017). These materials could be a source of heavy metal contamination of FS, especially if batteries have been discarded. IWMI and Sandec (2002) for instance showed evidence of Pb contamination in composting piles, which probably originated from discarded batteries. Contamination of sludge with solid wastes and potentially heavy metals less likely to occur in CBS systems given that excreta are only containers are smaller and collected every few days.

Emerging pollutants

Human activities generate new types of pollutants, which often find their way into wastewaters and excreta. These are broadly classified as emerging contaminants and include anti-biotic resistant microorganisms, new synthetic compounds and organic contaminants. These components are new and hence knowledge of their properties, potential toxicity and effects and persistence in ecosystems is limited (Bolong *et al.,* 2009). The presence of organic contaminants in biosolids for instance is increasingly a concern given that some of these have endocrine-disrupting properties but soil toxicity data of these compounds is limited and there is no consensus on their effect on human health (Smith, 2009; Verlichi *et al.*, 2015, Thomaidi *et al.*, 2016). New regulations and concentration limits for organic contaminants in biosolids are being developed to prevent negative health effects but the substances regulated and limits associated vary greatly between countries (Chang *et al.,* 2009; Smith, 2009). Smith (2009) argues that the concentration of organic contaminants has decreased in recent years due to more stringent regulations and technologically-advanced wastewater treatment mechanisms but also states that ongoing research, monitoring and assessment is needed for identifying new organic contaminants and evaluating their potential toxicity. After carrying out a risk-based analysis on the presence of emerging organic contaminants in biosolids from wastewater treatment plants in Greece, Thomaidi *et al.* (2016) also call for additional research to be carried out on the degradation and long-term fate of organic pollutants in the soil environment but also for stricter regulations of these compounds in the European Union, especially synthetic phenolic compounds (SPCs) and siloxanes (SLXs).

~~Similarly to heavy metals, most organic contaminants in wastewater originate from industries, household grey water and surface run-off (Smith, 2009). Chemicals originating from personal care products (PCPs) and pharmaceuticals~~

~~are most likely to be present in human excreta and their fate during treatment and effect on soil are being researched.~~

Certain treatment methods can degrade emerging contaminants: Xia and Pillar (2003) analysed biosolids from 12 wastewater treatment plants and resulting composts and found that composting significantly reduced the concentration of 4-nonylphenol (4-NP), one of the most detected non-naturally occurring endocrine disruptor. Malmborg and Magner (2015) characterised the fate of 23 pharmaceutical residues during anaerobic digestion finding that the digestion process reduced the concentration of these organic substances by 30% on average. Complex analytical methods and equipment are currently required to detect organic pollutants since they are usually present in very low concentrations. Methods are being researched and developed to simplify analytical procedures, reduce analytical times and increase compound selectivity (Zuloaga *et al.*, 2012; Dimpe and Nomngongo, 2016; Ferhi *et al.*, 2016).

2.3.2 Nutrient content of treated human excreta

Human excreta are composed of urine and faeces, which have different properties. Nutrients are mostly concentrated in the urine fraction of excreta, containing 70-90% of N, 70-95% of the K and 45-80% of the P in human excreta (Vinnerås *et al.*, 2003). Nutrients are present in soluble form in urine and hence readily available to plants. Faeces on the other hand are rich in P and K and contain N too but in organic form and needs to be mineralised before it can be assimilated by plants (Vinnerås *et al.*, 2003).

The exact nutrient content of human excreta is difficult to predict because it depends widely on the dietary habits of the local population (Drangert, 1998; Rose *et al.*, 2015). It was found for instance that the composition of faeces in Burkina Fasso was different to that of human excreta from Sweden (Esrey *et al.*, 2001; Kiba, 2005). Nutrients present in organic waste can be present organic form, immobilised by organic molecules, or in mineral form, readily available to plants. Nutrients become unavailable when bound to organic molecules of microbes and are released when the microoganisms die off and degrade (Bassan *et al.,* 2014). FS tends to contain high concentrations of ammonia N, which is one of the main nutrients required by plants but can also be a pollutant if discharged indiscriminately in the environment. Excess ammonia in water can cause algal blooms and potentially damage ecosystems and therefore should not be applied indiscriminately to soil. It is important to characterise the nutrients present in human excreta and its derived fertilisers to apply them to soil in a safe and environmentally sound manner.

The opportunity in HEDF lies not only in its nutrient content but also in its organic matter composition. In a field experiment Guzha *et al*. (2005) showed that fertilisers from human excreta increased maize crop production and crop water use efficiency. The urine and faeces produced by a human annually contain enough plant nutrients to grow 250 kg of cereals, which could theoretically fulfil the nutritional needs of one person over a year (Drangert, 1998).

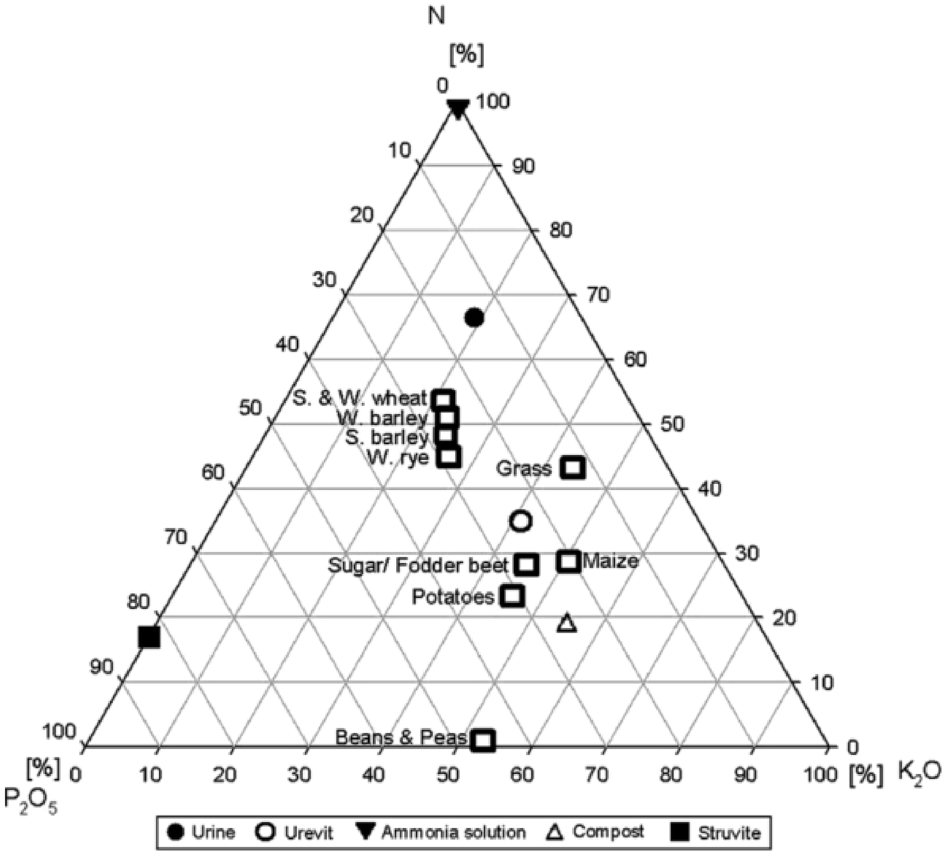

Figure 2-5 Nutrient compositions in fertilising products from new sanitation systems and nutrient requirements of common European crops. P is shown as

P_2O_5 and K as K_2O to achieve a better visual distribution in the graph. (Urevit is concentrated urine) (reproduced from Winker *et al. (2009)*

Winker *et al.* (2009) showed the potential of several HEDF to meet the nutrient demands of several crops. C^{HEDF} for instance could meet the NPK demands for beans and peas, Urevit, concentrated urine, could meet those of beet and potatoes and urine could meet macronutrient demands of wheat, barley and rye. There is therefore a great opportunity in producing and using HEDF in agriculture for creating incentives to treat FS and improve soil health.

Digestate from human excreta

Deriving anaerobic digestion from animal manure and sewage sludge from centralised wastewater treatment plants is common practice and the effects of sewage sludge digestate on land are well characterised (Tambone *et al.*, 2010; Nkoa, 2014). There are however few studies reporting the properties or effects of anaerobically digested source-separated digestate. Owamah *et al*. (2014) investigated the properties of human-excreta derived digestate with the organic material originating from digestion of human excreta and food waste mixed at a one to four mass ratio. They found that the digestate contained human pathogens (*Salmonella, Klebsiella spp.* and total coliforms) at concentrations above levels safe for direct application on farmland (Owamah *et al.*, 2014). Bonetta *et al*. (2014) also highlight the risk of pathogen transmission through land application of co-digestion digestate. Anaerobic digestion operates best at low solids concentration and the digestion of human excreta and household organic waste most often requires addition of large volumes of water, up to 100L daily for a 4 person household digester, which limits the feasibility of anaerobic digestion to areas where water scarcity is not an issue (Smith *et al.*, 2014)

Composting human excreta

The feasibility of transforming municipal solid waste (MSW) into compost has widely been studied and the beneficial effects of the MSW derived compost on soil have been characterised in detail (Shiralipour *et al.,* 1992; Montemurro *et al.*, 2005; Mulaji Kyela, 2011). There has been an interest in recent years in studying more specifically the composting of FS, which is less well known and understood

(Odey *et al.*, 2017). The use of composting for treating human excreta is particularly appealing because of the thermophilic nature of the process: temperatures naturally rise to levels adverse to the survival of enteric microorganisms and pathogen inactivation can be guaranteed if temperatures are maintained above 55^{o}C for several days (Bassan *et al.,* 2014). USEPA rules state that maintaining a temperature above 55^{O}C for 15 days achieves sufficient pathogen removal (Walker *et al.*, 1994).

As discussed previously, faecal matter is relatively high in N and moisture and hence composting of human faeces alone is not feasible because of an unbalanced C/N ratio of the initial organic material, which doesn't allow sufficient microbial growth for the temperature to increase (Niwagaba *et al.*, 2009). It is therefore recommended to add other carbon-rich organic material for composting human excreta. Additional material can be MSW, which is usually dry and high in C content or agricultural waste preferably low in lignin which is harder to degrade; rice straw for instance is a better co-composting material than corn stalks or straw, which are made of tough cellulose (Ronteltap *et al.,* 2014). Cofie *et al*. (2009) evaluated the best human excreta and MSW ratios for composting and the optimal operating conditions by testing different wastes and ratios and found that MSW was preferred over simple household waste and the optimal ratio of MSW to human excreta was 2:1. Germer *et al*. (2010) also showed the potential of co-composting human excreta but they highlighted the need for appropriate infrastructure such as confinement in chambers to prevent heat dissipation and allow temperature to increase in the pile. There was no temperature increase in open piles but when composting was carried out between brick walls, temperature increased and pathogen removal was realised. Sossou *et al*. (2014) demonstrated the pathogen removal efficiency of the composting process when treating human faeces, no Ascaris eggs were found after 30 days of composting

Vermicomposting and pathogens

Unlike composting, vermicomposting is not an exothermic process and the maximum operating temperature for most types of worms is below 35^{o}C. This processing temperature alone cannot ensure pathogen inactivation in the timeframe of the vermicomposting process. Some experiments however have shown a reduction in pathogen concentration through vermicomposting. Rodriguez-Canche *et al* (2010) report a reduction of pathogens to a level below the regulatory limits by the action of the worms on pig slurry and Eastman *et al*. (2001) showed that vermicomposting could achieve a fourfold reduction in faecal pathogens in class B sewage sludge biosolids[1]. Monroy *et al*. (2009) concur with these findings but also show that the extent of pathogen reduction is dependent on the ratio of waste to worms and warn of a risk of reinfection if the dose of pathogen-containing waste is too high (Eastman *et al.*, 2001; Monroy *et al.,* 2009; Rodríguez-Canché *et al.*, 2010). It is hypothesized that pathogen reduction through vermicomposting occurs from antibacterial substances such as hydrogen sulphide, ammonia or nitrates produced during vermicomposting but more detailed studies are needed for understanding the mechanisms involved (Edwards and Subler, 2011)

Combining the composting and vermicomposting processes would be beneficial for taking advantage of the sanitizing aspect of composting as well as the added benefits of vermicomposting in terms of nutrient and microbial content. Worms also require specific environmental conditions and cannot survive in faeces alone; temperatures need to range between 20°C and 35°C and humidity between 65% and 85 % (Shalabi, 2006; Yadav *et al.,* 2010). It has been shown that overall processing time is shorter when combining the two degradation processes pathogen reduction is guaranteed and the final product obtained has a better quality with a wider range of nutrients in available forms for plants than in compost (Ndegwa and Thompson, 2001; Alidadi *et al.*, 2005; Begum, 2011).

All these properties make vermicompost an attractive end-product from human excreta not only for its positive effects on soil but also its higher commercial value. There are few reports of vermicomposting of human faeces directly (Yadav *et al.,* 2010), most combine composting and vermicomposting.

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[1] Biosolids are classified as class B by the USEPA when biosolids contain detectable levels of pathogens but at concentrations that do no pause a public health threat. Land application of class B biosolids is permitted with restrictions to prevent human exposure to pathogens.

2.3.3 Research gaps in HEDFs investigation

It is recognised that HEDF have beneficial effects on soil in particular by increasing soil organic matter content although their exact nutrient content and effect on soil has not always been investigated in detail (Cofie *et al.* 2005). The application of HEDF to soil has been realised for centuries but their effect is not well characterised and there are still knowledge gaps in the properties of HEDF as Winkler *et al.* (2009) point out. The properties of certain human excreta derived products such as urine are well known, those of concentrated urine and struvite are known to some extent but the properties of digestate and compost derived from human excreta have not been studied in detail (Winker, Vinneras, *et al.*, 2009). Peer-reviewed reports of scientific research on the effects HEDF on soil and crops are scarce (Moya *et al.*, 2017).

A number of sanitation ventures have emerged in recent years as a response to the global sanitation crisis, in an effort to meet the SDGs and encouraged by donor's programs such as the Bill and Melinda Gates foundation's 'reinvent the toilet' challenge (Kone, 2012). This program has provided funding for several organisations, which are now implementing their systems in many low-income countries. These ventures aim to provide complete sanitation solutions: from supplying toilet infrastructures to waste collection, treatment and valorisation. Many of these such as SOIL in Haiti (Kramer *et al.,* 2013), Sanergy in Kenya, Clean Team in Ghana, Safi Sana in Ghana, BRAC in Bangladesh (Ubaid *et al.*, 2015) or X-runner in Peru have chosen to treat their waste by composting and sell the compost to local farmers. No certifications for C^{HEDF} exist in any of these countries apart from Bangladesh where the certification process is complex and lengthy (Evans *et al.*, 2015). The most important factors for the marketing of HEDFs is to ensure the absence of pathogens and characterise their nutrient content and effect on soil and crops.

It has been proven that pathogen inactivation is possible through composting of human excreta in field conditions, Berendes *et al*. (2015) found that a composting process in Haiti was effective at inactivating both *E.coli* and Ascaris spp within 16 weeks through a composting treatment process. The studies found in literature which measure the pathogen content of HEDF deal with the organic products prior to application to land (Eastman *et al.*, 2001; Koné *et al.*, 2007; Cofie *et al.*, 2009; Owamah *et al.*, 2014; Sossou *et al.*, 2014). Further, peer reviewed studies investigating the presence of human pathogens in soil are from cases where FS was applied directly onto fields with no or little prior treatment (Cofie *et al.,* 2005; Jensen *et al.*, 2008); no studies investigating soil pathogen content after application to soil of HEDFs were found in the literature.

There are also few reports of field crop trials with HEDF. Guzha *et al*. (2005) carried out a complete randomised complete block (RCB) field trial with maize as a test crop in Zimbabwe applying four different treatments: source-separated urine, humanure (faecal matter from urine diverting toilets) with subsequent urine applications and chemical fertilisers to grow corn. The plots treated with humanure and urine yielded the tallest plants with longest leaves and the highest yield compared to the other 2 treatments as well as the best water use efficiency (volume of water used per unit weight of crop produced) (Guzha *et al.,* 2005). Adamtey *et al*. (2010) evaluated the effect of several organic amendments on water use efficiency of maize in Ghana: MSW compost, dewatered FS, co compost of dewatered FS and MSW as well as N-enriched versions of the previous amendments. They found that N-enriched co-compost gave a higher dry matter yield, grain yield, transpiration efficiency and water use efficiency than chemical fertiliser and the other organic soil amendments. Mnkeni and Austin, (2009) evaluated the fertiliser value of 'human manure', dry faeces from urine-diversion toilets, in a crop trial with cabbage in South Africa applying goat manure, human manure at different rates and chemical fertiliser arranged in a RCB design. The highest cabbage yield was obtained with chemical fertiliser application and yields from human manure plots were higher than those of plots treated with goat manure. The authors hypothesised that the difference in the effect of goat and human manure could be attributed to higher levels of P and K release of human manure making these nutrients more readily available to the crop. These studies confirm the fertilising potential of C^{HEDF} and its positive effect on soil. No studies were found in the literature determining the fertiliser potential of digestate or vermicompost HEDF.

Few comparative studies between the nutrient content and effect on soil of different organic fertilisers from one same source material were found in literature. A comparative study comparing different organic soil amendments was carried out by Tambone *et al*. (2010) aiming to characterise digestates obtained from different organic materials from farming industries and municipal organic waste and wastewater. They compared the chemical, spectroscopic, and biological characteristics of digestates with those of compost and digested sludge and found the properties of digestates depend strongly on the materials they originate from whereas composts obtained from two different mixes of organic waste (100% ligno-cellulosic residues and mixed ligno-cellulosic residues and the organic fraction of MSW in a 1:2 ratio) had similar properties.

This research proposes to investigate the fertiliser value of human excreta products by comparing the nutrient content and effect on crops of different FS treatment products and studying the evolution of nutrients through different stages of treatment. The fertilisers will come from the Loowatt's pilot site in Madagascar; three different HEDF are obtained from one same source, enabling tracing of nutrient and pathogen evolution through the different treatments.

2.4 **Marketing of human excreta derived products**

Most sanitation businesses in LICs count on commercialising treatment by-products to cross-subsidise sanitation costs, which often proves difficult because of the lack of existing local markets for these products (Graf, Olivier and Brossard, 2014). In the case of fertiliser products, even though their positive effect on crops and soil is known, HEDF have often been reported to be hard to market profitably in LICs because of the often low willingness to pay of customers for waste-derived products (Danso *et al*., 2002). There are several barriers to the marketing of organic fertilisers, usually related to little local knowledge about these types of amendments and lack of information available or misinformation. Rouse *et al*. (2008) highlight the importance of a well-planned marketing strategy when it comes to selling compost because there are often misconceptions around it and its qualities. Most farmers know little about the properties of compost and expect it to have an effect on the productivity of their soil in the same timeframe as chemical fertilisers. When compost is produced from waste there is also often a stigma around it and its benefits are little appreciated (Rouse *et al.,* 2008).

The reuse of human excreta often faces stigmas and prejudices and many people reject the idea of recycling it because of a feeling of disgust towards it. Dellström Rosenquist (2005) studied the psycho-social relationship between humans and faeces and highlighted the need for sanitation products to fulfil the needs perceived by consumers which are most often not related to the product’s functionality. A study in Ghana showed some strong prejudices against HEDF use, 67% of the respondents to an interview in a rural area think that sanitised human excreta should not be used as fertiliser and 61% said they would never consume vegetables fertilised with sanitised human excreta. Cofie *et al*. (2005) on the other hand in another study in Ghana found that the availability of human excreta was the only limit perceived by local farmers for its reuse in agriculture. These two studies were carried out within the same country and found opposed perceptions to human excreta reuse showing that people’s attitudes towards human excreta are sometimes relative and vary between communities.

Schroeder (2011) analysed the market potential of HEDF in Uganda and found resistance from local farmers towards the reuse of human excreta as fertiliser. The study also points out the logistical issues related with transport of HEDFs because of their low nutrient content per unit weight compared to chemical fertilisers making transport a prohibitive cost for their marketing. The lack of adequate infrastructure for transporting liquid fertilisers is also another issue for marketing them in low income settings. Schroeder also found that 80% of Ugandan farmers are small scale farmers who don’t have the means to purchase HEDFs, making them the least attractive target customers for sanitation by-products. Larger scale farmers could therefore be more attractive target customers as well as landscape architects or real estate developers (Danso *et al.,* 2002).

It is clear that marketing HEDFs successfully is a challenging task. The success of a product depends widely on the location where it will be marketed and how well it is targeted to the local customers. Diener *et al*. (2014) investigated the marketing potential of different FS products and found that fertilisers are probably less profitable than energy recovery options. There has been a surge in recent years in business model research for sanitation, highlighting the need for innovation to achieve economically viable sanitation businesses (Graf *et al.*, 2014; Rao *et al.*, 2016, 2017).

2.5 Conclusions and research outline

The main points found through the present literature review are:

- That a fertiliser and sanitation crisis need addressing in SSA and the reuse of treated human excreta for agricultural purposes is an attractive solution to both issues.
- There are several fertiliser products that can be obtained from human excreta such as anaerobic digestate, compost and vermicompost. Although the properties, benefits and potential drawbacks of these soil amendments are known, their specific effects on soil when derived from human excreta haven’t been investigated in detail.
- There are few studies comparing the properties and effects of different types of organic fertilisers from the same source and no such comparative studies were found from HEDFs.
- Organic fertiliser marketing can be difficult in LICs and additional challenges are faced when fertilisers are derived from human excreta.

Based on these findings this study therefore set forth to evaluate and compare the nutrient content and effect on plants of three distinct HEDF obtained from one same source, digestate, compost obtained from digestate and vermicompost originating from compost. The three HEDF are derived from one another and so the evolution of nutrients from one treatment stage to the next will be studied. Pathogen studies will also be carried out to determine the safety of the final products obtained.

The aim of producing HEDF is to bring them to market and generate profit. However, many sanitation ventures find themselves in a situation where the local market conditions are unfavourable for organic fertiliser marketing and the final product has to be given away or sold at a loss. Another aim of this research is therefore to explore the barriers and enabling conditions that exist for the commercialisation of HEDF.

3 CHARACTERISING FERTILISERS DERIVED FROM HUMAN EXCRETA: TRENDS IN PATHOGENS, HEAVY METAL AND NUTRIENT CONTENT IN TWO SUB-SAHARAN AFRICAN NATIONS

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Abstract

Soil amendments from human excreta have been produced for centuries but reservations remain for their use in agriculture. In some countries assurance schemes specific to biosolids have been developed to ensure product quality and increase customer confidence. In cities where sewage networks do not reach the entire population, companies collecting and treating excreta are expanding. These companies are facing similar barriers of lack of confidence in the end products of sludge treatment. In this project, the product validation method specified in the Biosolids Assurance Scheme (BAS), developed by water companies in the UK, was applied to HEDF produced from source-separated human excreta from two companies in SSA. All the HEDF tested complied with heavy metal limits of a range of international regulations. Laboratory analyses showed efficient pathogen elimination through the treatment process for one of the sites. A recontamination issue was identified in the other site by following the BAS sampling schedule. Nutrient variability between batches was observed for all HEDFs. This was expected given that HEDFs are derived from organic materials, which inherently vary in composition depending on seasons, location and diet in the case of excreta. The value of adopting an assurance scheme was highlighted by the differences observed between sites and the identification of a contamination issue, suggesting that the creation of an assurance scheme specific to HEDF could be beneficial for improving their acceptance and commercialisation.

Keywords: human excreta, compost, fertiliser, pathogen, soil nutrient, heavy metal

The formatting of the original published manuscript has been adjusted to fit the format of this thesis.

3.1 Introduction

Recycling human and animal excreta into soil as soil amendments has been realised for centuries (Tajima, K., 2007). In the UK until the late 19th century human excreta were collected in cities as ‘night soil’ and sold as fertilisers (Velis *et al.*, 2009). Direct recycling of human excreta is still common practice in certain parts of the world such as Vietnam and Southern China (Jensen *et al.*, 2008). In the 20th century many Western countries built centralised sewage systems and wastewater treatment plants where excreta are mixed with grey water and industrial wastewaters. The remaining sludge can be treated and applied to land as biosolids. Currently in the UK for instance, nearly 80% of biosolids are applied to soils following Safe Sludge Matrix guidelines (Water UK, 2006). Unfortunately, many parts of the world still lack appropriate wastewater collection and treatment infrastructures (UNICEF and WHO, 2017). As a result, FS often ends up discharged untreated to the environment creating a threat to human and environmental health (Strande, 2014). Thermal treatments such as composting, eliminate harmful pathogens and transform human waste into a soil amendment rich in organic matter and nutrients with beneficial effects on soil and plants (Cofie *et al.*, 2009). There are, however, challenges with the perception of products derived from human excreta and an overall scepticism of the quality and safety of the products produced, whether in low or high-income countries despite regulations for the reuse of biosolids being in place (Krogmann *et al.*, 2001; Gale, 2007). In the UK the Biosolids Assurance Scheme (BAS) was developed in 2013 to ensure that biosolids recycling to land is transparent and subject to external controls (Water UK, 2013). This initiative came from the water utilities to provide evidence and assurance of the quality of their products and thereby increase customers’ confidence. It specifies additional criteria to those set out by regulations to ensure the production of high quality biosolids safe to use on agricultural land. The scheme sets out detailed testing schedules, limit values for pathogens and heavy metals as well as best practice guidelines for handling and application to land of biosolids produced from sewage sludge.

The aim of this project was to characterise the properties of different HEDF, evaluate their variability between batches in terms of key performance indicators and assess their conformity with the BAS scheme and current international regulations. This was achieved by analysing the nutrient, pathogen and heavy metal content of four different HEDFs (D^{HEDF}, V^{HEDF} and two C^{HEDF}) following the sampling and testing procedures set out in the BAS guidelines.

There are a range of potential contaminants in human faecal matter that can have major negative effects on human health hence the general caution and scepticism surrounding HEDF use in agriculture. The major components of concern are summarised below.

3.1.1 Heavy metals in biosolids

Heavy metals are a potential environmental pollutant if present at high concentrations; it is particularly of concern in soil and water since these metals can translocated from soil onto crops for human consumption. Heavy metal content is one of the major concerns regarding the use of biosolids on agricultural land (Singh and Agrawal, 2008). Biosolids originating from centralised wastewater treatment plants are more likely to have significant heavy metal loads since the incoming wastewater is a mix of household black water but also industrial wastewaters and urban run-off, which can be contaminated with heavy metals (Balmer, 2001; Tilley *et al.*, 2014, Sharma *et al.*, 2017). Certain heavy metals are present in the diet and are needed for healthy human functioning; Cu, Cr, Ni and Zn for instance are essential elements whereas Pb, Cd and Hg are not (Vinneras *et al.,* 2006; BNF, 2018). In a study carried out by Vinneras *et al.* (2006) comparing the quantity of heavy metals present in urine, faeces and grey water in building blocks equipped with dry urine-diverting toilets, it was found that the largest portion of heavy metals was in the grey water portion of household wastewater. It is therefore anticipated that HEDF should not have high concentrations of heavy metals since heavy metals should only originate from human excretions and therefore should not be present in concentrations harmful to humans. Indeed, in an experiment Adamtey *et al* (2009) mixed organic MSW and FS and showed that the resulting compost complied with heavy metal limits set by international standards summarised in Hogg *et al.* (2002).

3.1.2 Pathogens

Pathogens are usually the main concern when dealing with FS and designing the production process of sludge derived products since inadequate treatment could create significant contamination and health risks. Composting is effective in eliminating pathogens given its thermophilic nature. The composting process naturally heats up to temperatures at which enteric microorganisms cannot survive and when those temperatures are maintained for a certain period of time, all pathogens including the most resistant ones are inactivated (Figure 2-4) (Bassan *et al.*, 2014). It is not possible to test for all microorganisms so indicator organisms are chosen to represent the presence of harmful pathogens in sludge. Indicator organisms can be pathogenic or non-pathogenic but they need to fulfil specific criteria: (i) exclusively present in human excreta in higher concentrations than the pathogen of concern, (ii) more resistant than the pathogens of concern, (iii) measured reliably through a simple and inexpensive method and (iv) their removal mechanism needs to mimic that of the pathogen of concern (Mara, 2004). Regulations set final pathogen limits for specific indicator organisms: typically *E.coli*, *Salmonella* and Helminth ova. Faecal indicator organisms however behave differently in temperate and tropical climates with different survival rates in soil and water (Rochelle-Newall *et al.*, 2015). In tropical countries, some indicator microorganisms such as *E.coli* and enterococci may even already be present in the environment without necessarily being of faecal origin (Fujioka *et al.*, 1998; Byappanahalli and Fujioka, 2004). *Clostridium perfringens* has been shown to survive in surface water for longer than *E.coli*, faecal enterococci and oocysts and is more resistant to treatments; it is therefore considered as one of the most conservative indicators of bacterial faecal contamination (Medema *et al.*, 1997; Sidhu and Toze, 2009). *C. perfringens* was hence chosen as one of the indicator for pathogens of faecal origin in this study in addition to *E. Coli,* faecal coliforms, *Salmonella* and helminth eggs.

3.1.3 Emerging pollutants

New types of pollutants emerging from human activities such as organic contaminants, endocrine-disrupting components or antibiotic-resistant microorganisms are classified as emerging pollutants and their accumulation in biosolids raises concern. Most organic contaminants that are channelled to wastewater treatment plants originate from industrial sources, surface run-off, or domestic grey water; organic contaminants are therefore unlikely to be a concern with wastes originating from source-separated human excreta (Smith, 2009). The chemical contaminants most likely to be present in human excreta are pharmaceuticals and personal care products (PPCPs, their fate during treatment and after application to soil is a topic that is increasingly attracting attention (Xia *et al.*, 2005; Topp *et al.*, 2008; Wu *et al.*, 2010; Bischel *et al.*, 2015; Verlicchi and Zambello, 2015; Thomaidi *et al.*, 2016). In an experiment Xia and Pillar. (2003) showed that composting had potential for removing 4- Nolyphenol, a type of non-naturally occurring endocrine disruptor. Malmborg and Magner (2015) showed that anaerobic digestion also has the potential of reducing the concentration of a wide range of organic substances, by 30% on average on 9 out of 14 pharmaceuticals tested (Malmborg and Magner, 2015). The analytical methods for detecting this type of contaminants in sludge are still being developed, which constitutes the main issue with regulating these substances (Zuloaga *et al.*, 2012; Dimpe and Nomngongo, 2016; Ferhi *et al.*, 2016). These analyses require advanced equipment, which was not available in the locations where experiments were carried out so the presence of emerging pollutants in HEDF could not be evaluated in this study.

3.2 **Study context and objectives**

In this study it was proposed to analyse HEDFs produced by two sanitation ventures in SSA, which collect and treat waste from dry toilets in urban slums. Company A (CA) currently produce 300 tonnes of C^{HEDF} per year from human faeces collected from urine-diverting dry toilets where faeces are mixed with a carbon source such as sawdust. These faeces are mixed with additional organic matter such as food or agricultural wastes, varying according to seasonal availability. Composting is carried out in windrows (1.5m high, 2m wide), watered from a well on-site and turned mechanically with an automated windrow turner. The frequency of turning and watering is adapted according to the composting stage with more frequent turns at the initial thermophilic stage (daily) than in the maturation stages. A multi-stage internal quality control process is in place to ensure adequate product quality is achieved. Temperature and carbon dioxide (CO_2) concentrations are monitored daily and moisture measured weekly to ensure the thermophilic phase and maturation proceed as required and a stable product is obtained. Pathogens are tested for twice in the production process, after the thermophilic phase and at maturity before the C^{HEDF} is approved for packaging and sale. pH and electrical conductivity tests are carried out three times throughout the production process and lime is used to correct the pH of C^{HEDF} (between 6.5 and 8.5) before packaging if needed.

Company B (CB) currently produce D^{HEDF}, C^{HEDF}, V^{HEDF}. This system treats both faeces and urine unlike CA's system. Excreta are first anaerobically digested along with additional organic matter such as restaurant food waste. Water is also added to achieve the desired consistency for the digestion and the mixture is pasteurised (at >72 ^{o}C) prior to entering the anaerobic digester. The resulting digestate is then transported to the composting site where it is mixed with rice straw and composted. Once the thermophilic phase of composting is complete, the 'pre-compost' is fed to *E. Fetida* worms and vermicompost is obtained one week later. Temperature is continuously monitored across the whole treatment chain and moisture and pH are also recorded regularly in the composting stages. The quality control mechanism in the CB treatment process was still being developed when this study was carried out and regular testing schedules were not yet in place.

3.3 **Materials and methods**

The validity of the compost production process was evaluated by following the procedure set out in the BAS guidelines. The sampling procedure for the compost product followed throughout this experiment was that described in the BAS standard, which states “At least five sampling events […] must be commenced on different days and completed over a 10 - 60 day test period.” (BAS, 2016).

HEDFs from two different companies were tested following this procedure. In CA, 15 discrete C^{HEDF} samples were taken over a 30-day period, from 5 different composting windrows which had all reached maturity according to the company’s internal quality control verification. Samples were taken from 3 different points along each windrow and at different depths (at the surface and the middle of the windrow (approx. 50 to 70cm depth)). Nutrient analyses for samples collected from CA were carried out in an ISO 17025 certified laboratory specialised in soil analyses. The analyses carried out were: electrical conductivity (EC) and pH (ISO10390, 2005), dry matter (ISO11465, 1993), total carbon (BSEN13039, 2011), Total N by modified Kjeldahl method (ISO11261, 1995), total P (ISO14869-3, 2017) , exchangeable phosphorus (ISO11263,1994), ammonium and nitrate N (ISO14255,1998), cation exchange capacity and exchangeable micronutrients (K, Ca, Mg, S, Mn, Fe, Zn) (ISO23470, 2007) and total elements (K, Ca, Mg, S, Mn, Fe, Zn, Cu, and Na) were measured by atomic emission spectrometry (ISO22036, 2008; ISO14869-3, 2017). Pathogen analyses were carried out in an ISO 17025 accredited laboratory, *E. coli* (ISO16649-2, 2001), Faecal coliforms (ISO4832, 2006), *Salmonella spp* (ISO6579, 2012), *Clostridium perfringens* (ISO7937, 2004) were tested for in each sample. Helminth analyses were carried out in CA’s in-house laboratory since laboratories with such capacity did not exist locally.

In CB three different HEDF where tested, namely D^{HEDF} (liquid form), C^{HEDF} V^{HEDF}. Samples were taken every 6 days over a one-month interval and from different batches, 7 V^{HEDF} samples, 5 D^{HEDF} and 3 C^{HEDF} samples. 3 samples were taken from each batch and analysed separately. Only 3 C^{HEDF} samples were taken because the composting process lasted only 4 to 5 weeks, it is not a final mature compost and therefore was not considered as a product stream. Nutrient analyses in CB were carried out in a university laboratory in location B specialised in soil testing. The D^{HEDF}, C^{HEDF} and V^{HEDF} were analysed for pH (ISO10390, 2005), organic Cn (ISO14235,1998), available N (ISO14255,1998), Total N

(ISO11261, 1995), available P (ISO11263,1994), total P (ISO14869-3, 2017) and exchangeable micronutrients (K, Ca, Mg, Zn and Mn) (ISO11047,1998).

CB D^{HEDF}, C^{HEDF} and V^{HEDF} samples were tested for the presence of *E. coli*, faecal coliforms and *Salmonella*. *C. perfringens* analyses could not be carried out in this site because of the laboratory capacity limitations. Pathogen analyses were carried out at the microbiology laboratory of the local National Centre for Environmental Research, the only local laboratory that would test for pathogens in FS-derived products. Helminth analyses for CB fertilisers were carried out in South Africa at the University of Kwazulu Natal in the laboratory of the Pollution Research Group following the Standard Methods for recovery and enumeration of helminth ova in compost (Moodley *et al.*, 2008)

Heavy metal analyses for solid fertilisers (CA and CB C^{HEDF} and CB V^{HEDF}) were carried out at Cranfield University by aqua regia digestion (Anton Paar Multiwave 3000) followed by atomic absorption spectroscopy (PerkinElmer AAnalyst 800) (ISO11466, 1995). It was not possible to test the liquid digestate samples for heavy metals because no testing facilities were available in location B. It also was not possible to transport digestate samples to the UK due to transport restrictions of liquid samples.

Nutrient concentrations between batches were compared by analysing the variance between samples (ANOVA) using the software Statistica (Statsoft, 2011). Initially different significance levels were chosen to evaluate the strength of the differences between batches. Significance levels of $p<0.01$ and $p<0.05$ with 99% and 95% confidence levels respectively did not show major differences when analysing the data so the standard significance level of $p<0.05$ with 95% confidence interval was chosen for analysing all the data.

3.4 **Results and discussion**

3.4.1 Pathogen results

All pathogen tests results from CA were within regulatory limits, no *Salmonella spp.* was found (data not shown) in any of the C^{HEDF} samples analysed and concentrations were below 10 CFU/g for *E.coli,* Faecal coliforms and *C.*

perfringens. All C^{HEDF} samples were also free from viable helminth eggs and larvae (data not shown). This showed that the current composting process is successful at eliminating harmful pathogens and complies with WHO guidelines for the safe reuse of human excreta (WHO, 2006).

Bacterial pathogen results for CB on the other hand were less constant between batches as summarised in Table 3.1. The results show the presence of pathogens in at least one sample for each HEDF type. For each sampling event, 3 samples from one same batch were analysed and results from triplicates were therefore expected to be similar. Results from the laboratory however showed inconsistent results: pathogen concentrations in samples from one same batch differed by an order of magnitude or more in certain cases. The lack of certified laboratories to carry out analyses and specifically pathogen analyses on products derived from human excreta is an issue that is common in LIC, which is a barrier for showing the value and safety of sanitation products. The results obtained from location B cannot be considered reliable or representative of the pathogen concentration in the D^{HEDF}, C^{HEDF} and V^{HEDF} samples from CB. They can only be taken as indications of the potential contamination points and sources along the production process.

For CB, pathogen concentrations were higher in V^{HEDF} samples than D^{HEDF}, suggesting a recontamination occurred during the processing of the digestate or an insufficient pathogen elimination phase during composting. Recontamination during anaerobic digestion has been reported and one explanation for the survival of pathogens in digestate could be the abundance of nutrients in the system and the continuous addition of fresh material, providing fresh substrate to the pathogens (Gomez-Brandon *et al.*, 2016).

Helminth analyses for CB were carried out in a certified university laboratory in South Africa and showed mixed results for CB HEDFs Table 3.2. D^{HEDF} samples all contained at least one type of helminth, out of the 4 samples tested 2 would comply with WHO guidelines at present (according to current guidelines helminths can only be present at 1 or less helminth egg.mg^{-1}) (WHO, 2006). *Ascaris sp.* was the most commonly found helminth in the digestate samples, many viable eggs still present. The highest concentration of *Ascaris sp.* eggs was 152 eggs in a 45mL sample of digestate, equivalent to 10 eggs.mL^{-1}. The pasteurisation and anaerobic digestion stages did not kill the toughest pathogens. Despite the C^{HEDF} samples being clear of risk-causing helminths, all but one V^{HEDF} sample contained viable helminths (immotile *Ascaris* and *Trichuris* larva and *Hymenolepis diminuta* and *Trichuris* ova) although in concentrations low enough to comply with current regulatory limits. This suggests recontamination occurring between the compost and vermicomposting stages. It is interesting to note that *Hymenolepsis diminuta* is known as rat tapeworm since it can infect both rodents and humans (Mohd Zain *et al.*, 2012). Issues with the reduction of worm populations because of rats in the composting site were reported in the months prior to these samples being taken so it is likely that the ova found in V^{HEDF} were a result of the presence of rodents in the vermicomposting area. This finding highlighted the importance of maintaining a hygienic and pest-free processing site to avoid any cross-contamination or external contamination sources.

Table 3.1 Bacterial pathogen results for CB HEDFs. Highlighted cells show concentrations that would not fulfil current WHO guidelines for reuse of human excreta or BAS enhanced treatment standard guidelines

Sample date	Sample 1			Sample 2			Sample 3			Sample 4			Sample 5		
E. coli D^{HEDF}	<1	<1	<1	2	<1	<1	<1	<1	<1	180	76	<1	<1	<1	<1
E. coli C^{HEDF}	<1	<1	<1	20	94	22	55	<1	<1						
E. coli V^{HEDF}	110	74	92	2	6	50	<1	<1	<1	31	27	36	9	27	110
Faecal coliforms D^{HEDF}	<1	<1	2700	4	<1	4	<1	1	<1	3000	6700	<1	<1	<1	<1
Faecal coliforms C^{HEDF}	<1	<1	<1	41	290	48	1600	9700	8100						
Faecal coliforms V^{HEDF}	1500	120	160	13	50	67	<1	<1	<1	540	470	180	160	900	5400
Salmonella D^{HEDF}	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Salmonella C^{HEDF}	no	no	no	no	no	no	no	no	no						
Salmonella V^{HEDF}	no	no	no	no	no	no	no	no	no	present	no	present	no	no	no

Table 3.2 Helminth content of CB HEDFs (per 15g solids or 45mL (±2mL) for liquids). Concentrations exceeding WHO guidelines for reuse of human excreta[54] are highlighted

Sample type	**Sample number**	***Ascaris* sp. Infertile**	***Ascaris* - Dead**	**Ascaris Immotile larva**	***Trichuris sp.* Undeveloped ova**	***Trichuris* ova - Immotile larva**	***Trichuris* ova DEAD**	**Hookworm sp. ova**	***Enterobius vermicularis* - Dead**	***Toxocara* sp. ova**	***Hymenolepis diminuta* ova**	***Hymenolepis nana* ova**	***Fasciola hepatica* ova**
D^{HEDF}	1	14	132	0	0	0	9	1	0	0	0	1	2 dead
D^{HEDF}	2	**41**	241	0	0	0	17	1	1	0	0	1	1 dead
D^{HEDF}	3	0	5	0	0	0	0	1	0	0	0	0	0
D^{HEDF}	4	**152**	912	0	0	0	75	0	0	0	0	3	2 dead
C^{HEDF}	1	0	21	0	0	0	2	0	0	0	0	0	0
C^{HEDF}	2	0	5	0	0	0	3	0	0	0	0	0	0
C^{HEDF}	3	0	20	0	0	0	6	0	0	0	0	0	0
C^{HEDF}	4	0	21	0	0	0	1	0	0	0	0	0	0
V^{HEDF}	1	0	1	0	0	1	1	0	0	0	0	0	0
V^{HEDF}	2	0	0	0	1	1	0	0	0	1 dead	0	0	0
V^{HEDF}	3	0	0	1	0	1	0	0	0	0	0	0	0
V^{HEDF}	4	0	1	5	0	1	2	0	0	0	5	0	0
V^{HEDF}	5	0	0	3	0	1	2	0	0	0	0	0	0
V^{HEDF}	6	0	1	1	0	1	1	0	0	0	1	0	0
V^{HEDF}	7	0	0	0	0	0	0	0	0	0	0	0	0

3.4.2 Heavy metal limits

Maximum heavy metal concentration in soil amendments is generally carefully regulated to avoid soil contaminations and adverse effects to human health but the limits set vary considerably across the globe (Hogg *et al.*, 2002; Iranpour *et al.*, 2015). In contrast with nutrient content requirements, there are usually clear and often very stringent permissible limits to the concentrations of heavy metals for composts derived from wastes. The strictest and most lenient limits are summarised in Table 3.3, highlighting the differences and wide ranges that exist between different regulating bodies.

Table 3.3 Mean heavy metal concentrations in the HEDFs analysed compared with regulatory limits for compost in Western countries (summarised in Hogg *et al.* (2002)). Non-compliant values are highlighted in red.

Heavy metal	CA C^{HEDF} (mg.kg^{-1})	CB C^{HEDF} (mg.kg^{-1})	CB V^{HEDF} (mg.kg^{-1})	Strictest Limit (mg.kg^{-1})		Highest limit (mg.kg^{-1})	
As	2.51	0.45	0.61	5	Netherlands compost very clean)	75	Canada, category B
Cd	**2.77**	**6.81**	**1.74**	0.4	Denmark	39	US EPA sludge rule
Cr	17.9	10.8	12.3	50	Eco label, Netherlands	$1.2 .10^3$	No ceiling
Cu	24.2	6.11	12.9	25	Netherlands (compost, very clean)	$1.5 .10^3$	US EPA sludge rule
				70	Austria, Germany		
Pb	2.77	6.85	0.89	45	EEC organic rule	800	France
Ni	**33.1**	**18.5**	**19.9**	10	Netherlands (compost, very clean)	420	US EPA sludge rule
Zn	**201**	65.3	**274**	75	Netherlands (Compost, very clean)	$4.0 .10^3$	Denmark, Spain

European regulations are particularly strict on Cd restrictions at present (below 1 (mg.kg^{-1}) concentrations allowed) because of a historical accumulation of Cd in soils, this trend needs to be reversed to avoid further contamination (Pan *et al.*, 2010). None of the C^{HEDF} or V^{HEDF} samples analysed in this experiment fulfilled the current European limits for Cd application but they did fulfil the US limits. Composts derived from MSW reported by Alvarenga *et al.* (2017) also wouldn't fulfil the EU Cadmium limits. Zn concentrations measured in CA C^{HEDF} and CB V^{HEDF} exceeded the strictest limits but also fell below the highest limits. Similarly, maximum Ni concentrations vary widely between regulators and C^{HEDF} and V^{HEDF} analysed fulfilled the US EPA requirements but not the strictest EU limits (Netherlands).

Aside from Cd, Zn and Ni, the HEDFs both from CA and CB met all the most stringent heavy metal limits as shown in Table 3.3. A significant difference in heavy metal concentration was observed between C^{HEDF} and V^{HEDF} from CB. The V^{HEDF} originated directly from C^{HEDF} without addition of any other materials, the differences between the two were therefore resultant solely to the action of the worms. As a result of vermicomposting the average concentration of As increased by 35%, that of Cr increased by 14%, Ni concentration increased by 7%, Cu concentration doubled, and Zn concentration had a fourfold increase. The worms had the opposite effect on other heavy metals: Cd and Pb concentrations were reduced by 75% and 87% respectively. The mixed effect of worms on heavy metal content has been reported in literature: Mohee and Soobhany (2014) surveyed literature of experiments measuring the effect of compost and vermicompost on metal concentration and found no consistent trends. In most cases the composting process increased the concentration of heavy metals whereas vermicomposting had a varied effect on the total concentration of heavy metals, out of 16 vermicompost experiments surveyed, heavy metal concentrations increased in 4 of the studies as a result of vermicomposting whereas in the 12 others a decrease was reported (Mohee and Soobhany, 2014). Barrera *et al.* (2001) studied the effect of worms on specific metals and highlighted the different accumulation mechanisms: worms accumulate Cd and Zn in their tissues whereas Cu isn't bioaccumulated unless it exceeds a given level and Ni is never accumulated. The vermicomposting process did not cause regulatory compliance issues in terms of heavy metal concentration apart from Zn concentration, which reached a level similar to CA C^{HEDF} and remained between the lowest and highest regulatory limit.

Alvarenga *et al.* (2015) reported heavy metal concentrations from different organic wastes and the difference was particularly striking with Pb concentrations: agro-industrial sludge had a Pb concentration of 52.2 ($mg.kg^{-1}$), sewage sludge had less than 5.6 $mg.kg^{-1}$ Pb concentration and mixed MSW compost had 180 $mg.kg^{-1}$ Pb compared to 9.15 and 6.85 $mg.kg^{-1}$ Pb for the C^{HEDF} analysed in this experiment and 0.89 $mg.kg^{-1}$ for the V^{HEDF}. These results confirm that C^{HEDF} and V^{HEDF} do not represent a contamination threat in terms of heavy metals but also show the extent to which heavy metal concentration limits vary currently between different regulating bodies. These differences in regulatory limits for heavy metals represent a difficulty for selecting an appropriate limit for LICs.

3.4.3 Nutrient content analyses

Table 3.4 Mean nutrient content (n=3) of CA C^{HEDF} of samples taken in 5 different batches (± indicates results standard error). Highlighted cells show parameters that significantly varied between batches

	batch 1	**batch 2**	**batch 3**	**batch 4**	**batch 5**	**p value**
pH	4.95 ^{a} ± 0.18	5.09 ^{a} ± 0.14	4.72 ^{a} ± 0.02	6.27 ^{b} ± 0.19	6.37 ^{b} ± 0.2	0.023
Electrical conductivity (mS.cm^{-1})	9.90 ^{ac} ± 0.4	9.13 ^{a} ± 0.63	11.2 ^{c} ± 0.13	6.92 ^{b} ± 0.47	8.54 ^{ab} ± 0.23	0.000
Dry matter (%)	67.5 ^{ab} ± 2.26	74.1 ^{b} ± 7.3	52.6 ^{a} ± 0.98	68 ^{ab} ± 2.6	27.7 ^{c} ± 1.8	0.000
Carbon (%)	31.63 ^{a} ± 1.71	27.8 ^{a} ± 2.12	31.6 ^{a} ± 1.1	18.3 ^{b} ± 0.25	27.0 ^{a} ±1.8	0.001
Total N (%)	1.32 ^{a} ± 0.07	1.33 ^{a} ± 0.04	1.27 ^{a} ± 0.02	0.98 ^{b} ± 0.02	0.94 ^{b} ± 0.05	0.000
Nitrate N (mg.kg^{-1})	247 ^{a} ± 72	339 ^{a} ± 63	179 ^{a} ± 3.1	809 ^{b} ± 70.8	409 ^{a} ± 22	0.025
Ammonium (mg.kg^{-1})	180 ^{b} ± 36	13.4 ^{a} ± 5.51	18.1 ^{a} ± 5.22	4.86 ^{a} ± 0.52	3.53 ^{a} ± 0.5	0.015
C/N ratio	23.9 ^{bc} ± 0.2	20.9 ^{ab} ± 1.1	24.9 ^{c} ± 0.59	18.7 ^{a} ± 0.23	28.7 ^{d} ± 0.8	0.000
P (%)	0.85 ^{a} ± 0.1	0.81 ^{a} ± 0.04	0.80 ^{a} ± 0.07	0.46 ^{b} ± 0.03	0.73 ^{ab} ± 0.08	0.014
K (%)	0.99 ^{a} ± 0.07	0.81 ^{a} ± 0.07	0.87 ^{a} ± 0.07	0.74 ^{b} ± 0.04	0.92 ^{ab} ± 0.06	0.129
Exchangeable P (mg.kg^{-1})	528 ^{bc} ± 113	283 ^{ab} ± 63	679 ^{c} ± 35	52.1 ^{a} ± 20.1	35.7 ^{a} ± 11	0.017
Exchangeable K (mg.kg^{-1})	1320 ± 113	970 ± 36	1370 ± 74	947 ± 49	788 ± 69	0.118
Ca (%)	1.52 ± 0.12	1.88 ± 0.2	1.84 ± 0.34	1.70 ± 0.06	2.20 ± 0.23	0.299
Mg (%)	0.57 ± 0.02	0.60 ± 0.06	0.55 ± 0.06	0.51 ± 0.02	0.56 ± 0.01	0.64
S (%)	0.31 ± 0.4	0.36 ± 0.07	0.35 ± 0.07	0.19 ± 0.01	0.28 ± 0.03	0.149
Mn (mg.kg^{-1})	543 ± 24	727 ± 101	532 ± 47	675 ± 29	641 ± 14	0.109
Exchangeable Ca (mg.kg^{-1})	305 ^{a} ± 96	385 ^{ab} ± 39	598 ^{b} ± 13	368 ^{a} ± 12	173 ^{a} ± 26	0.001
Exchangeable Mg (mg.kg^{-1})	356 ^{ab} ± 101	370 ^{ab} ± 33	588^{b} ± 18	295 ^{a} ± 25	140 ^{a} ± 19	0.029
Exchangeable S (mg.kg^{-1})	196 ^{b} ± 38	144 ^{ab} ± 9	303 ^{c} ± 29	134 ^{ab} ± 5	68.8 ^{a} ± 8.5	0.000
Exchangeable Mn (mg.kg^{-1})	5.69 ^{ac} ± 2.19	6.95 ^{a} ± 0.8	10.6 ^{a} ± 1.1	0.06 ^{b} ± 0.02	0.93 ^{bc} ± 0.25	0.000

For each parameter, batch values followed by the same letter are not significantly different ($p<0.05$) following one-way ANOVA and post hoc Fisher LSD Analysis

Table 3.5 Mean nutrient content (n=3) of CB V^{HEDF} samples taken in 7 different batches (± indicates results standard error). Highlighted cells show parameters that significantly varied between batches

	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Batch 7	p value
pH	8.48 ^{b} ± 0.02	8.81 ^{c} ± 0.07	8.27 ^{ab} ±0.07	8.35 ^{ab} ± 0.02	8.19 ^{a} ± 0.01	9.08 ^{d} ± 0.01	8.12 ^{a} ± 0.08	0.005
Conductivity (mS.cm^{-1})	28.3 ^{a} ± 0.5	24.8 ^{bc} ± 0	26.4 ^{ab} ± 1.2	27.5 ^{ab} ± 0.5	27.2 ^{ab} ± 0	22.7 ^{c} ± 0.3	28.3 ^{a} ± 0.3	0.02
Organic C (g.kg^{-1})	340 ± 2	321 ± 0	342 ± 4	336 ± 4	322 ± 30	330 ± 3	341 ± 7	0.17
Organic Matter (%)	58.5 ± 0.4	55.2 ± 0.1	58.9 ± 0.7	57.8 ± 0.6	55.4 ± 5.2	56.7 ± 0.5	58.6 ± 1.2	0.17
Total N (g.kg^{-1})	18.4 ^{a} ± 1.1	22.1 ^{abc} ± 0.5	20.0 ^{ab} ± 1.5	25.4 ^{c} ± 0.3	24.2 ^{bc} ± 0.4	20.8 ^{abc} ± 1.2	20.6 ^{ab} ± 0.9	0.002
C/N	18.6 ^{b} ± 1.1	14.5 ^{ab} ± 0.4	17.3 ^{ab} ± 1.3	13.3 ^{a} ± 0.2	13.3 ^{a} ± 1.3	15.9 ^{ab} ± 0.8	16.6 ^{ab} ± 0.8	0.006
NH_4^+ (mg.kg^{-1})	77.9 ^{bc} ± 0.8	154 ^{e} ± 6	107 ^{cd} ± 11	123 ^{d} ± 4	72.4 ^{ab} ± 7.2	68.8 ^{ab} ± 1.3	47.1 ^{a} ± 5.4	0.00
Exchangeable P (mg.kg^{-1})	1.18 $.10^{3\ a}$ ± 7	1.30 $.10^{3\ abc}$ ± 38	1.40 $.10^{3\ c}$ ± 52	1.24 $.10^{3\ abc}$ ± 17	1.35 $.10^{3\ bc}$ ± 37	1.25 $.10^{3\ abc}$ ± 11	1.29 $.10^{3\ abc}$ ± 4	0.012
Total P (g.kg^{-1})	4.38 ^{a} ± 0.04	4.52 ^{ab} ± 0.04	4.82 ^{abc} ± 0.05	4.54 ^{ab} ± 0.05	5.19 ^{c} ± 0.06	4.91 ^{bc} ± 0.03	4.56 ^{ab} ± 0.22	0.00
Exchangeable K (g.kg^{-1})	29.7 ^{ab} ± 0.1	29.0 ^{ab} ± 0.3	29.1 ^{ab} ± 0 .4	29.3 ^{ab} ± 0.3	30.1 ^{b} ± 1.0	28.3 ^{ab} ± 0.5	27.3 ^{a} ± 0.8	0.05
Total K (g.kg^{-1})	35.5 ± 2.4	32.2 ± 1.0	32.6 ± 1.0	33.6 ± 2.1	33.4 ± 0.9	30.3 ± 0.9	28.8 ± 1.4	0.105
Exchangeable Ca (g.kg^{-1})	3.10 ^{a} ± 0.08	1.9 ^{c} ± 0.04	3.21 ^{a} ± 0.25	3.42 ^{a} ± 0	3.72 ^{a} ± 0.07	1.16 ^{b} ± 0.08	3.28 ^{a} ± 0.23	0.014
Total Ca (g.kg^{-1})	7.83 ^{a} ± 0.33	7.30 ^{ab} ± 0.31	8.05 ^{a} ± 0.32	7.82 ^{a} ± 0.18	9.11 ^{a} ± 0.26	8.06 ^{a} ± 0.88	5.70 ^{b} ± 0.18	0.05
Exchangeable Mg (g.kg^{-1})	1.65 ^{b} ± 0.04	1.33 ^{d} ± 0.01	1.77 ^{ab} ± 0.04	1.82 ^{a} ± 0.01	2.02 ^{e} ± 0.04	0.93 ^{c} ± 0.01	1.83 ^{a} ± 0.01	0.005
Total Mg (g.kg^{-1})	1.77 ^{ab} ± 0.09	1.61 ^{a} ± 0.07	1.83 ^{ab} ± 0.03	2.80 ^{c} ± 0.04	3.11 ^{c} ± 0.02	1.86 ^{ab} ± 0.18	2.13 ^{b} ± 0.16	0.012
Total Mn (g.kg^{-1})	10.0 ^{a} ± 0.2	9.73 ^{ab} ± 0.32	10.0 ^{a} ± 0.3	15.1 ^{c} ± 0.6	15.8 ^{c} ± 0.2	10.5 ^{a} ± 0.7	7.61 ^{b} ± 0.69	0.012
Total Fe (g.kg^{-1})	1.91 ^{a} ± 0.16	2.12 ^{a} ± 0.1	2.54 ^{a} ± 0.24	3.88 ^{b} ± 0.21	4.45 ^{b} ± 0.08	2.56 ^{a} ± 0.36	2.18 ^{a} ± 0.28	0.018

For each parameter, batch values followed by the same letter are not significantly different ($p<0.05$) following one-way ANOVA and post hoc Fisher LSD Analysis

Table 3.6 Mean nutrient content (n=3) of CB D^{HEDF} samples taken in 5 different batches (± indicates results standard error). Highlighted cells (in blue) show parameters that significantly varied between batches

	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	p value
pH	7.95 ^{c} ± 0	7.85 ^{ab} ± 0.01	7.82 ^{a} ± 0	8.08 ^{d} ± 0.01	7.86 ^{b} ± 0.01	0.011
Conductivity (mS.cm^{-1})	24.3 ^{a} ± 0.3	25 ^{a} ± 0	26 ^{b} ± 0	26 ^{b} ± 0	27.3 ^{c} ± 0.3	0.009
Organic C (g.L^{-1})	2.01 ^{b} ± 0.03	2.63 ^{c} ± 0.06	2.96 ^{a} ± 0.05	3.06 ^{a} ± 0	3.09 ^{a} ± 0.02	0.012
Organic Matter (%)	0.35 ^{b} ± 0.01	0.45 ^{c} ± 0.01	0.51 ^{a} ± 0.01	0.53 ^{a} ± 0	0.53 ^{a} ± 0	0.012
Total N (g.L^{-1})	1.4 ^{b} ± 0.01	2.82 ^{d} ± 0	2.96 ^{a} ± 0	2.39 ^{c} ± 0	2.96 ^{a} ± 0	0.01
C/N	1.43 ^{d} ± 0.02	0.93 ^{a} ± 0.02	1 ^{b} ± 0.02	1.28 ^{c} ± 0	1.05 ^{b} ± 0.01	0.01
NH_4^+ (mg.L^{-1})	1.35 ^{b} ± 0.01	2.59 ^{a} ± 0.01	2.74 ^{a} ± 0.02	2.19 ^{c} ± 0.02	2.51 ^{a} ± 0.11	0.012
Total P (mg.L^{-1})	157 ^{b} ± 2	128 ^{a} ± 1	167 ^{c} ± 1	178 ^{d} ± 1	185 ^{e} ± 2	0.009
Total K (mg.L^{-1})	1.51 10^{3} ^{a} ± 41	1.33 10^{3} ^{ab} ± 36	1.33 10^{3} ^{ab} ± 47	1.34 10^{3} ^{a} ± 66	1.12 10^{3} ^{b} ± 20	0.002
Total Ca (mg.L^{-1})	5.12 ^{b} ± 0.17	6.19 ^{a} ± 0.24	6.16 ^{a} ± 0.08	6.45 ^{a} ± 0.08	8.75 ^{c} ± 0.33	0.019
Total Mg (mg.L^{-1})	6.46 ^{a} ± 0.16	6.66 ^{a} ± 0.13	7.92 ^{b} ± 0.29	7.51 ^{b} ± 0.1	9.33 ^{c} ± 0.04	0.00
Total Mn (mg.L^{-1})	1.25 ^{b} ± 0.01	1.24 ^{b} ± 0.03	1.41 ^{a} ± 0.04	1.42 ^{a} ± 0	1.49 ^{a} ± 0.02	0.00
Total Fe (mg.L^{-1})	9.63 ^{ab} ± 0.1	8.4 ^{a} ± 0.32	8.65 ^{a} ± 0.27	10 ^{b} ± 0.4	10.2 ^{b} ± 0.1	0.003

For each parameter, batch values followed by the same letter are not significantly different ($p<0.05$) following one-way ANOVA and post hoc Fisher LSD Analysis

Variabilities between batches were detected for all the HEDFs analysed in this study. CA C^{HEDF} had significant differences between batches for all parameters except total and available K, Ca, Mg, S and Mn (Table 3.4). There were significant differences between batches for all the parameters analysed in the CB D^{HEDF} samples (Table 3.6). CB V^{HEDF} samples also showed significant differences between batches for all parameters except for organic C, organic matter and total K concentrations (Table 3.5). Significant differences between samples of CB C^{HEDF} were not evaluated because the maturation process was not completed hence the product was not considered marketable. The compost process had only undergone the initial thermophilic stage and subsequent cooling whereas a full composting process includes several weeks of maturation. Compost can typically achieve maturation in 3 to 6 months (Rothenberger *et al.*, 2006)

The compost piles sampled from CA were all acidic, with pH ranging from 4.6 to 6.8, considered low for composts (Diaz *et al.,* 2011). There were no changes to the feedstock between these batches so the differences of pH are likely due to operational differences rather than variations in the organic material input. Fast increases in temperature during the initial stages of composting could explain the low pH in the pile. If thermophilic temperatures are reached too fast, pH can remain low (Smårs *et al*., 2002; Sundberg *et al*., 2013). This is likely to occur at the CA’s compost treatment site, where the compost piles are directly under the sun and ambient temperatures are high all year round. It should be noted that the pH of the samples from the different composting piles did not correspond to the pH of the final product since it is adjusted prior to packing by adding lime to increase the alkalinity to reach a neutral pH, set as an internal target by CA.

The pH in CB V^{HEDF} varied significantly between batches, ranging from 8.1 to 9.1, similarly the pH of digestate varied between batches ranging between 7.8 and 8.1. This is considered high but could be beneficial for certain types of soils, applying basic (high pH) fertilisers to acidic soils could help increase the pH and improve soil quality. Acidic soils show reduced P availability in soil (Otinga *et al.,* 2013); it is immobilised under acidic conditions by metals such as aluminium and iron (Buresh *et al.,* 1997). Otinga *et al.* (2013) highlighted the potential of organic soil amendments in highly weathered soils for increasing organic matter and pH and therefore reduce P immobilisation and reduce the quantities of chemical P fertiliser required. This type of highly weathered soils dominates tropical Africa and benefits from the application of fertilisers with a high pH such as lime and dolomite or the V^{HEDF} from CB tested in this experiment (Millenium Ecosystem Assessment, 2005; Smaling *et al.*, 2006).

The variability between batches for the majority of nutrient parameters could be seen as a hindrance for marketing these HEDFs. However, such is the nature of organic amendments; given the biological nature of treatment processes involving a wide range of microorganisms that are sensitive to many environmental changes, it is difficult to obtain identical batches. Any changes in feedstock, ambient conditions or processing parameters can have an effect on the properties of the final product (Shiralipour *et al.*, 1992; Banegas *et al.*, 2007). Human excreta themselves are variable between individuals and depend on dietary intakes (Rose *et al.*, 2015) hence HEDFs will also show variability. The quality of organic amendments however cannot be evaluated on the same basis as chemical fertilisers given the differences in nutrient availability and the additional organic matter content contribution. The variation in nutrient content of organic fertilisers can be quantified and ranges of nutrient content can be provided as guidance to farmers. Additional certification of this type of fertilisers could be beneficial for increasing customer confidence as well as commercial value of these soil amendments (Cesaro *et al.*, 2015; Danso *et al.*, 2017).

Table 3.7 Physico-chemical characterisation of the HEDFs sampled as compared with similar sewage sludge and Animal EDFs reported in the literature (± indicates results standard error)

		CA Compost	CB Compost	CB Vermi compost	CB Digestate	CX[b] Compost	Alvarenga *et al.* (2015) Compost	Mantovi *et al.* (2005) Compost	Alidadi *et al.* (2005) Vermi compost	Begum (2011) Vermi compost	Owamah *et al.* (2014)	Owamah *et al.* (2014) Compost	Atiyeh *et al.* (2002) Vermi compost	Adamtey *et al.* (2010) Compost
Parameter	Input materials Unit	Agricultural wastes and human faeces	Straw and CB digestate	CB compost	Food and agricultural wastes and human excreta	Sugar cane bagasse and human faeces	Agricultural wastes and sewage sludge	Anaerobically digested sewage sludge and agricultural wastes	Composted sewage sludge	Municipal sewage sludge	Food waste and human excreta	Dewatered digestate (food and human waste)	Pig manure	Sewage sludge and MSW
pH		5.48 ±0.2	9.54 ±0.05	8.47 ± 0.07	7.91 ±0.02	5.7	5.8	7.11		7.5	6.5	7.2	5.3	7.8
Electrical conductivity	mS.cm^{-1}	9.13 ±0.41	27.82 ±1.58	26.44 ± 0.42	25.73 ±0.28	8.5	6.37						11.76	
Dry matter	%	57.99 ±4.7				61.6	73.3	51.82						
Carbon	%	27.29 ±1.43	34.7 ±1.7	33.31 ± 0.4	0.27 ±0.01	17.34			29.71	20	20.1	37.9	27.38	
Total N	%	1.17 ± 0.05	2.07 ±0.1	2.16 ±0.06	0.251 ±0.01	1.93	3.2	2.95	2.24	0.9	0.7		2.36	1.35
P	%	0.73 ± 0.05	0.29 ±0.02	0.47 ± 0.01	0.02 ±0	0.83	2.1	1.43	2.71				4.5	1.6
K	%	0.87 ±0.03	3.46 ±0.09	3.23 ±0.07	0.13 ±0	0.71	2.85	1.11		1.13E^{-3}			0.4	1.9
Ca	%	1.83 ±0.1	0.48 ±0.03	0.77 ±0.02	0 ± 0	2.76	0.87			0.49E^{-3}			8.6	
Mg	%	0.56 ±0.02	0.13 ±0	0.22 ±0.01	0 ±0	0.51	0.48			0.2E^{-3}			0.5	

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[a] CX refers to another established sanitation venture

		CA Compost	CB Compost	CB Vermi compost	CB Digestate	CX[b] Compost	Alvarenga *et al.* (2015) Compost	Mantovi *et al.* (2005) Compost	Alidadi *et al.* (2005) Vermi compost	Begum (2011) Vermi compost	Owamah *et al.* (2014)	Owamah *et al.* (2014) Compost	Atiyeh *et al.* (2002) Vermi compost	Adamtey *et al.* (2010) Compost
S	%	0.30 ±0.02				0.35								
Mn	(mg.kg^{-1})	624 ±29	6930 ± 630	11260 ± 640	1.36 ± 0.03	209							1170	
Fe	(mg.kg^{-1})	9180 ±455	2120 ± 400	2800 ± 210	9.37 ±0	7300							8000	
Zn	(mg.kg^{-1})	259 ±15				170				45.9			824.7	
Cu	(mg.kg^{-1})	63.1 ±3.5				74				32			378.8	
Na	(mg.kg^{-1})	1857 ±99				3100	20.1	3100		8.8				
C/N ratio			17.2 ± 1.4	15.4 ±0.9	1.14 ±0.05	8.2	14.2		13.26		30.5	15.8		7.6
Exchangeable P	(mg.kg^{-1})	316 ±72	757 ± 75	1287 ± 30						354000				2392
Exchangeable K	(mg.kg^{-1})	1079 ±77	32130 ±830	28960 ±460						276000				
Exchangeable Ca	(mg.kg^{-1})	366 ±41	1300 ±90	2830 ±340										
Exchangeable Mg	(mg.kg^{-1})	350 ±43	650 ± 40	1620 ± 130										
Ammonium	(mg.kg^{-1})	44 ±19	490 ± 95	93 ±14	0.002		36.7	4300						223
Nitrate N	(mg.kg^{-1})	397 ±62					349							218

The overall average values for the parameters analysed are summarised in Table 3.7. Characteristics of similar HEDFs and animal EDFs described in literature were included to compare different organic fertilisers from similar feedstocks. Compared to other composts, CA C^{HEDF} had a relatively low pH although it is similar to that obtained by CX and Alvarenga *et al.* (2015) with similar feedstocks of agricultural waste and sewage sludge. The pH of CB HEDFs on the other hand was significantly higher than that of other similar fertilisers. The P content was relatively low in the HEDFs compared to the other amendments, less than 1% for all HEDFs, whereas the average P concentration higher than 2% for the other composts derived from sewage sludge reported in Alvarenga *et al*. (2015) and Alidadi *et al.* (2005). These lower P concentrations could be due to the difference in origin of the sludge: centralised wastewater treatment plants receive greater quantities of P in the greywater and industrial wastewaters and the resulting sludge therefore has higher concentrations of these nutrients (Barnard, 2009).

The concentration of total K in CB V^{HEDF} and C^{HEDF} was 3 times higher than CA and CX C^{HEDF}, also higher than the other K concentrations in compost found in literature. CB C^{HEDF} and vermicompost also had higher concentrations of N but CA C^{HEDF} had higher P and Fe concentrations, similar to those of CX C^{HEDF}. The electrical conductivity of soil amendments from CB were about 3 to 4 times higher than CA C^{HEDF} and other composts derived from sewage sludge reported in Alvarenga *et al*. (2015), Mantovi *et al.* (2005), Begum (2011) and Adamtey *et al.* (2010), which could be due to urine also being collected in CB's system unlike CA. Differences in Mn, exchangeable K and, Ca and Mg concentrations showed that CB HEDFs had high concentration of salts, at least 4 times higher in CB C^{HEDF} and V^{HEDF} than the other two C^{HEDF}. The urine fraction of human excreta contains the highest concentration of salts, N, K and P and has a neutral to alkaline pH (Rose *et al.*, 2015), which could explain the differences between CB HEDFs and the other two C^{HEDF}. The salt concentrations (Mn, Ca, Mg) in CB HEDFs were higher than those in all the other similar fertilisers and could be a hindrance for plant growth. CB C^{HEDF} and V^{HEDF} had lower total P concentrations than CA and CX C^{HEDF}, which could be due to a difference in dietary intakes in the area where CB excreta are collected compared to the other two sites (lower protein intake). The P concentration was however increased by more than 50% between the compost and vermicompost stages in CB by the action of the worms. The concentration of K in CB V^{HEDF} was about 30 times higher than that in CB D^{HEDF}, highlighting the effects of composting and vermicomposting on nutrient concentration and fixation.

3.4.4 BAS product validation results and recommendations for higher consumer confidence and product acceptance

The BAS standard sets limits for pathogen concentrations in the final product as well as maximum allowed heavy metal concentrations. The C^{HEDF} samples analysed from CA fulfilled all the requirements set by the BAS standard for enhanced biosolids to be applied on arable land, the highest quality possible for biosolids with the least restrictions for land application. The BAS procedure for CB on the other hand identified pathogen contamination issues in the process and potential contamination sources.

The BAS procedure is underpinned by Hazards Analysis and Critical Control Points (HACCP) procedures. HACCP is a systematic approach commonly used in the food and the water industry but is now being applied in sanitation systems as well. It is an efficient contamination prevention measure for all processes involving sensitive biological materials, identifying hazards, establishing monitoring systems and reducing risks to minimise the likelihood of product contamination (Winkler *et al.*, 2017). The WHO developed a Sanitation Safety Planning manual in 2016 for implementing a system based on HACCP procedure, which involves mapping out the process flow diagram of the excreta treatment process, optimising it to avoid potential cross contamination pathways (through physical design of the plant and use of personal protection equipment by plant staff) and implementing a quality monitoring and risk control at different stages of the production process (WHO, 2016). This tool identifies hazards and puts prevention mechanisms in place, which reduce the need for extensive inspection and analysis of the final product. It has already been shown that the implementation of SSP leads to safer and more efficient systems, helping to identify key issues and identify stakeholders potentially at risk (Winkler *et al.*, 2017). The benefits of this approach were highlighted in this experiment by the potential rodent infestation identified in CB's fertiliser production site through the helminth analysis tests. HACCP procedures specific for each HEDF production site would prevent production contamination risks as well as allow early identification of potential problems.

3.5 **Conclusions**

The production of HEDFs is not new but their production at a large scale and commercialisation is novel. The product therefore needs to overcome prejudices and scepticism concerning its safety and contamination potential.

Comparing the properties of HEDF produced in different locations showed that the nutrient content varied between batches and locations but remained within the range expected for HEDF, similar to that of composts from similar sources. The 'recipe' and raw materials for producing C^{HEDF}, V^{HEDF} and D^{HEDF} varied between sites and the types of organic materials available for co-composting differed as well as people's diets depending on the geographical area, which lead to differences in the final products. The variability between batches as well as between HEDF processing methods in different locations is a constraint for establishing absolute values for defining the quality of HEDFs. Given the variability of the feedstock, it would be difficult to make a product with constant nutrient concentrations, but ranges can be provided as user guidance. This study for the first time provides a comprehensive synthesis of key parameters to characterise HEDF in SSA and its variability in comparison to other work. The heavy metal concentrations in the HEDF remained within the regulatory limits set for biosolids and pathogen concentrations remained below the regulatory limits in CA. Following the testing procedure set out in the BAS proved valuable for identifying contamination sources in CB. Another point highlighted in this project was the issue of availability of accredited laboratory facilities, which is an issue often encountered in low-income countries. In one of the locations it is only when samples were tested overseas for the presence of helminths that contamination issues were confirmed. Sending samples overseas for testing pathogens is challenging in terms of sample storage and transport and has significant cost implications, posing a challenge for routinely testing the quality of HEDF in these locations. Testing for other potential chemical pollutants such as pharmaceuticals or other emerging pollutants in HEDF is also a challenge with testing methods currently requiring advanced equipment.

The quality and nutrient content of composts is directly linked to the feedstock used for their production. Comparison between source-separated HEDF and biosolids, fertilisers that originate from centralised wastewater treatment plants, showed differences in their properties. It is therefore proposed that a certification or assurance scheme specific to products obtained from source-separated excreta could be valuable for ensuring their quality and safety in terms of nutrients, pathogens, heavy metal content and other chemical contaminants.

4 EVALUATING THE EFFICACY OF FERTILISERS DERIVED FROM HUMAN EXCRETA IN AGRICULTURE AND THEIR PERCEPTION IN ANTANANARIVO, MADAGASCAR

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Abstract

Sustainable food production to achieve food security and increased access to safely managed sanitation are major global challenges. Treating human excreta and producing safe nutrient-rich soil amendments is an effective way of creating an incentive to tackle these two challenges. This research analysed the quality of HEDFs and evaluated their acceptability within the local market. Antananarivo (Madagascar) was the field site for crop trial and three different HEDFs were used to grow maize: D^{HEDF}, C^{HEDF} and V^{HEDF}, each derived from the previous one. The three fertilisers had different characteristics: certain nutrients such nitrogen were more concentrated in compost (23 $g.kg^{-1}$ Total N) and vermicompost (11 $g.kg^{-1}$ Total N) and mineralisation stages varied between them but did not cause any detrimental effect to crop yield. When compared to chemical fertilisers, the three HEDFs resulted in comparable yield which is encouraging. A series of 81 interviews were also carried out with farmers of the peri-urban area of Antananarivo, which highlighted the importance of characterising the market, identifying users' perceived needs and developing a product responding to these. The majority of local farmers perceived HEDFs as acceptable and gave great importance to their texture and general appearance. In this study, both the field trials and interviews suggest that there is a good potential to produce HEDFs, which have a positive effect on crops and can be adopted in the local market.

Keywords: human excreta, fertilisers, compost, vermicompost, digestate, crops

The formatting of the original published manuscript has been adjusted to fit the format of this thesis.

4.1 **Introduction**

4.1.1 Food security challenges

Global food security is recognised as one of the major challenges for sustaining 9 billion people on Earth by 2050. Considering the current rate of population growth it is predicted that the demand for food will double by 2050, putting unprecedented pressures on natural resources (Tilman *et al.*, 2011). This resonates with the concept of the ‘Perfect Storm’, introduced by Sir John Beddington in 2009 to illustrate the pressures of increasing demand of food, water and energy worldwide on our finite resources on Earth (Beddington, 2009). This issue is exacerbated by the increasing urbanisation rates worldwide: current food production and consumption patterns have turned cities into nutrient ‘sinks’. Food is produced in rural areas, transported and consumed in cities where the nutrients remain, creating an additional demand for artificial fertilisers to replenish lost soil nutrients. In recent years the concept of a circular economy has gained interest and the need for shifting from linear to circular production processes where waste streams become input streams into new processes has been recognised (Ellen MacArthur Foundation, 2013). This is especially true in agriculture where the predicted increase in fertiliser demand is combined with finite mineral nutrient reserves creating an urgent need to close nutrient loops by returning reclaimable nutrients into soil (Drangert, 1998; Cordell *et al.*, 2009).

The issue of soil nutrient depletion will only become more critical in coming years with larger urban populations, which combined with a global rise in fertiliser prices will constitute a major issue to tackle especially in LICs (Bracken *et al.*, 2009). There is indeed a gradual nutrient depletion of soils in SSA due to the agricultural practices and lack of fertiliser use in the area (Cofie *et al.*, 2009; Wanzala and Groot, 2013). Mueller *et al*. (2012) identified that in order for SSA to attain its maximum theoretically attainable yield for major cereal crops, there is a need for additional nutrient inputs into soil. SSA is indeed the region in the world that currently uses the least fertiliser quantities, about 8 kg.ha^{-1} which is less than one tenth of the world average (Chauvin *et al.*, 2012). This trend needs to be shifted to increase the agricultural output of the area and allow food production to meet the requirements of an ever-increasing population. The term fertiliser covers both inorganic and organic sources and in the latter case the source is also mentioned to indicate its origin.

4.1.2 The opportunity of HEDFs

Over 34% of the world's population still lacks access to adequate sanitation nowadays with cost implications of over $260 billion a year which calls for action and a shift in the conventional approach to sanitation (WHO, 2012). Non-sewered sanitation is often the norm in most LICs and especially in informal settlements of rapidly expanding cities; it is estimated that 65-100% of sanitation access in urban areas in SSA is provided through on-site technologies (Strauss *et al.*, 2000). This type of facility requires emptying and an associated disposal system, which often is not in place in these areas and results in a discharge of the FS in the local environment creating a threat to human health. It is therefore essential to put systems in place for the safe handling and transport of FS and provide incentives for its safe disposal through treatments that generate marketable products from human excreta. One type of product that can be produced from human excreta is HEDFs used as soil amendments. Once they have reached adulthood, humans do not incorporate nutrients into new body tissue, thus the amount of nutrients consumed and excreted by adult humans is roughly equal (Bracken *et al.*, 2009). Human excreta therefore constitute a substantial source of nutrients: it is estimated that if excreta of the whole world population were collected, it would constitute 28% of the current N, P and K consumption worldwide (Ellen MacArthur Foundation, 2013).

The opportunity in HEDFs is recognised but their value is underestimated (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Human excreta have a great fertiliser potential; not only do they contain essential plant nutrients such as N, P, K and other micronutrients but it they are also made up of organic matter that improves soil health by increasing its water retaining capacity, reducing erosion and building better soil structure (Guzha *et al.*, 2005). The reuse of human excreta as a fertiliser is therefore an attractive solution to both the sanitation crisis and the nutrient depletion of soils in SSA. Sanitation crisis occurs where health conditions decline due to poor practices in managing disposal of faecal matter exacerbated with increasing population. The conversion of faecal matter into valuable products such as HEDFs also minimises environmental risks linked with pollution incidences if managed properly (Kone *et al.*, 2009).

Studies to evaluate the fertilising potential of treated sludges have been carried out with materials derived from different substrates, the most common being animal manure as shown in Table 4.1. The feasibility of composting and vermicomposting human excreta and obtaining a product safe to use on crops has been demonstrated (Cofie *et al.,* 2009; Kone *et al.,*2009; Yadav *et al.*, 2010; Kramer *et al.*, 2011) but reports of their effect on soil in field trials is limited (Guzha *et al*., 2005, Adamtey *et al.,* 2010)

Table 4.1 Summary of crop trials completed with application of anaerobic digestates (AD) or vermicompost derived from excreta (animal and human)

Type of fertiliser	Crop	Country	Application rate	Reference
FS	Reeds (*E. pyramidalis, C. papyrus*)	Missing info	Missing info	Kengne *et al.* (2008)
FS		Ghana	455 kg.ha^{-1}	Asare *et al.* (1998)
Raw FS		Ghana	56 m^{3}.ha^{-1} FS	Cofie *et al.* (2005)
Dewatered FS, MSW compost and Co-compost (FS+MSW)	Maize	Ghana	91, 150, 210 kg N.ha^{-1}	Adamtey *et al.* (2010)
Urine and humanure	Maize	Zimbabwe		Guzha *et al.* (2005)
Vermicompost from septic tank sewage sludge	Habanero peppers	Mexico	1, 2 and 2.5 kg.m^{-2}	Rodríguez-Canché *et al.* (2010)
Municipal sewage vermicompost	Tomato	Mysore	10, 20 30 t.ha^{-1}	Begum (2011)

Type of fertiliser	Crop	Country	Application rate	Reference
AD from wine distillery wastewater and organic material	Lettuce	Italy	140 kg N.ha^{-1}	Montemurro *et al.* (2010)
Pig manure vermicompost (11 different mixes)	Tomato	USA		Atiyeh *et al.* (2000)
AD from cow dung and chicken droppings	Maize and guinea corn	Nigeria		Alfa *et al.* (2014)
Guinea pig manure digestate	Potato and forage	Peru	50 kg N.ha^{-1}	Garfí *et al.* (2011)
4 different digestates and pig manure	Spring wheat	Sweden	35, 70 and 140 kg N.ha^{-1}	Abubaker *et al.* (2012)
Liquid swine manure, raw and treated through different processes	Maize	Canada	100 kg N.ha^{-1}	Chantigny *et al.* (2008)
Digestate from cattle slurry and maize mix	Maize	Italy	340 kg N.ha^{-1}	Cavalli *et al.* (2016)
Digestate, cattle slurry, pig slurry and mineral fertiliser	Maize, winter wheat, Italian and perennial ryegrass	Germany	60, 120, 180 kg N.ha^{-1} for maize	Sieling *et al.* (2013)

4.1.3 Challenges in commercialising HEDFs in LICs

Whilst the positive effects of organic amendments on soil have been proven, compost has often been reported to be hard to market profitably in LICs. This is often associated with low willingness to pay of customers for waste-derived products due to perception (Danso *et al.*, 2002). Producing effective HEDFs therefore does not guarantee their commercial success and if local market conditions are not favourable for organic fertiliser marketing, it is unlikely that a profit will be made from their sale.

For most farmers, the use of HEDFs would involve a change in their agricultural practices to a certain degree, it would be an innovative adoption which is always perceived as carrying some risk. Smallholder farmers in LICs most often have very limited capital, preventing them from investing in their farming activities. It is for this reason that they are generally very risk-averse and that it is difficult to change their habits and practices (Graf *et al.*, 2015).

This is one of the major challenges for commercialising innovative fertiliser products in low income settings. Social capital however can lower the barriers to the adoption of new products and can be a driving factor for innovation among farmers. By facilitating collective work, social capital encourages cooperation and support between farmers as well as lowering costs and therefore overall reduces the risk of adopting innovative practices (Pretty, 2003).

4.1.4 The context in Madagascar

Madagascar is a country where both access to sanitation and agricultural productivity are current issues. Madagascar remains one of the lowest fertiliser users in Africa with about 4 $kg.ha^{-1}$ of fertiliser applied per annum (NEPAD-CAADP, 2015) yet agriculture is a pillar sector of the economy, employing 80% of the workforce but producing only around one third of the GDP (US International Trade Commission, 2002). The urban population in Madagascar is rapidly increasing with 40% of the population expected to live in urban areas by 2020 (Godinot, 2010). Peri-urban agriculture plays an essential role in supporting the food requirements of the urban population. There are however great pressures on land in the peri-urban areas of the capital due to urban expansion. Agricultural activities are gradually being pushed to areas that had not been cultivated before due to their lower soil quality, creating new challenges for making these soils fertile (Dienor *et al.*, 2011). There are also sanitation issues in Madagascar, only 12% of the population has access to improved sanitation and 40% of the population still practises open defecation according to UNICEF statistics from

2015. The situation has only marginally improved over the years with only 8% more of the population gaining access to sanitation since 1990 (WHO and UNICEF 2015). Madagascar and in particular the capital Antananarivo therefore constitute an ideal site for investigating the properties of HEDFs and their commercialisation potential locally. This study aimed to demonstrate the efficacy of three different types of HEDFs (D^{HEDF}, C^{HEDF} and V^{HEDF}) compared to chemical fertilisers and investigate their acceptability amongst farmers in the peri-urban area of Antananarivo. The focus of this study in entirely on the agronomy and valorisation whilst an on-going study is taking place to cover the pathogen and safety aspects of the HEDFs investigated.

4.2 **Methodology**

4.2.1 Field trial

A field trial was carried out in Antananarivo between November 2014 and March 2015 on a 60m^2 plot of land with maize (*Zea mays*) as a test crop. The field was in the peri-urban area of Antananarivo, in the neighbourhood of Ambohijanahary (Coordinates of the site: 18° 49´ 37.74" S 47° 29´ 30.12" E). The soil in this area according to the World Reference Base (WRB) can be classified as Umbric Gleysol or Ferralsol. The soil texture was loamy sand, determined by the sieving and sedimentation method (Table 4.3). Top-soil samples were analysed across the whole length and width of the field before application of HEDFs to test the soil homogeneity (Samples taken at 5 different points at a depth of 20 cm, each sample was a composite of 3 subsamples)

The HEDFs (Table 4.2) applied on the experimental plots (Figure 4-2) were obtained from human excreta derived from a staged treatment process (Figure 4-1). Excreta were first collected from Loowatt Ltd dry toilets (equipped with a biodegradable liner and their patented sealing system), which was then anaerobically digested. The resulting digestate was composted with rice straw (0.45 kg straw/ kg digestate) for one month in windrows (approximately 80 cm wide and 2 m long) turned twice every week. Finally, the resulting compost was vermicomposted using *E. Fetida* worms at ambient temperature, overall yielding three products with potential fertilising value: D^{HEDF}, C^{HEDF} and V^{HEDF}. These three HEDFs are derived from one another, which allowed an investigation of the evolution of nutrients from one treatment stage to the next. The effect of these HEDFs was compared to that of the chemical fertiliser most commonly used in the area of experimentation: NPK at 11-22-16 ratio.

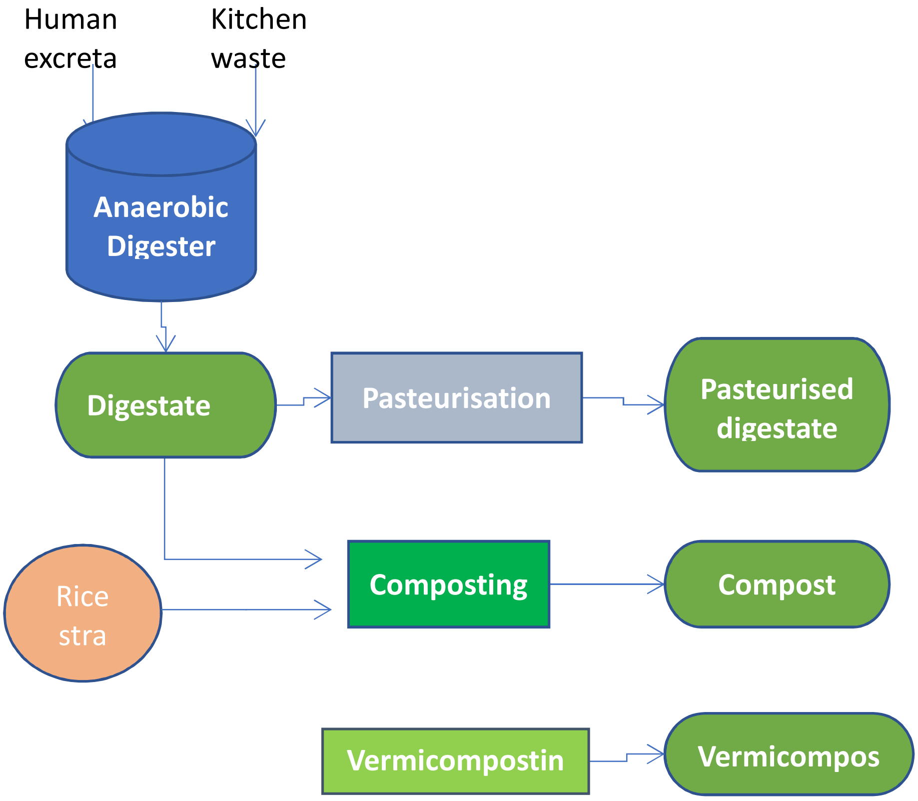

Figure 4-1 Fertiliser production process

The effect of 4 different treatments were compared : D^{HEDF}, C^{HEDF}, V^{HEDF}, inorganic chemical fertiliser (I) with application rates ranging from 20% to 100% of total recommended fertiliser application (Maep *et al.*) with 20% increments between successive rates. A randomised complete block design was followed in this experiment: three replicates per treatment were randomly distributed in the field in 0.6 m^2 plots with each replicate made up of 3 maize plants.

Approximately 33 $kg.ha^{-1}$ of N was applied for maize following Malagasy government's guidelines (Maep *et al.*, no date; Husson *et al.*, 2010) and using the N content of each fertiliser shown in Table 4.2 as the basis for calculating fertiliser quantities. The 100% rate of application for V^{HEDF}, C^{HEDF} and D^{HEDF} were 0.3 kg.m^{-2}, 0.14 kg.m^{-2} and 2.9 L.m^{-2} respectively. The field layout is shown in Figure 4-2. The total dose of C^{HEDF}, V^{HEDF} and D^{HEDF} was applied before sowing the seeds. No crop irrigation was necessary since crops were planted during the rainy season, corresponding to an average monthly precipitation of 237mm between the months of November and March (WMO, 2016).

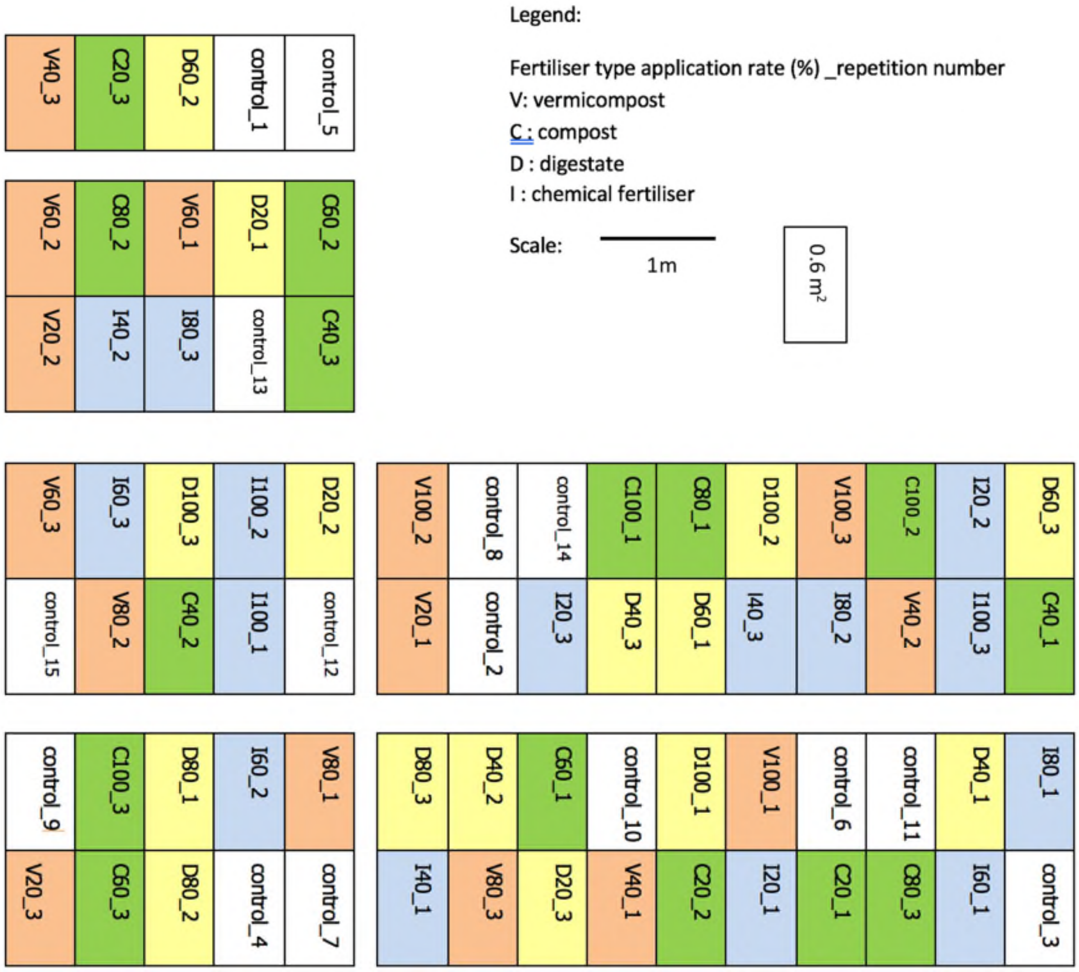

Figure 4-2 Maize plots layout

The nutrient content of the fertiliser was analysed in July 2014 by a commercial laboratory in Antananarivo, LRI (Laboratoire Radio Isotopes). Standard methods were used for the nutrient analyses: pH determined in 1M KCl (ISO10390:2005), organic Carbon by the wet oxidation method (ISO14235:1998), available N by extraction by $CaCl_2$ followed by thermocolorimety (ISO14255:1998), Total N was determined by the Kjeldhal method (ISO11261:1995), exchangeable micronutrients (K, Ca, Mg, Zn and Mn) were extracted by cobalt hexamine followed by spectrophotometric measurement (ISO11047:1998), available P was determined by extraction using sodium hydrogen carbonate and measured colorimetrically (ISO11263:1994) and total P by mineralisation by $HClO_4$ and measured by colorimetry (ISO14869-1:2001).

Plant parameters were monitored weekly throughout crop growth (plant height, stem thickness and number of leaves). When crop maturity was reached, maize cobs were harvested from each plot and measured and weighed to obtain yield information. Final Fresh Weight (FW) plant biomass was also recorded for each plot. Data were analysed by factorial ANOVA using the statistical analysis software Statistica 11 (Statsoft Inc., 2011), and means compared by a Least Significant Differences (LSD) test with significance determined at $p \leq 0.05$. There were three replicates for each parameter.

Nutrient use efficiency (NUE) is a parameter used to evaluate the effectiveness of fertilisers by relating the crop yield obtained to the fertiliser rates applied according to Equation 1. NUE was evaluated for each treatment applied and the different application rates associated.

$$NUE = \frac{Maize\ yield\ per\ plot}{Nitrogen\ applied\ per\ plot} \qquad (1)$$

4.2.2 Farmer interviews

A series of 81 face to face structured interviews with individual farmers were conducted in the peri-urban area of Antananarivo between January and March 2015. Interviews were carried out in 17 different neighbourhoods within a 1 hour bus journey from the capital’s city centre and each interview lasted roughly 1h. Farmers were found by walking through the fields of each neighbourhood and inviting them to participate in an interview. The central topics of the interview were the farmer’s socio-cultural background, their agricultural practices as well as their fertiliser use and their reaction to HEDFs. To find out the influence of the origin of the fertilisers on the farmers’ perception of them, farmers were first presented with the HEDFs without the origin of the fertiliser being disclosed. Once they had given their opinion and stated whether they would be willing to use them, interviewees were then told the fertilisers were HEDFs and they were asked again their opinion about the product.

The interviews were structured questionnaires; answers were recorded on paper during each interview and subsequently transcribed for statistical analysis. The structured nature of the interviews allowed quantitative analysis of the data to produce descriptive statistics.

4.3 **Results**

4.3.1 Comparison of the nutrient content of the different HEDFs applied

The nutrient concentration of the three types of HEDFs used in this trial differs as can be seen in Table 4.2, showing the nutrient transformations that occur in each treatment step.

Table 4.2 Comparison of the nutrient content of the different HEDFs applied (± indicates results standard error)

Parameters	**D^{HEDF}**	**C^{HEDF}**	**V^{HEDF}**
pH	8.5 ± 0.05	8.7 ± 0.1	7 ± 0.1
Total N	877 ± 57 (mg.L^{-1})	23 ± 4 (g.kg^{-1})	11 ± 0.1(g.kg^{-1})
Ammonium N (mg.kg^{-1})		210 ± 27	32 ± 0.9
Nitrate (mg.kg^{-1})		7 ± 2.6	977 ± 36
Organic C (g.kg^{-1})		393 ± 17	175 ± 8
C/N ratio		17	16.6
Total P (mg.L^{-1})	42 ± 3		
Extractable P (g.kg^{-1})		21 ± 1	212 ± 6.3
Exchangeable K (g.kg^{-1})		26.4 ± 2.8	5. 07 ± 0.2
Exchangeable Ca (mg.kg^{-1})		349 ± 122	881 ± 24
Exchangeable Mg (mg.kg^{-1})		252 ± 60	946 ± 18
Exchangeable Mn (mg.kg^{-1})		6.6 ± 0.5	6.6 ± 0.3
Exchangeable Zn (mg.kg^{-1})		3.5 ± 0.8	0.9 ± 0.2

Fewer parameters were analysed for the D^{HEDF} than the C^{HEDF} and V^{HEDF} because of the limited capability of the local laboratory in Antananarivo. The nutrient content of the digestate and compost could not directly be compared because not all the parameters were analysed due to the challenges in dealing with liquid samples such as digestate. The Total N content increased from 0.88 g.L^{-1} in the D^{HEDF} (approximately equivalent to 0.88 g.kg^{-1} given that the digestate had a density similar to that of water) to 23 g.kg^{-1} in C^{HEDF}, due to the addition of rice straw and the concentration phenomenon that occurs during composting through the degradation of organic carbon compounds (Bernal *et al.*, 1998).

The Total N concentration in the V^{HEDF} was 85% lower than that in C^{HEDF}, however the N compound form was different: the overall amount of available N (ammonium and nitrate concentrations combined) in V^{HEDF} was 1009 mg.kg^{-1} compared to only 217 mg.kg^{-1} in C^{HEDF}. The available P concentration was ten times higher in V^{HEDF} than C^{HEDF}; similarly as with N, the digestion process of the worms changed the form in which the P is present from an organically bound to a soluble and available form.

Project-related time pressures and difficulties in securing trial sites in the peri-urban area of Antananarivo meant that soil tests could not be carried out before selecting the experimental site. The soil properties at the trial site are given in Table 4.3 and was of good quality as a result of regular chicken and cow manure applications during previous crop growing seasons; the organic matter content of the soil was as high as that in forests (Foth, 1991) and the pH was acidic (Table 4.3), which affected the results of the crop trial. Here the term soil quality is based on the Soil Quality Indicators detailed in the UK Environment Agency publication in 2006 (Environment Agency, 2006). Whilst this is not directly applicable to Madagascar it provides some ball park figures for soil organic carbon value in arable which ranges between 2 - 7.6% (clay soil) and 1 - 5.6% (sandy loam). In Table 4.3 the total carbon value is 1.92% and based on the soil texture it falls within the good soil quality range of organic C for sandy loam.

Table 4.3 Initial soil conditions at pilot site (before applying HEDFs)

Parameters	Value
pH	4.89
Total Carbon	1.92 %
Organic matter	3.3 %
Clay content	10 %
Silt content	5 %
Sand content	85 %
Ammonium concentration (NH_4)	3.68 ± 0.47 $mg.kg^{-1}$
Nitrate concentration (NO_3)	28.54 ± 3.82 $mg.kg^{-1}$

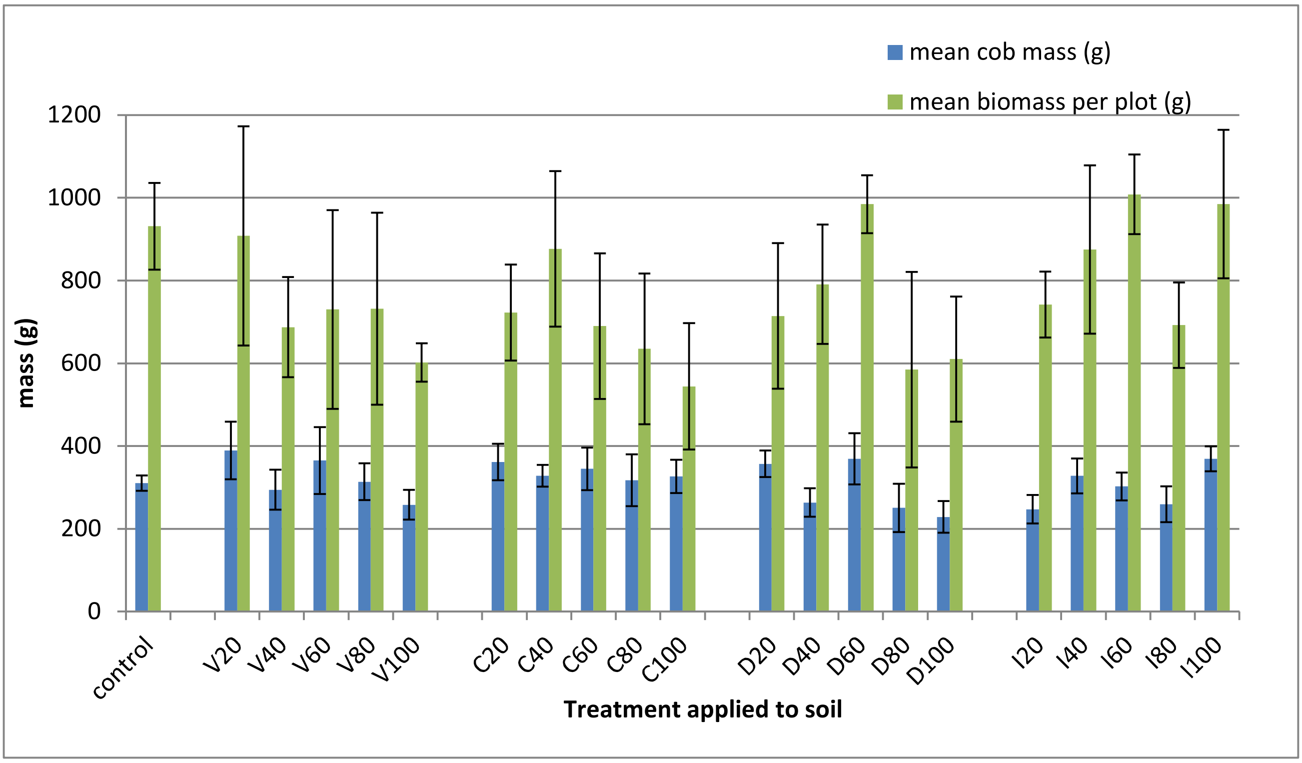

Figure 4-3 Maize yield from experimental plots: mean (n=3) cob mass (FW) and biomass yield (FW) per plot (the first letter indicates the treatment type and the number corresponds to the treatment application rate. Error bars indicate ± 1 SE

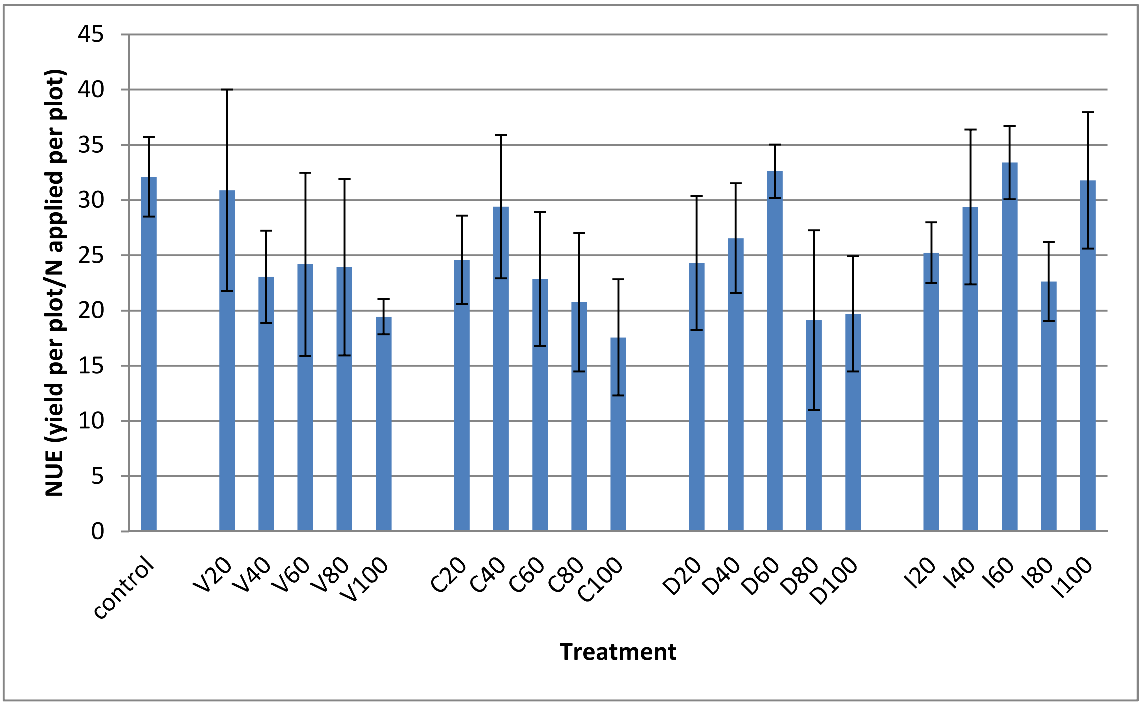

Figure 4-4 Nutrient Use Efficiency calculated using the mean maize biomass yield (FW) per plot (the first letter indicates the treatment type and the number corresponds to the treatment application rate. Error bars indicate ± 1 SE

No clear trends were observed between the yields or the size of cobs harvested (FW) from plots treated with different fertilisers applied at different rates as can be seen in Figure 4-3. No statistically significant differences (p>0.05) were observed between the FW yields obtained with between any of the HEDF or Chemical fertiliser treatments and un-treated control. Whilst little differences were observed between the different fertilisers applied, it could be noted that the HEDFs did not have a negative effect on soil or crop growth and that in this experiment the effect of the HEDFs and chemical fertilisers was comparable.

In this study, currently there is limited information about the pathogens as further work is in progress to quantify it (presented in Chapter 3). However, the preliminary data shows that the risk from *E. coli* is below the risk levels outlined by the WHO guidelines for the safe use of wastewater, excreta and greywater (WHO, 2006).

4.3.2 Interviews with farmers of the peri-urban area of Antananarivo

The main findings from the interviews are summarised in Table 4.4.

Table 4.4 Farmer interview responses

Parameter	% of positive response
Men	78%
Women	22%
Any farming related training received	9%
Community involvement, member of any community group	27%
Have another occupation aside from farming	51%
Member of a farmers' group	4%
Own the land they grow crops on	46%
Subsistence farming	81%
Sell produce	77%
Fertiliser use	93%
• Organic fertiliser	81%
• Chemical fertiliser	47%
• Liquid fertiliser	0%
Reaction to HEDFs	
Willing to use Loowatt's HEDFs after simple visual inspection	88%
Not willing to use the HEDFs any more when told they originate from human excreta	16%
Prefer C^{HEDF} or V^{HEDF}	59% prefer V^{HEDF}

One of the aims of the interviews was to understand the social capital of farmers of the peri-urban area of Antananarivo in order to identify suitable channels to reach potential fertiliser customers. It was however found that only 28% of interview respondents were members of local groups or associations, none of these were related to farming. It was also found that farming in the peri-urban area was mostly based on traditional practices since only 9% of respondents had received agriculture-related training and hence their knowledge of soil health is based on traditions more than understanding nutrient content of soil or plant needs. 93% of farmers use fertilisers on their land with many of them using a mix of both organic (animal manures) and chemical fertilisers. Farmers in the peri-urban area are subsistence farmers with small plots of land and a very low purchase power; 51% wanted to change the fertiliser they used and out of those, 39% stated that a lack of financial means was their main barrier to change.

After being asked about their background and farming habits and experiences, interview respondents were presented with HEDFs without being given any information on their origin; 88% were willing to use them on their field. They were then told that the fertilisers were made from human excreta and only 16% changed their mind once they knew. None of them had ever heard of vermicompost before it was shown to them and it was not perceived to have a higher value than other organic soil amendments. Farmers were unaware of the process of vermicomposting, which highlighted the low farming-related education level of farmers of the peri-urban area. About half of the interviewees however stated they would prefer using V^{HEDF} to C^{HEDF} on their fields, principally because of its appearance and structure rather than its added beneficial properties compared to C^{HEDF}.

No farmers had ever used liquid fertilisers previously, implying that liquid digestate as a fertiliser would be unlikely to be adopted in the area by smallholder farmers. These two examples highlighted the importance of product structure, presentation and perceived ease of use for farmers when adopting new products.

4.4 Discussion

From the differences in nutrient concentration observed between the three forms of HEDF, it was anticipated that there would be differences in the effect on plants when applied to soil. The initial soil quality of the trial site was very high as a result of regular organic fertiliser (manure) applications in previous years, reducing the need for nutrient additions to the soil for healthy crop growth. This reduced the probability of crop response to the fertilisers applied and hence also reduced the likelihood of obtaining statistically relevant differences between experimental plots. The rainfall during the rainy season of 2015 in Madagascar was also particularly high, due to two tropical storms, Chedza and Fundi which caused severe flooding in the capital (IFRC, 2015). This high rainfall also affected the crops and soil; it is likely that higher nutrient leaching took place with rain infiltration, which could be another factor in the reduced crop response to the different fertiliser quantities and types applied.

The nutrient content of composts and vermicomposts has been shown to be highly dependent on the raw materials used to produce it (Campitelli and Ceppi, 2008; Yan *et al.*, 2013); it is therefore difficult to directly compare them unless they originate from the same material. In this experiment however the vermicompost was derived from the same compost used in the crop trial so the nutrient transformation through the vermicomposting process could be traced. The digesting action of the worms had a significant effect on the macro and micronutrient content of the final product; notable differences were observed between the nutrient concentration of C^{HEDF} and V^{HEDF}. Vermicomposting has been shown to accelerate the process of nutrient mineralization and as a result nutrients in vermicomposts are present in more plant-available forms (Orozco *et al.*, 1996). The concentration of organic carbon in vermicompost was half of that in compost, which is characteristic of vermicomposting, which accelerates C mineralization (Aira and Domínguez, 2008). Vermicomposting also had a notable effect on the concentration of secondary micronutrients. The vermicomposting process more than doubled the concentration of Ca ($p < 0.001$) and the concentration of Mg was more than three times higher in V^{HEDF} than in C^{HEDF} ($p < 0.001$). The Zn concentration decreased during the vermicomposting process by more than one third ($p < 0.001$); this is because the worms bioaccumulate metals (Suthar and Singh, 2009).

The concentration of Total N was significantly reduced ($p < 0.001$) during the vermicomposting process; the final concentration of Total N in V^{HEDF} was less than a quarter than that in C^{HEDF}. This effect has been observed with vermicomposts obtained from different sources; it is most likely due to ammonia losses in the initial stages of the process and is strongly related to the carbon to nitrogen ratio (C/N) of the initial feedstock (Benitez *et al.*, 1999; Sánchez-Monedero *et al.*, 2004; Yadav *et al.*, 2010). The concentration of organic carbon in C^{HEDF} was almost double to that in V^{HEDF}, which originated from the rice straw added to the digestate for composting. Lower organic carbon in vermicompost could be related to it being assimilated by the worms and partly released as (CO_2) through respiration thus lowering the carbon concentration in the vermicompost casts. This is in agreement with experimental results reported by Yadav *et al*. (2010) and Orozco *et al*. (1996). However, the primary nutrients N and P were present in soluble and mineralised forms in vermicompost, making them more readily available to plants and making it a faster acting amendment than compost despite the relative lower nutrient concentrations. The ammonium and nitrate concentrations were significantly different between C^{HEDF} and V^{HEDF}. The ammonium concentration in C^{HEDF} was almost seven times higher than in V^{HEDF} and the nitrate concentration was one hundred times higher in V^{HEDF} than C^{HEDF}. This suggests that vermicomposting process enables nitrification to take place through the worms' activity digesting organic matter and producing casts, which are more easily consumed by the microorganisms that assist the mineralisation process of producing nitrate. The decrease in pH as a result of vermicomposting is another factor showing that a nitrification process occurred between the compost to vermicompost stage since protons are released in that reaction, increasing the acidity of the vermicompost.

When comparing the NUE between plots in Figure 4-4, no clear trend was observed, in accordance with the observations made with the yields per plot. Due to the already high initial N concentration in soil, adding different fractions of N to the plots did not have a significant impact on the yield obtained. The amount of N added was one order of magnitude smaller than the concentration of available N already present in the soil, there was therefore no visible effect of the fertiliser application rates on yields. The highest NUE was obtained with 60% application of chemical fertiliser and the lowest with 100% application rate of C^{HEDF}. Higher application rates (80 and 100%) of V^{HEDF}, C^{HEDF} and chemical fertiliser led to a lower NUE than the lowest application rates. This observation is in accordance with the fact that no significant differences in yield were observed between plots: the lowest and highest fertiliser application rates achieved similar results and hence the lower application rates resulted in a higher efficiency in terms of yield per amount of fertiliser applied.

The NUE trends showed that the highest NUEs were achieved at the lower fertiliser application rates (20%, 40% or 60% depending on the treatment), reflecting the initial good soil health in the field, which did not require additional N. Low NUE at high rates showed that higher HEDFs applications yielded no added benefits and lower application rates were more efficient in terms of nutrient use.

Aside from the agronomic value of HEDFs, their commercial value also needed to be considered in order to produce a product viable in the local market. The farmer interviews in the peri-urban area helped explore this issue and provided a picture of the local potential customers and their perceived needs. The main point that came out from the interviews is that farmers of the peri-urban area of Antananarivo were not a united or organised collective with little formal agronomical knowledge. The vast majority of farmers in the peri-urban area of Antananarivo had received no formal agronomy related training and their practices were based on local traditional knowledge and know-how passed down through generations. This is a common trend observed in SSA for smallholders, which limits their access to fertilisers and prevents higher crop yields to be achieved (Njoroge *et al.*, 2015). No farmer associations or groups exist in the peri-urban area of the capital, indicating a low social capital at present. Kampen and Shapland (2004) recognised the importance of existing social capital for introducing innovation for agricultural development in SSA: cases where farmers' social capital was used for shaping and introducing agricultural extension programs were more successful than those where programs were implemented in a top-down approach. Sanginga *et al*. (2001) also highlighted the importance of building social capital in farmer groups to achieve successful results in extension programs. Training is an essential part of introducing a change in farming practices, but experience has shown that training alone rarely gives rise to long term adoption of technologies (Heemskerk and Wennink, 2004). It is in cases where social capital was used and increased alongside training where uptake of new technologies tends to be higher. At present farmers of the peri-urban area of Antananarivo do not have a common voice, they are not interconnected, nor do they have access to knowledge-sharing or trainings, limiting the possibilities for introducing and disseminating innovative practices or products.

In the peri-urban area it was also common for the farmers to have another source of income, 51% of farmers interviewed had another occupation aside from farming, which implied that the time and attention they dedicated to their fields was limited. Half of the respondents stated finding out about new products through TV or radio adverts, highlighting a lack of connectivity between farmers. The lack of farmers' networks would make it more difficult to target them as a group or implement changes in their agricultural practices.

The positive attitude of farmers towards HEDFs however indicated that there were little prejudices against HEDFs, suggesting that there is no local stigma against FS reuse, which was observed in other contexts (Cofie *et al.*, 2005). It is however difficult to make a definite statement about the local acceptability of HEDFs because of potential interviewer-related bias. In market research and customer satisfaction interviews it is common for a 'courtesy bias' to occur: respondents give the answers they think the interviewer is expecting and not their true opinion so as to not cause offence (Thomas *et al.*, 2011; Adida *et al.*, 2016). According to the interview responses, potential barriers to the use of HEDFs would not come from a moral prejudice but would rather be related to low purchase power or lack of awareness about new products. The majority of farmers however stated they would not tell their customers about the origin of the fertilisers, showing that there is a fear of stigma of using faecal matter of human origin to produce the fertilisers.

Farmers in the peri-urban area were accustomed to using organic fertilisers but did not buy them in shops, rather bartered them or bought them locally from other farmers. When farmers buy fertilisers, they expect them to have similar effects to chemical fertilisers, which is difficult to achieve with organic fertilisers. These characteristics constitute challenges for marketing HEDFs to local farmers of the peri-urban area of Antananarivo, they do not constitute the ideal customer group for the marketing of a new fertiliser Given the low purchase power of small scale farmers, their farming methods being based on traditional practices and the lack of networking structures within the peri-urban area, farmers of the peri-urban area are unlikely to be the best initial customers for these fertilisers.

4.5 Conclusions

Notable nutrient concentration differences were observed between D^{HEDF}, C^{HEDF} and V^{HEDF}. A nutrient evolution was observed through the treatment chain of human excreta: the composting process concentrated the nutrients present in digestate and vermicomposting modified the form in which nutrients (such as nitrates, phosphates, Ca and Mg) were present making them more easily available to crops. The quality of the C source, which is the substrate for the soil microorganisms, was different in compost and vermicompost and influenced the mineralisation and availability of nutrients to crops. The field study showed that HEDFs did not have a detrimental effect on maize. Further field studies on soils with different properties should be carried out to further characterise the effect of the different HEDFs on soil and crops. Interviews with local farmers of the peri-urban area of Antananarivo highlighted the importance of developing fertiliser products appropriate for the local market targeted. From the interview results it was clear that adoption of liquid digestate as a fertiliser by smallholder farmers would be more challenging than that of a fertiliser in solid form, which farmers are most used to in the peri-urban area. The importance of fertiliser texture was also highlighted by a majority of farmers stating a preference for V^{HEDF} over C^{HEDF} because of its dry and granular texture, perceived as easier to handle and apply. These findings suggest that if new practices such as the use of HEDFs are to be adopted by local farmers, there is a need to provide training to increase farmers' understanding of soil health management and fertiliser use. The interviews highlighted the importance of understanding the local market's needs and expectations for successfully commercialising HEDFs as well as adapting product features to potential customer's perceived needs.

5 EFFECT OF COMPOST AND VERMICOMPOST DERIVED FROM HUMAN EXCRETA ON THE GROWTH OF MAIZE: EVIDENCE FROM A GLASSHOUSE POT EXPERIMENT

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Abstract

Increasing urbanisation rates worldwide are blurring the boundaries between agricultural and urban landscapes, impacting the traditional flows of organic materials in agriculture. Increasing urban population densities also increase the need for sustainable FSM solutions, especially in low and middle-income countries currently lacking infrastructure. Closing the nutrient loop by recycling human excreta is an attractive solution to increase the sustainability of both peri-urban agriculture and urban sanitation. The effects of two types of HEDFs, compost and vermicompost, on the growth and productivity of maize (*Zea Mays*) and their effect on soil nutrients and heavy metal concentrations were investigated in a greenhouse experiment. These were compared to the effect of chemical fertilisers as well as to the mixture of chemical and organic fertilisers. The largest fresh grain weights at maturity resulted from pots treated with V^{HEDF} and the lowest from those treated with chemical fertilisers only. The application of V^{HEDF} led to an increase in organic matter, K and Mg concentrations in soil. Soil analyses showed several benefits of C^{HEDF} and V^{HEDF}: an increase in soil pH and gradual release of nutrients during crop growth (K and Mg), also seen with the application of mixtures of HEDF and chemical fertilisers. The heavy metal concentrations in soil were not affected by the application of the HEDFs.

The formatting of the original published manuscript has been adjusted to fit the format of this thesis

5.1 Introduction

Soil is a non-renewable resource upon which humans depend for growing their food; it is of prime importance to preserve healthy soil systems to guarantee sustainable food production worldwide. Every year 12 million hectares of agricultural land are lost to soil degradation worldwide, adding to the billions of hectares that are already degraded (Rickson *et al.*, 2015). In many parts of the world soils are gradually being depleted of organic matter, mainly due to continued application of chemical fertilisers without efficiently replenishing soil in organic matter after crop harvests. Organic matter is essential for maintaining good soil health supporting a diverse microbial community, key for maintaining productive soil systems (Reeves, 1997).

With urbanisation rates rising worldwide, food is increasingly grown in urban or peri-urban areas. This is especially true for leafy vegetables due to their limited freshness if unrefrigerated; in many cities of Africa and Asia, leafy vegetables are mostly grown within 30km from urban centres (De Bon *et al.*, 2010). In these peri-urban areas, access to traditional sources of organic matter is generally limited. The most common sources of organic matter are animal manure and agricultural waste, which in peri-urban areas can only be produced in limited volumes due to competition for land use, creating challenges to meet future food demands from growing cities (Dienor *et al.*, 2011). Organic matter sources readily available in urban areas are organic wastes such as food waste and human excreta.

Another issue that will become critical in the near future is the availability of nutrients for crop growth; there is a need to decrease reliance on finite mineral nutrient resources and close nutrient loops by efficiently recycling organic wastes. Phosphorus reserves are especially of concern because of the limited quantity of phosphate rock available and the locations of these mineral resources, which are in geopolitically sensitive areas (Rosemarin and Ekane, 2016). Cordell *et al.* (2009) highlighted the issues related to current consumption and production of phosphate fertilisers and showed the need for realisation of alternative sustainable sourcing of phosphorus at large scale. In an effort to increase selfreliance for food production, many countries are now exploring options for recycling nutrients to land by producing soil amendments and promoting the concept of a circular economy for fertiliser production (European Commision, 2015). Human excreta are a valuable source of P since almost 100% of the P eaten by adults is excreted, with the highest concentration in the urine fraction (Bracken *et al.*, 2009). With ever increasing urban populations, it can be argued that excreta are the largest source of P in cities (Jonsson *et al.*, 2004; Cordell *et al.*, 2009). It is estimated that if all urine and faeces were collected and their P harvested, it could account for 22% of the global P demand (Mihelcic *et al.*, 2011). Moreover, many low-income countries do not have efficient systems in place for managing human FS with most of it ending up untreated in the local environment posing a health threat. It is estimated that currently only 32% of the population in least developed countries have access to basic sanitation and worldwide less than half (39%) of human excreta and waste water are safely managed (i.e. includes transport and adequate treatment of excreta) (UNICEF and WHO, 2017). Transforming human excreta into HEDF is one way of creating economic incentives for treating and generating value from toilet waste while producing an organic soil amendment in the form of HEDF to improve soil fertility and recycling nutrients in soil in a resource-constrained and increasingly urbanised world (Haq and Cambridge, 2012).

The composition of organic fertilisers is directly related to the organic matter it originates from and to the treatment process the material has undergone (Fuchs *et al.*, 2008). There is therefore a need to investigate the potential fertiliser products that can be obtained from organic materials such as human excreta and evaluate their quality. The positive effect on soil of fertilisers derived from human excreta has been demonstrated but there are few controlled plant studies that have been carried out to evaluate the effect of these fertilisers (Cofie *et al.*, 2005; Guzha *et al.*, 2005; Adamtey *et al.*, 2010; Drechsel *et al.*, 2010; Impraim *et al.*, 2014; Moya *et al.*, 2017).

Eliminating pathogens contained in faeces is one of the main challenges for treating human waste. Composting is a treatment that efficiently eliminates pathogens given that it is a naturally exothermic process and can transform excreta into a soil amendment rich in nutrients and organic matter. In the first week of composting, microbial organisms feed on the raw organic material and multiply, this increase in microbial activity in turn causes an increase in temperature in the pile. Temperatures reach over 65^{O}C, which if sustained for several hours can kill the most persistent pathogens (Feachem *et al.*, 1983). US EPA rules state that materials that maintain a temperature above 55^{O}C for 15 days achieve sufficient pathogen removal (Walker *et al.*, 1994).

Another process for the treatment of FS that has recently received more attention is vermicomposting. Vermicomposting is the digestion of organic matter by specific earthworms, *E. fetida,* which degrade organic matter and produce worm casts to give a final product that has higher concentrations of nutrients in plant-available forms than compost but also contains organic matter as opposed to chemical fertilisers (Orozco *et al.,* 1996; Atiyeh *et al.*, 2000). Unlike compost, the vermicomposting process occurs at room temperature and is not an exothermic reaction; high temperatures for pathogen inactivation are therefore not achieved. However, pathogen inactivation by vermicomposting has been reported. Eastman *et al* (2001) showed significant decrease in pathogen concentrations of class B biosolids that had been strongly inoculated with pathogens and subsequently vermicomposted. Through a series of experiments Monroy *et al* (2009) found that it is the action of the microorganisms in the gut of the worms that caused a decrease in the number of total coliforms possibly by being out-competed by another group of microorganisms in the gut of the worm.

In order to benefit from the advantages of both composting and vermicomposting, mixing the two techniques has been recommended to achieve pathogen removal as well as reduce the time required for vermicomposting (Nair *et al.*, 2006). Ndegwa and Thompson (2001) showed that doing an initial composting step before vermicomposting enabled meeting EPA compost guidelines and also yielded a more stable product. When comparing composts and vermicomposts originating from the same material it has been found that vermicompost contains higher concentrations of available nutrients as well as Total N and organic matter

(Tognetti *et al.*, 2007). The vermicompost used in this experiment was part of a two-stage process and derived from compost, which allowed for testing these observations.

There have been studies evaluating the effect of compost derived from sewage sludge on maize (Guzha *et al.*, 2005; Adamtey *et al.*, 2010; Vaca *et al.*, 2011) as well as vermicompost derived from human excreta (Rodríguez-Canché *et al.*, 2010; Begum, 2011) and manure (Atiyeh *et al.*, 1999, 2000, 2001) on different crops. Doan *et al*. (2013 and 2015) compared the effect of compost and vermicompost derived from organic wastes on tomato and maize crops. Research specifically on organic fertilisers which are derived from each other to allow nutrient evolution tracing is scarce, as is research on HEDFs (as opposed to sewage sludge). Moya *et al.* (2017) (presented in Chapter 4) compared the effect of digestate, compost and vermicompost derived from human excreta on maize crops in a field trial and in this experiment those same C^{HEDF} and V^{HEDF} were used to grow maize in a greenhouse. The aim of this study was to evaluate the efficacy of C^{HEDF} and V^{HEDF} on the growth of maize compared with chemical fertilisers under controlled conditions. A glasshouse pot experiment was carried out to provide a more detailed mechanistic understanding of the nutrient evolution in soil as a result of the different treatments applied. The potential of organomineral fertilisers to optimise crop growth and soil health has been shown (Adamtey *et al.*, 2010; Akanni *et al.*, 2011; Antille *et al.*, 2013; Deeks *et al.*, 2013; Pawlett *et al.*, 2015; Antille *et al., 2017*). Another objective of this experiment was therefore to evaluate whether mixing HEDFs with chemical fertilisers also had increased benefits on maize growth.

5.2 **Materials and methods**

5.2.1 Experimental design and treatment

A pot scale experiment was carried out between the months of May and August 2015 in a greenhouse of Cranfield University in the UK. Maize (*Zea mays L.)* was grown in circular pots of 28cm in diameter on sandy soil (Westerham subsoil) obtained from a commercial supplier (Bourne Amenity Ltd). The bottom of the pots was filled with a 2cm layer of gravel for water drainage. Six different fertiliser treatments were applied: C^{HEDF}, V^{HEDF}, chemical inorganic fertiliser (I), a mix of compost and chemical fertiliser (C^{HEDF}+I), a mix of vermicompost and chemical fertiliser (V^{HEDF}+I) and control. The compost and vermicompost were produced in Madagascar as described in Moya *et al.* (2017), derived from source-separated human excreta, which were first anaerobically digested with food waste. The chemical fertilisers nutrient mixes were mixed manually from Nitram (34.5%N), Tri-single super phosphate (46% P_2O_5) and Muriate of potash (60% K_2O). Fertilisers quantities applied were calculated to fulfil N crop requirements: the N content of each fertiliser was measured and quantities required calculated accordingly taking the surface area of a pot as reference (0.05 m^2). The reference N application was taken as that recommended by the Malagasy authorities, which is 300 $kg.ha^{-1}$ of NPK (11-22-16) fertiliser, corresponding to 33 $kg.ha^{-1}$ of N added, P: 66 $kg.ha^{-1}$ added, K: 48 $kg.ha^{-1}$ added (Husson *et al.*, 2010). Each treatment was applied at 5 different rates (20%, 40%, 60%, 80% and 100%) to test the effect of fertiliser concentration on plant growth of each treatment. There were 3 repetitions of each treatment for reproducibility making up a total of 78 pots for the experiment. Pots were laid out in a randomized way in the glasshouse to limit the influence of external factors such as differences in sun exposure, wind and potential spatial temperature variations. Fertilisers were applied as a single dressing at the start of the experiment given the small quantities added to each pot (Table 5.1).

Table 5.1 Fertiliser application rates and corresponding quantities of fertiliser applied per pot

	V^{HEDF}	C^{HEDF}	Chemical fertiliser 11-22-16			V^{HEDF} + chemical fertiliser				C^{HEDF} + chemical fertiliser			
	V	C	N	P	K	V	N	P	K	C	N	P	K
Application rates (g)													
20%	36	17	1.1	4.9	2.8	17.85	0.6	2.4	1.4	8.5	0.6	2.4	1.4
40%	71	34	2.3	9.9	5.5	35.7	1.1	4.9	2.7	17.1	1.1	4.9	2.7
60%	107	51	3.4	14.8	8.3	53.55	1.7	7.4	4.1	25.6	1.7	7.4	4.1
80%	143	68	4.5	19.8	11	71.4	2.3	9.9	5.5	34.1	2.3	9.9	5.5
100%	178	85	5.7	24.7	13.8	89.2	2.8	12.4	6.9	42.7	2.8	12.4	6.9

Three seeds were planted per pot and thinned down to one seedling per pot after 3 weeks, selecting the strongest seedling in each pot (the one with the widest stem or the tallest if stem width did not differ). Plants were irrigated by automatic drip irrigation with drippers of 1.1 $L.h^{-1}$ capacity per dripper and adjusted to maintain soil moisture around 70%. Soil moisture field capacity was measured experimentally following the method detailed in part 5.5 of BS 7755 by saturating a known volume of soil with water, applying a 0.5 bar suction to the sample, allowing it to come to equilibrium and measuring the water content of the sample (BS 7755 section 5.5, 1999). Microbial activity has been shown to be inhibited beyond field capacity moisture levels and higher at soil moistures below field capacity (Zhang *et al.*, 2005). Here it was chosen to maintain 70% field capacity to ensure enough water availability for crops while promoting microbial activity in soil. This was achieved by evaluating the soil evapotranspiration and adjusting irrigation accordingly.

5.2.2 Plant measurements and soil analyses

Plant height, number of leaves and stem thickness (at 5 cm above soil surface) were recorded weekly. Flowering date was also recorded as well as the number of cobs per plant at maturity, above ground biomass DW excluding cobs (g) (dried in an oven at 65°C until a constant weight was achieved), cob sizes (cm), cob FW (g) and grain yields (FW in g) after crop harvest.

Soil samples were taken from each pot one week after planting, during crop growth, 8 weeks after planting, and after harvesting of the corn plants. A range of soil analyses were carried out: pH (ISO10390, 2005), available P (BSI, 1995), organic and total carbon (ISO10694:1995), and available Mg, K, Zn, Cu, Ni, Cd, Cr and Pb were analysed using *aqua regia* digestion (Anton Paar Multiwave 3000) followed by atomic absorption spectroscopy (PerkinElmer AAnalyst 800) (ISO11047:1998; BSI, 1994).

Pathogen analyses were not carried out on the fertilisers used for this experiment since the focus of this study was on the effect of HEDF on soil nutrients and crop growth. Detailed pathogen analyses on these HEDFs were reported in Moya *et al.* (2018) (Chapter 3).

5.2.3 Statistical analyses

The effects of each treatment and application rate on the measured parameters using a range of non-parametric tests since the datasets did not meet normality and homogeneity of variance assumptions needed for ANOVA tests. The analyses carried out were Friedman ANOVA followed by Wilcoxon Matched Pairs tests and Kruskal-Wallis tests followed by Mann-Whitney tests using Statistica 12.0 (Statsoft, 2011) to determine significant differences between different rates and treatments applied. Significantly different levels of treatments were identified using least significant differences at a probability of 0.05 with all tests apart from Mann-Whitney tests where Bonferroni corrections were applied depending on the number of tests carried out.

5.2.4 Soil and treatment characteristics

The initial soil selected for this experiment had low nutrient concentrations (Table 5.2) it was chosen to allow an evaluation of the effects of the fertilisers alone, without interference of nutrients naturally present in soil. This type of soil was also chosen to represent a nutrient-depleted soil, which are prevalent in parts of Madagascar, where these fertilisers are produced and sold.

Table 5.2 Characteristics of the starting soil and organic fertilisers used for the glasshouse. Values in parentheses indicate ± 1 SE)

Sample	Unit	Soil	C^{HEDF}	V^{HEDF}
pH		7.93 (± 0.07)	9.8 (± 0.15)	9.23 (± 0.07)
Dry matter	%	99.8 (± 0.03)	61.1 (± 0.33)	89.7 (± 0.33)
Available P	mg.L^{-1}	7.0 (± 0.4)	180 (± 3.84)	215 (± 3.71)
Available K	g.L^{-1}	<20.10^{-3}	15.9 (± 0.90)	15.7 (± 0.4)
Available Mg	g.L^{-1}	<15.10^{-3}	0.122 (± 0.013)	0.224 (± 0.002)
Nitrate N	mg.kg^{-1}	2.6 (± 0.1)	1.95 (± 0.40)	0.303 (± 0.038)
Ammonium N	mg.kg^{-1}	0.81 (± 0.05)	333 (± 115)	22.8 (± 1.34)
Total N	% w.w^{-1}	0.01 (± 0.0)	2.78 (± 0.05)	2.23 (± 0.01)
Total C	% w.w^{-1}	0.08 (± 0.01)	22.7 (± 0.57)	19.4 (± 0.23)
C/N	:1	8 (± 1.0)	8.13 (± 0.12)	8.7 (± 0.06)

5.3 **Results**

5.3.1 Plant growth and yields

Plants across all treatment types and rates aside from control pots reached similar final heights as shown in Figure 5-1. Pots treated only with C^{HEDF} reached final heights on average lower than the other treatments, but the differences were not significant for all treatment rates. Pots treated with C^{HEDF} at rates 20%, 40% and 60% were significantly shorter ($p<0.003$) than plants treated with V^{HEDF}, chemical fertiliser or mixes of HEDFs and chemical fertilisers at the same rates. Differences in plant growth rate were more significant between treatments than differences in plant height; maximum growth rate was reached at different dates between different treatments as shown in Figure 5-2.

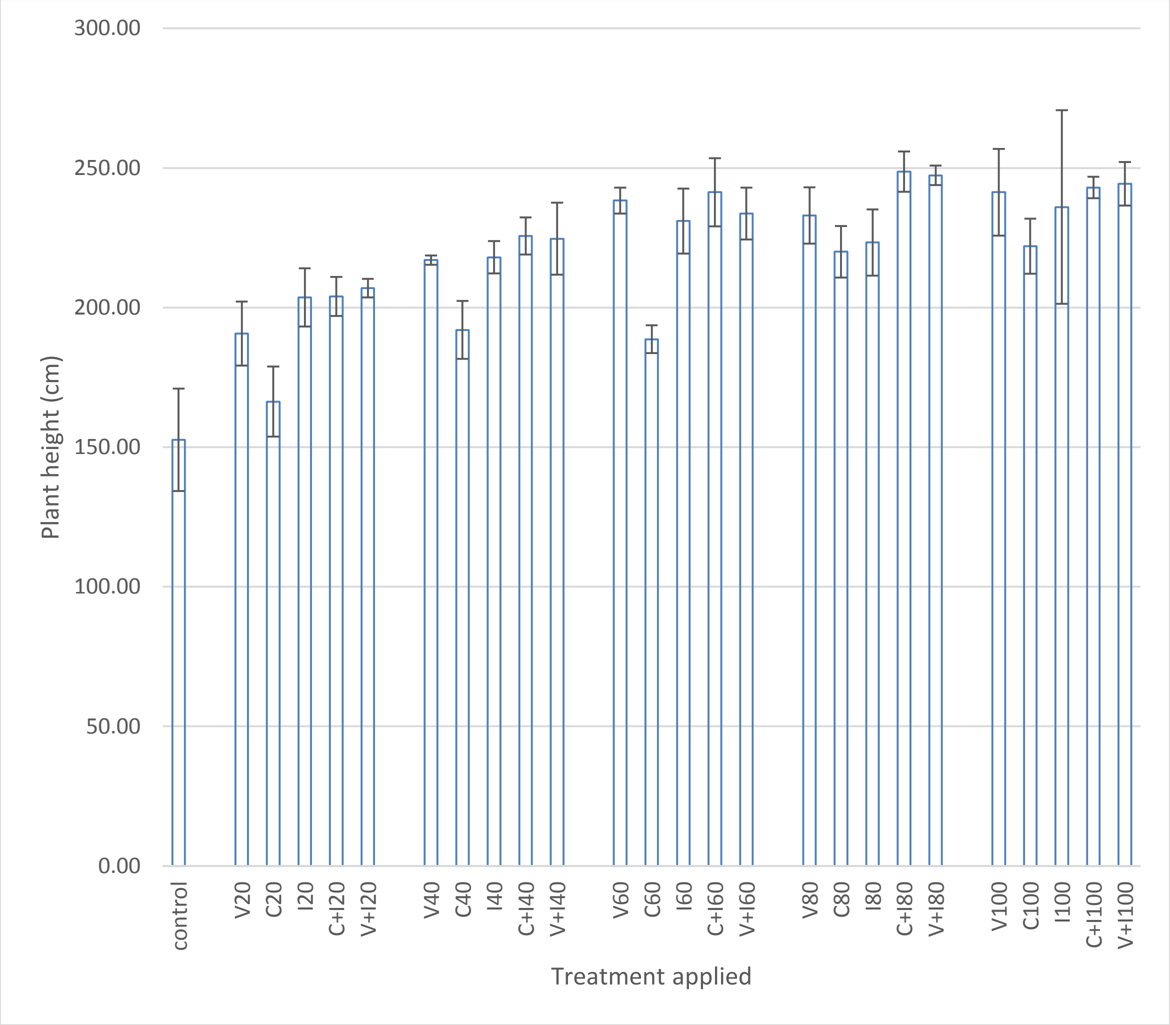

Figure 5-1 Maize plant height reached at maturity (the first letter indicates the treatment type (V is V^{HEDF} and C is C^{HEDF}) and the number corresponds to the treatment application rate. Error bars indicate ± 1 SE).

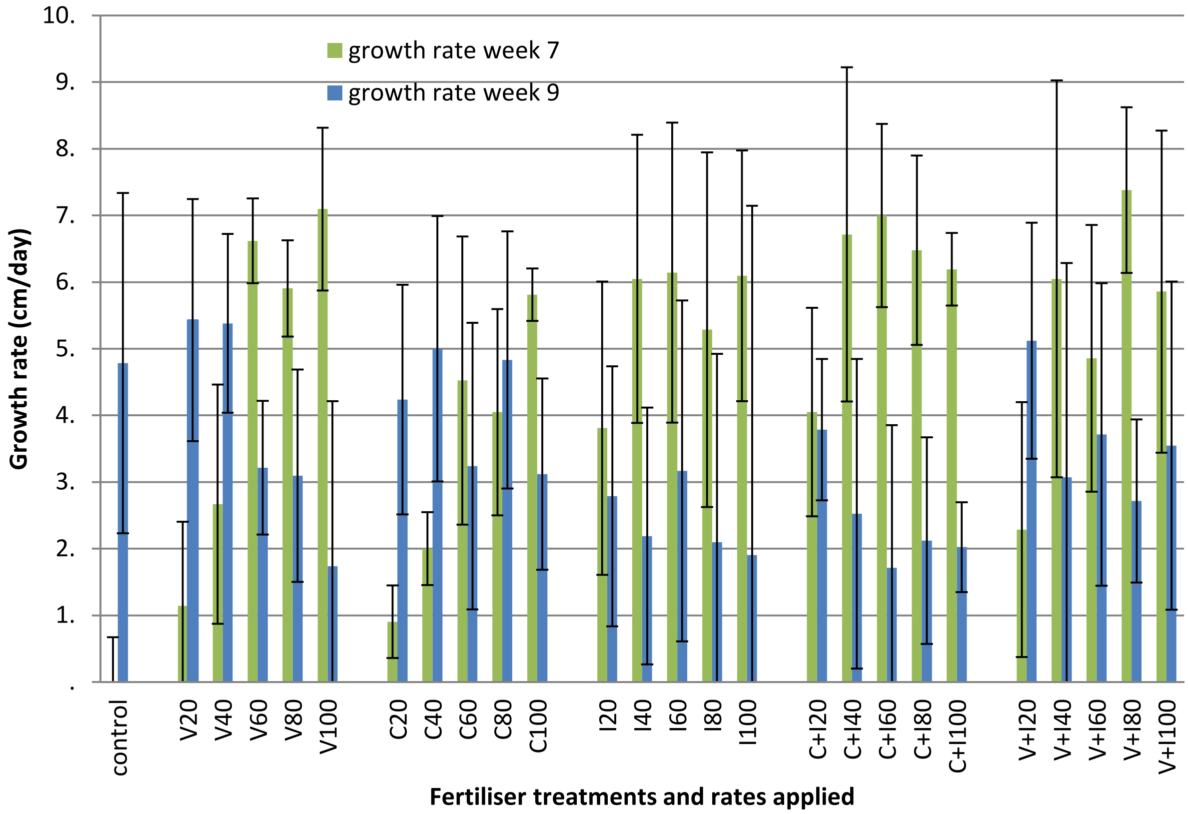

Figure 5-2 Comparison of growth rates between week 7 and week 9 of maize growth between the different treatments applied (the first letter indicates the treatment type (V is V^{HEDF} and C is C^{HEDF}) and the number corresponds to the treatment application rate. Error bars indicate ± 1 SE).

Maximum plant growth occurs before flowering, which for maize is between week 8 and week 10 (Asongwe *et al.*, 2017). In this experiment all plants reached their maximum growth rate 7 weeks after sowing except for control pots and those treated with V^{HEDF} at rates 20 and 40%, C^{HEDF} at rates 20, 40 and 80% and V^{HEDF} mixed with chemical fertilisers (V^{HEDF}+I) at 20% treatment rate. This shows that the type of fertiliser and rate of application influenced plant growth even though similar final heights were achieved at plant harvest. The highest final plant biomass was reached in pots treated with V^{HEDF}+I (95.5g at 80% application rate) followed by pots treated with chemical fertiliser alone (86.9g at 80% application rate).

Despite all plants reaching a similar final height, they didn’t all produce the same number of cobs. Maize harvest from the plants was low, which was expected given the environment in which the plants were grown, small pots kept under artificial conditions. Cobs were much smaller than commercial maize cobs, on average 11.5 cm cob length. The quantities of cobs harvested however did allow for comparison between treatments. All plants produced cobs but only the ones that had developed grains were harvested. As shown in Figure 5-3 plants that received C^{HEDF}80, I20, C^{HEDF}+I20, C^{HEDF}+I40 treatments did not produce harvestable cobs whereas all pots that received treatments that included V^{HEDF} produced cobs. The differences in average cob mass (DW) and grain weight (DW) were not significant between treatments at a given rate given the high error margins due to the low number of cobs harvested from the 3 plant repetitions for each treatment (sometimes only one cob for 3 plants). All treatments produced cobs with higher average cob mass and grain weight than plants from control pots, but statistical analyses did not give significant results when comparing treatments to control pots since only one cob was produced from the three control replicate plants, which didn’t allow for evaluating a standard error for that value. Mann-Whitney tests however showed significant differences ($p<0.01$) between pots treated with V^{HEDF} and those that received chemical fertilisers ($U=16$, $r=0.64$). Aside from the number of cobs produced, their quality also varied between treatments, reflected in the grain weight measurements. As illustrated in Figure 5-4, in certain cases cobs from plants treated with the same fertiliser at the same rate were of different quality.

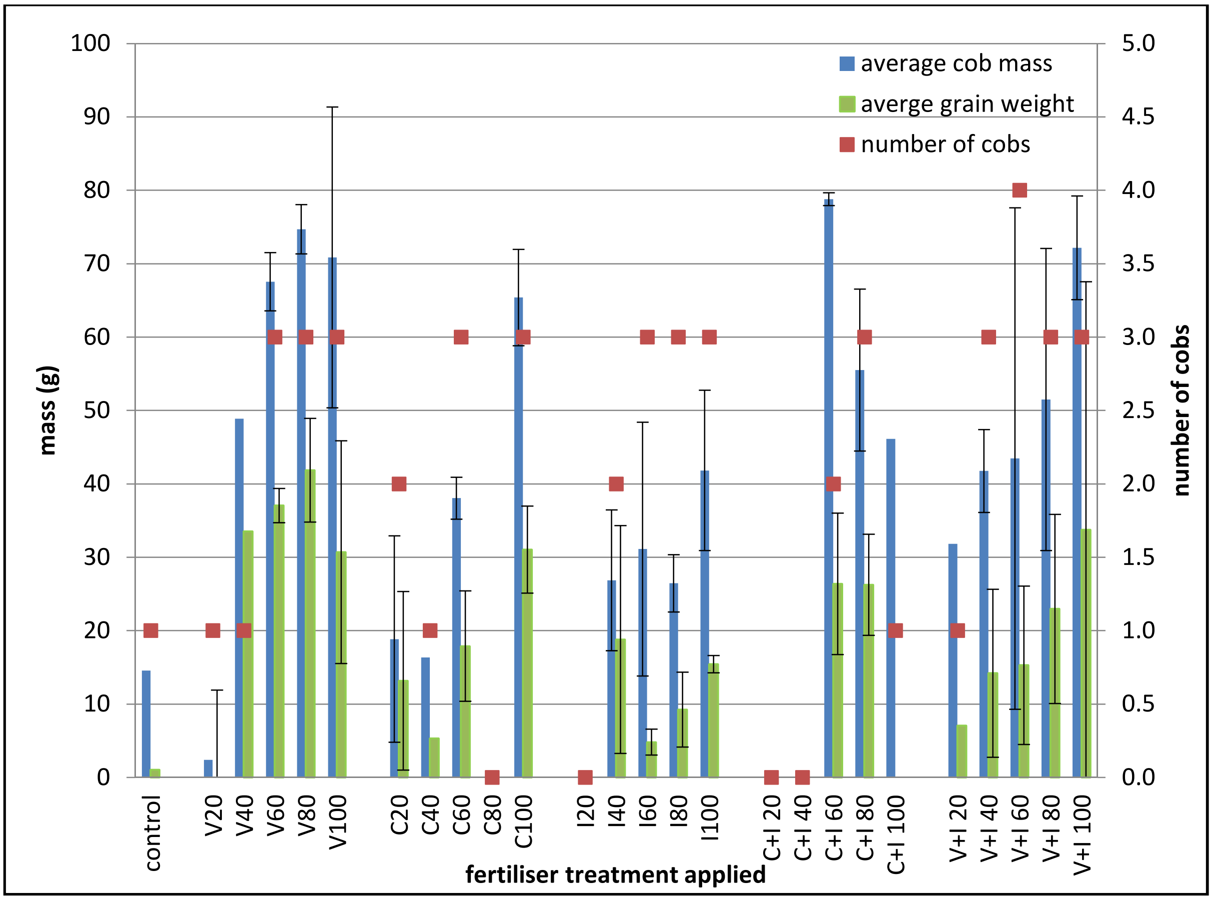

Figure 5-3 Harvested maize yields grouped by treatment and rate applied (the first letter indicates the treatment type (V is V^{HEDF} and C is C^{HEDF}) and the number corresponds to the treatment rate. Error bars indicate ± 1 SE (error bars could not be calculated where only one cob was produced).

Figure 5-4 Photos of the maize cobs harvested from 3 different plants that received the same fertiliser treatment (C+I80 indicates C^{HEDF} treatment with added chemical fertiliser at 80% rate of application and 1, 2, 3 indicates the three replications)

5.3.2 Soil nutrient concentrations

Statistical analyses indicated that available K concentrations in soil were significantly affected by the treatments applied, H(5)=26.06 $p<0.05$. Mann-Whitney tests showed significant differences between the control pots and all other treatments for K concentrations in soil ($p<0.003$) aside for the intermediate soil K concentration in pots treated with C^{HEDF}+I ($p=0.039$), those treated with V^{HEDF} +I in the initial ($p=0.005$) and intermediate ($p=0.005$) maize growth stages and pots treated with chemical fertilisers in the intermediate stage ($p=0.056$). Pots treated with vermicompost had the highest K concentrations for all rates and they increased gradually with increasing fertiliser application rates (Figure 5-5). V^{HEDF} applied at 100% rate had the highest concentration of K after crop harvest (93.9 mg.kg^{-1}), which was 2.3 times higher than the next highest concentration observed (40.34 mg.kg^{-1} for V^{HEDF}+I applied at 60% rate).

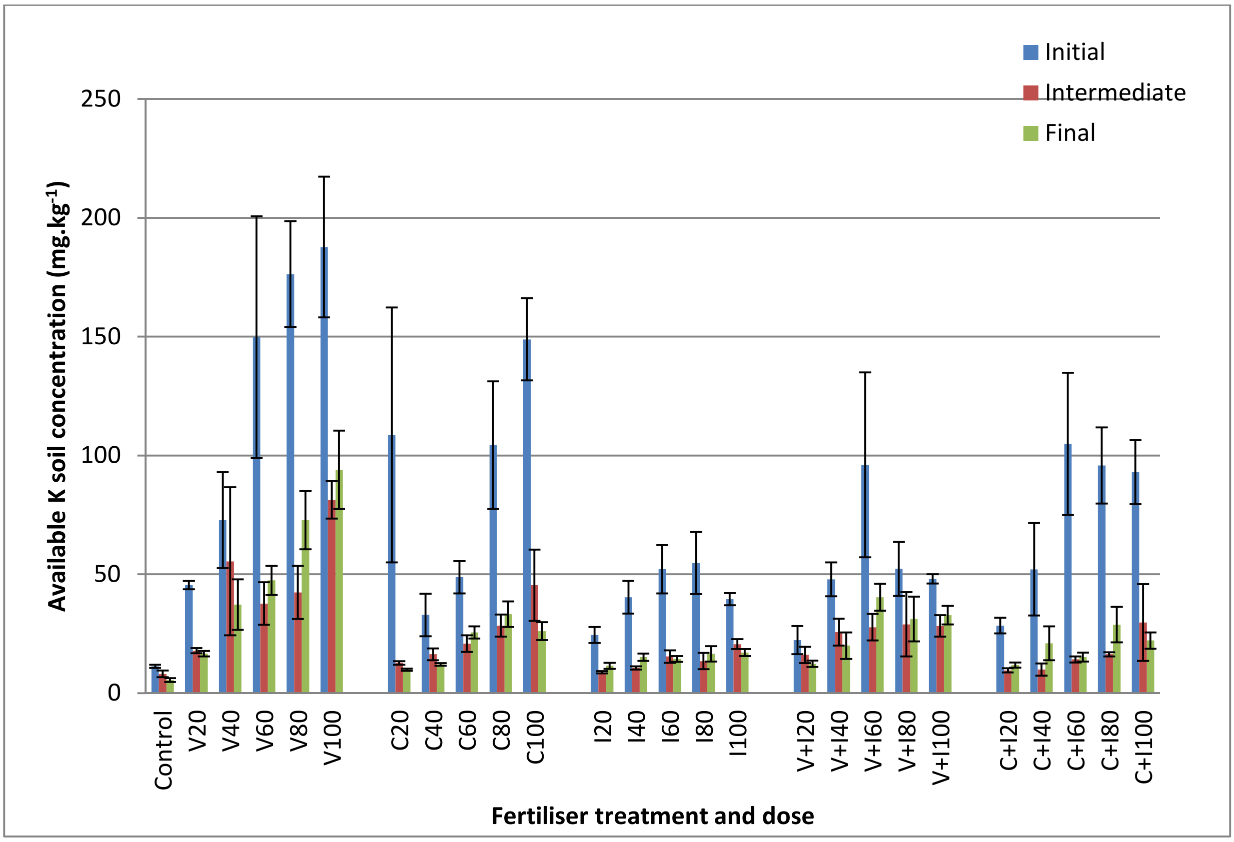

Figure 5-5 Available K concentration in soil in pots treated with different fertilisers (the first letter indicates the treatment type (V is V^{HEDF} and C is C^{HEDF}) and the number is the treatment application rate. Error bars indicate ± 1 SE).

The initial concentrations of K in pots treated with C^{HEDF} and V^{HEDF} were not significantly different in the initial (p=0.2) and intermediate (p=0.02) stages of the experiment but the differences in soil K were significant at the end of the experiment (p=0.003). Similarly, the differences between pots treated with V^{HEDF} and C^{HEDF}+I was not significant at the start of the experiment (p=0.04) but became significant during crop growth (p=0.00) and in the final stage (p=0.001). On the other hand, pots treated with V^{HEDF} and those treated with V^{HEDF}+I had significant differences in K concentration initially (p=0.001) but not in the intermediate (p=0.06) and final (p=0.02) stages. This indicates that nutrient evolution in the pots treated with V^{HEDF} and C^{HEDF} was different, but pots treated with V^{HEDF}

showed similar trends in terms of K release to soil as shown by the similarities between the V^{HEDF} and V^{HEDF}+I treatments.

The concentration of K in pots treated with chemical fertilisers was significantly lower than those in V^{HEDF} but not C^{HEDF} or V^{HEDF}+I or C^{HEDF}+I pots, highlighting again a different behaviour in pots treated with V^{HEDF}. The lower K content of the chemical fertilisers was also due to the type of fertiliser mix used (NPK, 11-22-16), where the concentration of K was controlled whereas with V^{HEDF} application rates were calculated on the basis of N concentration, which is low in comparison with the K concentration in V^{HEDF}. Plants treated with V^{HEDF} and C^{HEDF} absorbed more K from soil than those that received the other treatments, the difference between the final and initial K concentration in soil was on average 72.8 $mg.kg^{-1}$ for pots treated with V^{HEDF}, 67.4 $mg.kg^{-1}$ for C^{HEDF}, 55 $mg.kg^{-1}$ for C^{HEDF}+I, 27.3 $mg.kg^{-1}$ for I and 25.9 $mg.kg^{-1}$ for pots that received V^{HEDF}+I.

Available P concentrations in soil were highest in pots treated with chemical fertiliser, alone or mixed with the other organic fertilisers, concentrations ranged from 9.2 $mg.kg^{-1}$ for C^{HEDF}+I at 20% rate to 109 $mg.kg^{-1}$ for chemical fertiliser alone applied at 100% rate. There were no significant differences in the concentrations of available P between all the pots that had chemical fertiliser applied (I, C^{HEDF}+I, V^{HEDF}+I). The concentrations of available P did not have any variations during plant growth for pots treated with C^{HEDF} or V^{HEDF} and remained low compared to the other treatments (between 3 and 10 times lower than pots that received chemical fertilisers). Most of the P is present in organic form in compost and vermicompost and has to be mineralised before it is available to plants. The lack of variation before, during and after crop growth was likely due to P being directly assimilated when the organically bound P is mineralised.

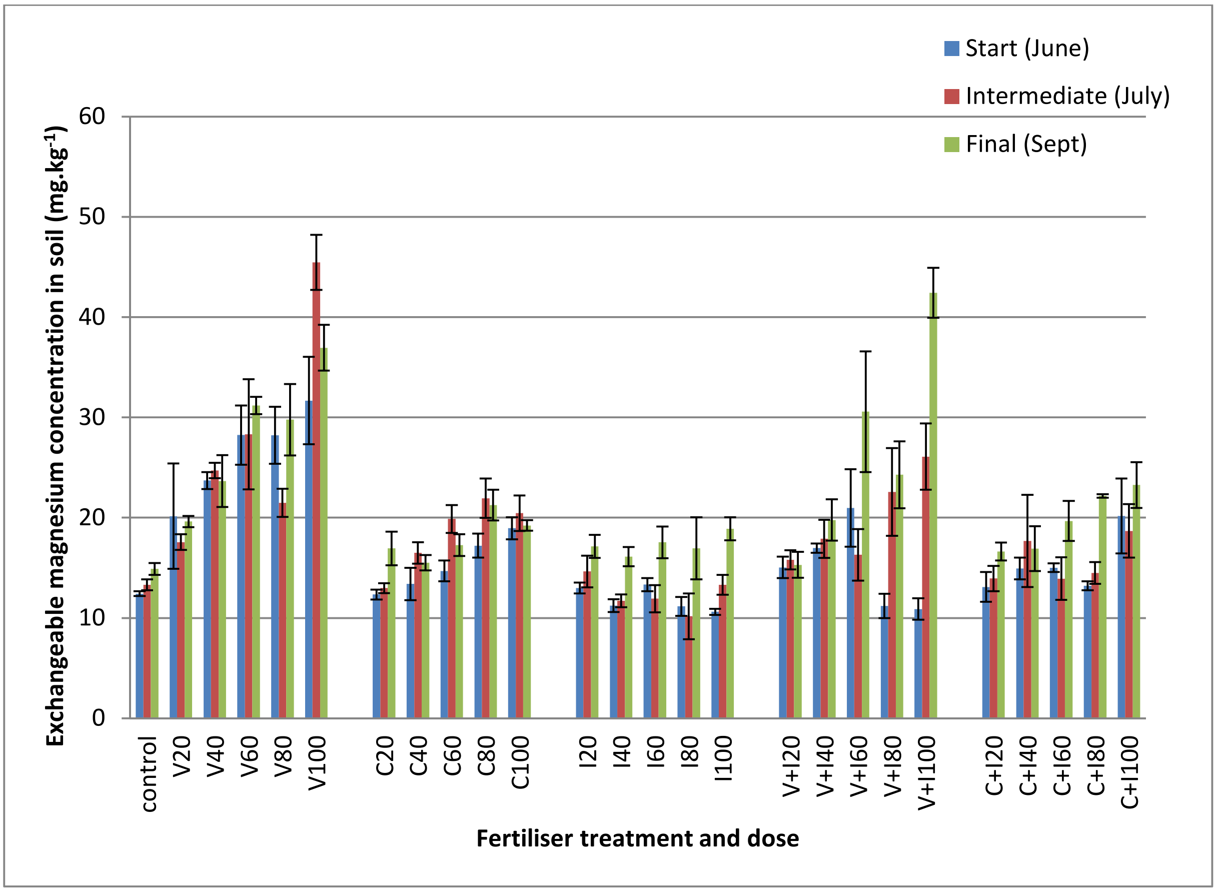

Figure 5-6 Available Mg concentrations in soil for the different fertiliser treatments applied (the first letter indicates the treatment (V is V^{HEDF} and C is C^{HEDF}) and the number corresponds to the treatment application rate. Error bars indicate ± 1 SE).

Available Mg concentrations were significantly affected by the type of fertiliser applied in the initial (H(5)=37.4, p<0.01), intermediate (H(5)=38.37, p<0.01) and final (H(5)=27.21, p<0.01) stages of the pot trial experiment. There were also significant differences in the concentrations of Mg between the different plant growth stages overall (X(2)=30.91, p<0.001) and more specifically within the C^{HEDF} (X(2)=8.71, p=0.013), V+I (X(2)=7.60, p=0.022) and chemical fertiliser (X(2)=18.43, p<0.001) treatments. The highest concentrations of Mg in this experiment were found in pots treated with V^{HEDF}. The highest concentration was 42.4 mg.kg^{-1} for mixed V^{HEDF}+I applied at 100% rate and the next highest was vermicompost at 100% rate at 36.9 mg.kg^{-1}. The following highest Mg concentration was 1.6 times lower: 23.25 mg.kg^{-1} for C^{HEDF}+I applied at 100% rate.

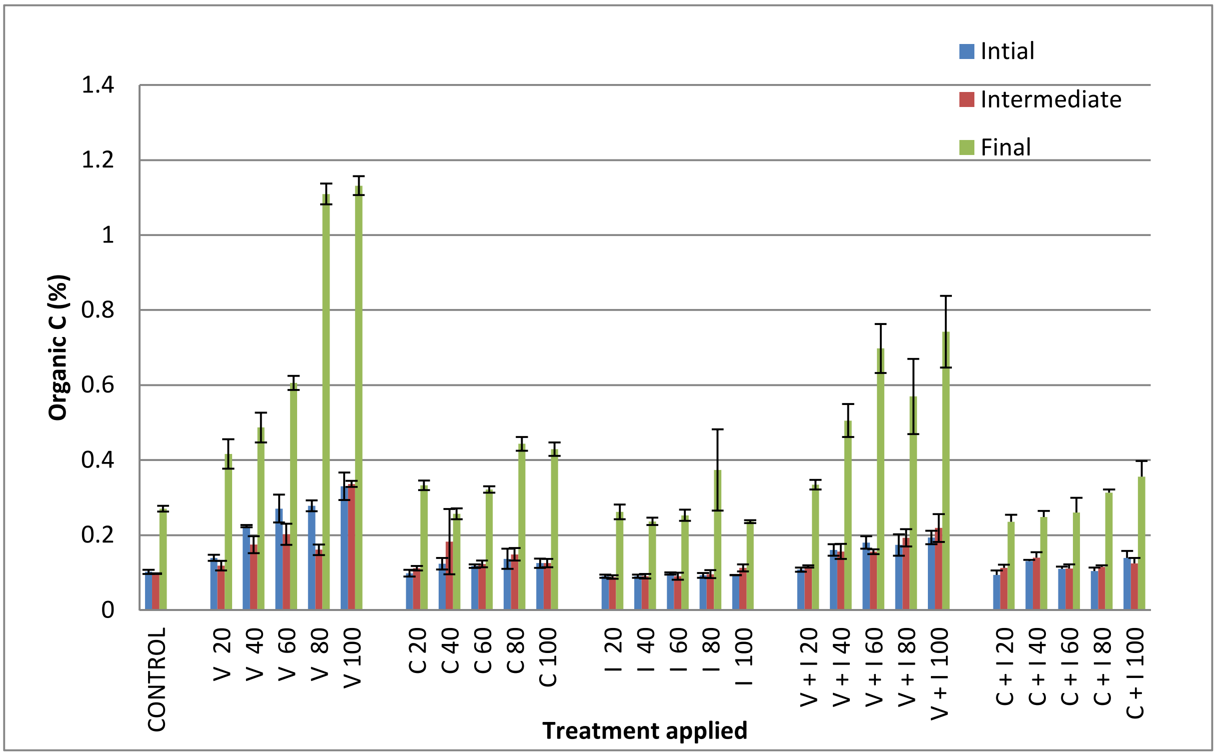

Figure 5-7 Organic carbon concentrations in soil for the different fertiliser treatments applied (the first letter indicates treatment type (V is V^{HEDF} and C is C^{HEDF}) and the number corresponds to the fertiliser application rate. Error bars indicate ± 1 SE)

The concentration of organic C was highest in pots treated with V^{HEDF}, having the highest concentrations of both initial (0.33%) and final (1.13%) organic C. The type of fertiliser treatment applied had a significant effect on the organic C concentration of soil before plant growth (H(5)=49.97, p<0.01), during plant growth (H(5)=41.85, p<0.01) and after plant harvest (H(5)=49.28, p<0.01). Before plant growth, organic C concentrations in soil in pots that received fertiliser treatments were not significantly different (p>0.003) from that in control pots aside from pots that were treated with V^{HEDF} (U=0, r=-0.67). The organic C concentration in pots treated with V^{HEDF} was significantly different from that of all other treatments after harvest, significantly higher than control pots (U= 0, r=0.69), C^{HEDF} (U=16, r=1.00), than chemical fertiliser (U=7, r=1.10), than C^{HEDF}+I (U=3, r=1.15) and, than V^{HEDF}+I (U=39, r=0.78) treatments. Similarly pots treated with V^{HEDF}+I also had significant differences with all other treatments after harvest, with control pots (U=0, r=0.67), pots that received C^{HEDF} (U=35, r=0.82), chemical fertiliser (U=7, r=1.12) and C+I (U=12, r=1.07). Organic C concentrations in pots treated with compost were not significantly different from control pots at any stage of plant growth but they did have differences with pots treated with chemical treatments at the initial (U=30, r=0.83), intermediate (U=30, r=0.86) and final (U=33, r=0.85) stages.

The mixes of HEDF and chemical fertilisers (V^{HEDF}+I and C^{HEDF}+I) also had significant differences in organic C between each other initially (U=41, r=0.76), during plant growth (U=36, r=0.81) and after crop harvest (U=12, r=1.07); pots that received V^{HEDF}+I treatments had higher organic C concentrations than pots treated with C^{HEDF}+I. Pots treated only with chemical fertilisers also had significant differences with those treated with mixes at all stages, with V^{HEDF}+I at the initial (U=3, r=-1.14), intermediate (U=3, r=-1.17) and final (U=7, r=-1.12) stages and with C^{HEDF}+I at the initial (U=27, r=-0.87) and intermediate (U=30, r=-0.88) stages.

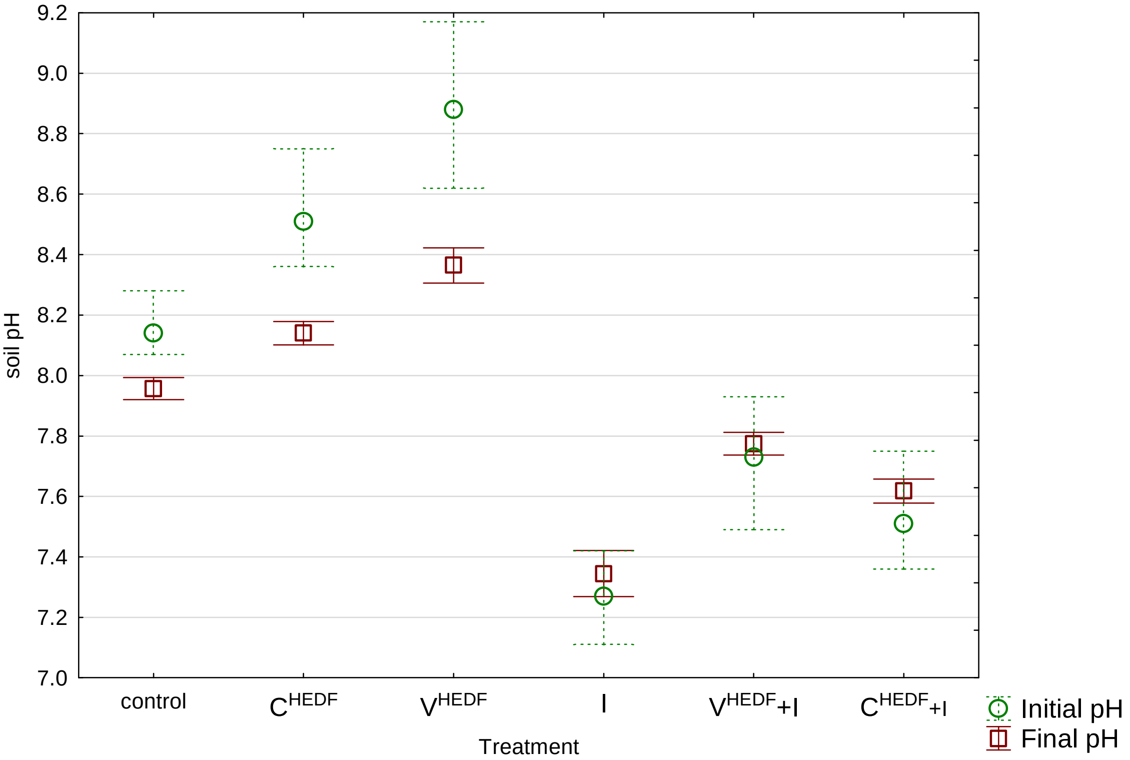

Figure 5-8 Mean pH (n=15) of soil before and after plant growth for the different treatments applied (Error bars indicate ± 1 SE)

The pH of soil changed as a result of fertiliser addition and crop growth for certain fertilisers (Figure 5-8). pH values of soils that received different treatments were significantly different (H(5)=60.82, p<0.01). The soil pH of pots treated with chemical fertilisers and with a mix of chemical fertilisers and HEDFs (V^{HEDF}+I, C^{HEDF}+I) was significantly lower than that of pots treated with C^{HEDF} and V^{HEDF}. The changes in pH were evaluated by Wilcoxson Matched Pairs Tests with a Bonferroni correction for each treatment comparing initial and final soil pH and the results showed that there were no significant changes in pH (p>0.008) before and after crop growth in the control pots (p=0.108) or those that received the chemical (p=0.019), V^{HEDF}+I (p=0.069) and C^{HEDF}+I (p=0.33) treatments. On the other hand pots treated with C^{HEDF} (T(0), r=0.88) and V^{HEDF} (T(0), r=0.88) did experience a significant change in soil pH. V^{HEDF} had the highest effect on soil pH, reducing it by 0.5 on average followed by pots treated with C^{HEDF} that showed a pH reduction of 0.4 on average. The pH of control pots also decreased after crop growth by 0.2 units on average.

5.3.3 Heavy metal concentrations

Only soil from pots that received fertiliser treatments at 80 or 100% were tested for heavy metal content since they were the most likely to have highest concentrations of heavy metals due to the rate of fertiliser application. Statistical analyses showed that there were no significant differences between the treatments applied or the concentrations at which they were applied for all the heavy metal concentrations measured: Cu, Zn, Ni, Pb, Cd and Cr. There were also no significant differences between the different fertiliser treatments and the control pots.

5.4 **Discussion**

5.4.1 Impact of HEDFs on crop yield

All plants reached statistically similar final heights regardless of the treatment applied but there were differences in productivity depending on the fertiliser treatment and rate applied: pots treated with chemical fertilisers only (I) produced cobs with a significantly lower grain weight than those treated with HEDFs. This is similar to the findings reported by Vaca *et al*. (2011) and Lazcano *et al.* (2011), where no differences in the number of cobs produced were observed among the treatments applied (sewage sludge, sewage sludge compost and chemical fertilisers), but the production of grains was affected by the type of treatment applied. Tambone *et al.* (2007) also found that there were no differences in yield between control plots and those treated with C^{HEDF} when growing maize, but they did find differences in the nutrient content of the grains (enriched in C, N and P). The significantly lower concentration in soil available K in pots treated with chemical fertilisers alone as compared to HEDFs could have led to a K deficiency in the plant, which could be related to the lower grain yield of cobs treated with chemical fertiliser alone.

Another difference observed was that all the pots treated with V^{HEDF} produced at least one cob per treatment (one per 3 plants) whereas plants treated with the other fertilisers did not all produce harvestable cobs for all application rates (C^{HEDF}80, I20, C^{HEDF}+I20, C^{HEDF}+I40, C^{HEDF}+I100 treatments produced zero cobs per triplicate). Rodríguez-Canché *et al.* (2010) grew habanero pepper seedlings using vermicompost made from sewage sludge from septic tanks and found that the highest seedling height was obtained with the highest concentration of vermicompost and with the highest concentration of straight sewage sludge. Lazcano *et al.* (2009) as well as Zaller (2007) had similar experiences successfully replacing tomato potting media by vermicompost. These differences suggest that the additional components present in vermicompost such as organic matter and microorganisms have beneficial effects on fruit development in plants and can increase crop productivity. It has been suggested that plant growth regulating components (such as enzymes and hormones) are present in vermicompost and contribute to their beneficial effect on crops (Atiyeh *et al.*, 2001). In a different experiment however, Atiyeh *et al*. (2000) found that the application of vermicompost alone inhibited their growth of tomato seedlings. Further experiments with this vermicompost derived from human excreta over longer periods of time and with several crop types would be needed to confirm the findings from this pot trial.

5.4.2 Effect of HEDFs on soil properties

The results from the soil analyses carried out across treatments during the different plant growth stages showed that the nutrient evolution in soil was also different between HEDFs and chemical fertilisers. The most well-known benefit of organic fertilisers is the addition of carbon material to soil, which was also found in this experiment. There were significant differences in soil C between chemical fertilisers pots and all other treatments at all stages of crop growth, the concentrations of organic C in pots treated with chemical fertiliser remained at a similar level to control pots throughout plant growth. There were also significant differences between pots treated with V^{HEDF} alone, with higher concentrations of organic C at all stages than the rest of the treatments, suggesting that V^{HEDF} added more organic matter to soil than the other treatments.

Through the action of the worms' digestive systems, materials are further decomposed in the vermicomposting process and therefore nutrients in vermicompost are present in more plant-available forms (Orozco *et al.*, 1996). This was reflected in the concentrations of available K and Mg, which were significantly higher in pots treated with V^{HEDF} compared to the other treatments. A release in nutrients was observed during plant growth in pots treated with C^{HEDF} and V^{HEDF} at certain rates. The differences were not significant for all treatment rates but an overall trend in increasing available Mg concentration during crop growth reflected the gradual release of nutrients in soil through nutrient mineralisation, characteristic of organic fertilisers.

The concentrations of available P in pots treated with chemical fertilisers were 10 times higher at the 100% rate than pots treated with HEDFs only. This is expected since all nutrient fractions are in plant available form in chemical fertilisers but analyses also showed that there was a release of P during crop growth in pots treated with HEDFs. The reduction of available P during crop growth was proportionally lower for combined treatments (C^{HEDF}+I and V^{HEDF}+I) than chemical fertilisers alone, probably due to the gradual release of P from HEDFs through microbial mineralisation. These data suggest that the effect and evolution in soil between chemical and HEDFs are different and suggests the benefits of mixing mineral and HEDFs.

The effects of the three HEDFs on soil pH were different, HEDFs decreased pH as a result of crop growth whereas treatments with chemical fertiliser didn't modify the pH of the soil during one crop growing season. Even though soils treated with C^{HEDF} and V^{HEDF} experienced slight acidification during crop growth, pots treated with the HEDFs had an overall pH higher than those treated with chemical fertilisers. The soils with the lowest pH were those treated with chemical fertilisers, ranging between 6.7 and 7.7 and the ones with the highest pH were those treated with V^{HEDF}, between 8.3 and 9.2. With an initial soil pH of 8.2 on average, it can be said that the application of chemical fertiliser decreased the pH of the soil whereas the addition of HEDFs, in particular V^{HEDF}, increased the pH of soil. An increase in pH can be beneficial for certain soil types, such as ferralitic soils, which are prevalent in many parts of SSA and have issues with weathering and acidification. A higher pH is also better for P availability in iron-rich soils and organic amendments have been shown to immediately increase pH upon application (Cong and Merckx, 2005). Cong and Merckx (2005) also showed that the addition of organic amendments to soil reduced the availability of aluminium in soil, which reduced P fixation. The increase in residual P concentrations in soil is beneficial in certain soils, especially soils in SSA (Otinga *et al.*, 2013), but as Korboulewsky *et al.* (2002) pointed out it is not good for all soil types. They carried out experiments with biosolids in vineyards in France and found that there was a risk of P leaching more than N leaching from the application of biosolids.

Soil analyses showed different effects from chemical fertilisers and HEDFs on soil. HEDFs provided higher organic matter to soil as well as higher concentrations of micronutrients and showed a gradual release of nutrients during crop growth. V^{HEDF} provided more benefits than C^{HEDF} to soil in terms of C and available nutrients as well as crop productivity but these results reflect only the application over one crop season, it is not possible to draw clear conclusions from this experiment. One of the unique aspects of this study was that the V^{HEDF} was directly derived from C^{HEDF} used in this experiment; the differences observed between the effects of C^{HEDF} and V^{HEDF} could be directly linked to the nutrient transformations carried out by the *E. Fetida* worms. Doan *et al.* (2013) argued that the benefits of vermicompost are only in the short term and that in longer term timeframes the effect of compost and vermicompost on soil is similar. In a different experiment however, Doan *et al.* (2015) also advocated the benefits of vermicompost over compost and manure for improving the resistance of plants to water stresses and showed that combining vermicompost with biochar had the most noticeable effects on crop growth and reduction of nutrient leaching to water.

5.4.3 Heavy metal residues in soil after fertiliser application

There were no negative effects due to heavy metal concentrations from any of the treatments applied. Regulatory limits for heavy metals in soil in Europe were specified in a decree in 1986, summarised in Table 5.3. The final heavy metal concentrations in soils treated with the different HEDF and chemical fertilisers in this experiment all complied with the UK's limits for soils following sewage sludge application. They also complied with the Dutch target values for heavy metal concentrations in soil aside from Cr, which was above the target concentration value for all treatments including the control pots but below the stated EU intervention value. The fact that the control pots also had soil concentrations of Cr higher than the regulatory limit suggest that it was present in the original soil already rather than being a result of treatment application.

These results agree with those of Korboulewsky *et al.* (2002) and Vaca *et al.* (2011) who also found no differences in heavy metal content with the application of sewage compost to soil.

Table 5.3 Limit concentrations of heavy metals in soil and concentrations measured in soils from the different experimental pots (adapted from (European Commission, 1986; Merrington *et al*., 2006)) Highlighted in red is the value that exceeds regulatory limits

	Limit values of heavy metals in soil (mg.kg^{-1})			Maximum heavy metal concentration measured in experimental pots (mg.kg^{-1})						p value
	EU	UK	Nether-lands	Control	C^{HEDF}	V^{HEDF}	I	C^{HEDF} +I	V^{HEDF} +I	
Cd	1 -3	3	0.8	0.007	0.15	0.06	0.22	0.1	0.08	0.13
Cu	50-140	80-200 (pH dependent)	36	4.89	5.27	4.59	5.69	4.07	10.03	0.26
Ni	30-75	50-110 (pH dependent)	35	15.08	16.01	14.77	21.18	14.1	13.32	0.95
Pb	50-300	300	85	7.2	7.73	8.88	8.47	3.8	4.73	0.32
Zn	150-300	200-450 (pH dependent)	140	19.67	20.58	20.46	21.34	18.69	20.29	0.33
Cr	-	400	100	271.8	326.7	269.5	805.6	285.9	281	0.95

5.5 **Conclusions**

Differences in maize yield and soil nutrient concentrations were observed between the fertiliser treatments applied in this glasshouse experiment. Maize yields were highest with V^{HEDF} treatments and lowest in pots treated with chemical fertilisers only. V^{HEDF} contributed significantly to increasing the concentration of C, K and micronutrients such as Mg in soil. This study provides a unique representation of nutrient tracing of vermicompost that is derived from compost. The differences observed between C^{HEDF} and V^{HEDF} in their effect on crops and soil showed the significant effect *E. fetida* worms have in transforming nutrients and modifying the properties of organic matter. Both the applications of C^{HEDF} and V^{HEDF} increased soil organic C as well as overall soil pH, both signs of soil health improvement for acidic soils that prevail in SSA. There was also evidence of a gradual release of nutrients into soil during plant growth with C^{HEDF} and V^{HEDF}. There was no evidence of heavy metal contamination from the application of the HEDF or chemical fertilisers used in this experiment. The benefits of mixing HEDF and chemical fertilisers was also made evident, in particular for V^{HEDF}+I which combined the benefits of having nutrients present in plant-available form and providing gradual release of certain such as K and Mg as well as higher concentrations of micronutrients and organic matter. The findings from this study were similar to those reported in literature with other organic amendments such as animal manure and sewage sludge. This experiment showed that V^{HEDF} and C^{HEDF} provide a range of nutrients beneficial for crop growth and soil health, making them attractive soil amendments for peri-urban areas where organic matter sources for agriculture are often scarce. HEDFs could provide a circular solution to the management of human excreta in non-sewered urban areas by providing a beneficial agricultural input locally. Larger scale studies over several seasons with this type of HEDF are needed to further characterise their promising effects on crops and soil.

6 FERTILISERS FROM CONTAINER-BASED SANITATION SYSTEMS: ASSESSING ENABLING CONDITIONS AND BARRIERS TO THEIR COMMERCIALISATION IN HAITI AND KENYA

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Abstract

Efficient alternative FSM solutions to centralised sewerage networks need to be established to achieve the target set by the Sustainable Development Goals (SDG) of providing 100% access to safely managed sanitation worldwide by 2030 (Target 6.2). This is especially a challenge in densely populated urban informal settlements, where space is limited and land tenure uncertain. This study also covers other SDGs related to agriculture and sustainable nutrient management (SDG 2 (food security, nutrition and sustainable agriculture), 15 (land degradation) and 17 (global partnership for sustainable development)). The integrated approach proposed in this work aims to convert HEDF into an agricultural resource, tackling both sanitation and agronomy issues at once by collecting and treating human excreta to produce soil conditioners for use in agriculture. CBS solutions aim to provide safely managed sanitation and create marketable products from the treatment of excreta. This study focused on CBS ventures that produce and sell HEDFs. Stakeholder interviews showed that challenges faced by these ventures were similar: unclear regulations on the use of HEDFs, undeveloped markets for organic fertilisers in general, difficulties in securing secondary sources of organic matter for composting as well as complex transport and distribution logistics. In all cases however the full volume of HEDFs produced was sold but none of the companies currently recovers the cost of sludge transport and treatment from HEDF sales. The findings of this study emphasized the need for clear policies for HEDF as well as institutional involvement to incentivise the sale and use of HEDF locally to ensure sustainable

The formatting of the original published manuscript has been adjusted to fit the format of this thesis.

and safely managed sanitation systems are available in all urban and peri-urban areas.

6.1 **Introduction**

The global community adopted the 12 SDGs in 2015 setting the agenda for addressing a range of global economic, social and environmental issues (UN, 2015). SDG 6 is to “ensure availability and sustainable management of water and sanitation for all” with Target 6.3 including “By 2030 […] halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally”. This is an ambitious target, given that in 2015, 3 out of 5 people worldwide did not use safely managed sanitation services, systems where excreta are safely disposed in situ or safely transported and treated off-site (UNICEF and WHO, 2017). 100% coverage of safely managed sanitation will not be achieved by 2030 with sewerage networks alone given the significant infrastructure, investment and operation and maintenance requirements of these systems. With water scarcity increasing worldwide, there is also a need to shift away from ‘traditional’ sewerage systems that require large volumes of water to operate. Urban sanitation has been recognised by experts as one of the greatest challenges to achieve the SDG on sanitation (Hueso, 2016). FSM is often neglected in cities; sewerage is often seen as the go-to solution by urban planners but this is not realistic especially in fast-growing cities of LICS where the sewerage network cannot reach all parts of the city (Peal *et al.*, 2014).

There are several sanitation ventures that have emerged in recent years, providing CBS systems, which do not rely on sewerage networks or any permanent infrastructure (CBSA, 2017). These use mobile toilets that do not require any investment into additional infrastructure, which is often attractive for most urban slum dwellers who rent the spaces they live in. The model is based on a rental and servicing fee making it affordable but also ensuring a lasting relationship with the service provider and appropriate and safe management of the toilet waste (Graf *et al.*, 2014). CBS has been recognised as a promising solution to sanitation in densely populated areas but has not yet been extensively studied (Andersson *et al.*, 2017; Mara and Evans, 2017; Orner and Mihelcic, 2018).

The global sanitation sector also recognises the need and opportunities for resource recovery and value creation from FS, from energy to nutrient recovery creating products that have a wide range of applications (Diener *et al.*, 2014; Rao *et al.*, 2017). Resource recovery also creates a great opportunity for incentivising and stimulating sustainable sanitation (Andersson *et al.*, 2016). Recovering nutrients from FS constitutes a great avenue for returning nutrients back to soil, which could help tackle other SDGs. SDG 2 for instance aims to achieve zero hunger with Target 2.3 aiming to double the agricultural productivity of small-scale farmers by increasing access to inputs and access to markets. Target 15.3 is also associated with farming aiming to combat desertification and restore degraded land. Composted sewage sludge is made up of 50% organic matter and therefore attractive for restoring soil health (Binder and Patzel, 2001). Targets 11.6, 12.2 and 12.5 of the SGDs aim to reduce waste generation and adverse human impact on the environment. FSM fits within the water-energy-food nexus and recovering nutrients from excreta contributes to tackling water and food production challenges simultaneously, especially in the case of P recovery, given its limited reserves (Drechsel and Hanjra, 2016). Shift in policies to integrate several dimensions of this complex nexus are needed, instead of the usual trend of focusing policies on a single issue or discipline (Bhaduri *et al.*, 2015).

When considering resource recovery from FSM, and in this case from CBS systems specifically, it is essential to assess the market for potential products (Koné, 2010). Composting is a relatively ‘low tech’ solution for accelerated organic matter decomposition, which can remove pathogens from FS if the high temperatures achieved in the initial thermophilic phase are maintained for long enough (15 days above 55^{o}C (Walker *et al.*, 1994)). Composting can therefore constitute an attractive solution for FSM, providing an opportunity to sanitise FS, recover nutrients from human excreta and returning them back to soil, often in areas where soil organic matter is becoming depleted. Compost however is recognised as being a low-value product (Graf *et al.*, 2014) and it is essential to consider the economics of composting when planning a new facility (Niemeyer *et al.*, 2001; Rouse *et al.*, 2008). Composting of municipal solid waste (MSW) is well known but composting of FS is less well-known and not well understood (Odey *et al.*, 2017). An advantage of composting of CBS sludge is that there are few risks of external wastes (eg: plastics, batteries and other household waste) being present in the waste, avoiding contamination issues that are common with FS composting (Odey *et al.*, 2017). Several CBS companies successfully produce HEDF and sell their full production into the local market, despite the aforementioned difficulties. The aim of this paper is to identify the enabling conditions for their success and the challenges they are faced with. Two CBS ventures that successfully sell their compost were selected to determine the factors that enabled their success as well as the challenges overcome and barriers still faced.

6.2 **Methodology**

A case study research approach was chosen to investigate the barriers and enabling conditions for commercialising HEDF and determine the factors that are location or case-specific and those that are common across geographical locations. A case study approach was most appropriate to explore this question, as Yin (2014) points out: "*A case study is an empirical enquiry that investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident".*

Yin (2014) also emphasizes the need to clearly define boundaries for a case study, which he calls "*bounding the case".* In this research, the criteria to select the cases were as follows:

Case studies were developed on sanitation ventures which:

- provide CBS systems emptied at least weekly (i.e. not pit latrines),

- cover the full sanitation value chain (provide toilets, collect the waste and treat it),
- operate in low and middle-income countries,
- produce HEDFs at full scale,
- were selling the HEDFs in the local market in July 2016.

The sanitation organisations that fulfilled the criteria set for selecting case studies when the study was carried out were Sustainable Organic Integrated Livelihoods (SOIL) in Haiti and Sanergy in Kenya. The characteristics of each venture and the HEDFs they produce will be presented in the following section.

The same research activities were carried out for both case studies to allow for comparison from a range of different sources: interviews and observations. A series of stakeholder interviews were carried out in each location including the sanitation venture's employees, international organisations such as the FAO, local food industry stakeholders such as vegetable exporters and NGOs implementing agricultural projects, as summarised in Table 6-1. Customer interviews could only be carried out with SOIL customers, Sanergy customers could not be contacted because of Sanergy's data protection policies. A purposive sampling approach was followed to identify interviewees. Company employees were purposively sampled according to their job position and involvement in either fertiliser production or sales. HEDF customers selected were those who were available and agreed to be interviewed in the time period when the fieldwork was carried out (5 weeks in July 2016). Interviews were carried out in a semi-structured format to allow for comparison between interviews whilst also allowing for conversation to flow and for the interviewee to expand more freely in certain areas encouraged by the interviewer's prompts. Interviews with employees aimed to characterise the perceived success factors for HEDF sales, their understanding of the HEDF's properties and their suggestions for improvement. The topics covered in the interviews with the sanitation company employees included different aspects of the HEDF production process, the challenges faced for selling it and company strategies.

Interviews with HEDF customers were centred on their perceptions, experiences and opinions with HEDF use. The topics discussed in the interviews with international organisations covered the agricultural context of the country, the fertiliser market, soil health and the main challenges faced by farmers.

Pre-arranged interviews were recorded and transcribed, certain interviews occurred through spontaneous conversation and detailed notes were taken. Consent for data collection and use was obtained from all respondents. Interview transcriptions and notes were manually coded using the software NVivo (QSR International, 2015) following a descriptive coding approach as outlined by Saldaña (2013), by initially coding sections by describing their general topic without considering the connection between different codes. These codes were then arranged into themes to allow comparison across stakeholders and case studies (Saldaña, 2013).

Table 6-1 List of stakeholders and numbers of interviews completed

Stakeholder	Number of interviews carried out
SOIL employees	5
Sanergy employees	5
SOIL customers	3
FAO Kenya	1
FAO Haiti	1
Interamerican Development Bank (IDB) Haiti	1
Haitian organisations working with smallholders	2
Kenyan organisations working with farmers	2

6.3 **Results**

6.3.1 Sanitation ventures' background

SOIL started as a not-for-profit organisation in 2006 in Northern Haiti with the approach that access to safe sanitation is a human right. Their aim is to provide dignified and safe sanitation to deprived communities that are not served by municipal sanitation in two cities of Haiti, Cap Haitian and Port au Prince. SOIL provides household dry toilets, which are leased; a service fee is collected periodically directly from customers.

SOIL provides its customers with urine-diverting toilets, collects the faeces periodically and transforms them into HEDF in the form of compost (C^{HEDF}). Urine is not collected at present, customers are responsible for disposing of it. Faeces are contained in buckets which are collected in carts and transferred to the waste treatment site by truck. Toilet customers add a cover material after each toilet use: sugar cane bagasse or peanut husks, provided by SOIL, to obtain the optimal C to N ratio for composting. The buckets are emptied in large composting bins, the walls are made up of pallets filled with carbon-rich material to allow for air to flow through and provide sufficient aeration in the bin. The treatment process has previously been described in Berendes *et al.* (2015) and Piceno *et al.* (2017). The bin is sealed when full and left untouched for 2 to 3 months depending on the temperature and evolution of pathogen concentration in the compost bins. The compost bin is then emptied, and the material arranged into windrows where further degradation of the material occurs. The piles are turned once a month for about 6 more months until the C^{HEDF} properties fulfil the quality criteria set internally Temperature, moisture, pH and *E.coli* concentration are monitored throughout the process to ensure compliance with WHO standards for thermophilic composting and the safety of the final C^{HEDF} product (WHO, 2006).

Sanergy is a social enterprise that provides safe sanitation in urban slums of Nairobi through shared dry toilets since 2011. Their urine-diverting dry toilets are part of a franchise system, Fresh Life Initiative (FLI), which local entrepreneurs join. They invest in a toilet and operate it as a pay-per-use public toilet. Another model exists where toilets are installed in accommodation compounds and leased to landlords as an extra service provided to tenants. The toilet entrepreneur or tenants (depending on the toilet model) are responsible for the maintenance and cleaning of the toilet, for sourcing cover material, usually sawdust, and adding it to the faeces. A third model exists for toilets installed in schools where toilets are sold to head teachers at a subsidised price to ensure adequate sanitation coverage for all pupils. A trial system with household toilets was also underway at the time of the visit. The sanitation and the waste management arm of Sanergy are separate; the toilet business, FLI, being not-for-profit and the waste management arm, Sanergy, as a social enterprise, which collects and treats toilet waste.

Similarly to the previous system, the waste is collected in sealed buckets and transported by truck to the waste treatment facility. There the buckets are emptied into a mixing tank where additional organic wastes are added such as agricultural residues. After the mixing phase, the material is laid out in windrows, which are mechanically turned and watered. Process performance is periodically monitored by measuring process parameters (temperature, moisture, pH, CO_2, pathogen concentration, germination tests). Once the piles meet the quality standards set internally, the resulting C^{HEDF} is sieved, bagged and sold for agricultural use.

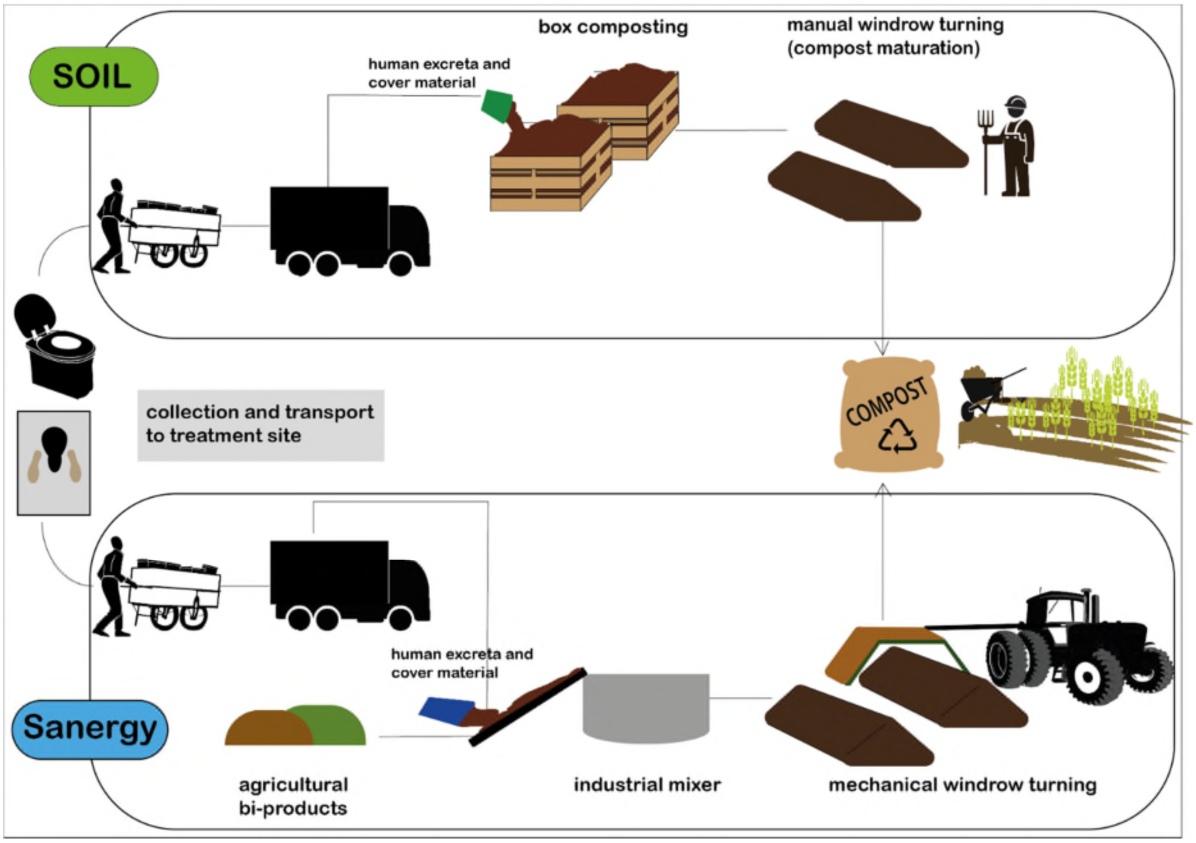

Figure 6-1 Visual summary of SOIL and Sanergy's C^{HEDF} production processes

The fertiliser production processes are different between the two ventures as illustrated in Figure 6-1 but several of the challenges they face are similar.

6.3.2 Challenges faced in the production of HEDF

Sourcing of additional composting material

Additional organic matter needs to be sourced locally to obtain the right C to N ratio for composting (around 20) and ensure efficient treatment of the excreta. SOIL needs to source the cover material for the faeces that it provides customers with. In Sanergy's treatment system faeces are co-composted with additional organic matter such as food waste or agricultural by-products. Seasonal variation in material availability and changes in attitudes from providers created challenges for both companies for the procurement of extra organic materials. Arrangements with providers were informal and changed often.

“If people have to get rid of their waste they will pay to do it. The thing is when we come to say: we want your waste, we can get rid of it for you. They say ‘okay but we actually want you to pay‘ and that's not logical “ Sanergy employee

Variation in the additional organic material also affects the properties of the final C^{HEDF} so variations in supplier are not desirable. Both companies were trialling different composting materials and trying to secure reliable suppliers of organic matter. High costs of transport also added difficulty for sourcing additional composting material. In Kenya for instance agricultural areas are far from Nairobi and transport of waste from these areas to the C^{HEDF} processing plant is not always economically feasible.

“it’s really difficult, especially for carbon sources. […]. A lot of it is where the large-scale farming is which is mid- to western Kenya so even if it’s cheap then transportation makes it expensive” Sanergy employee

Transport

Transport was also a challenge for the transfer of excreta from the toilets to the treatment sites, which often have to be in specific areas. Cities often have designated areas for waste treatment, which are in the outskirts of the city and difficult to access, creating an additional challenge to the economic viability of the treatment process. In Port au Prince for instance at the time of visit, the treatment site was initially confined to an area behind the municipal landfill, which was unhygienic. The landfill was made up of disorganised mounds of waste and open fires causing thick smog as well as puddles of leachate and stagnant water where animals roamed. The treatment site then had to be relocated to another waste management area because it was often inaccessible due to indiscriminate waste dumping blocking roads or roads being inaccessible after heavy rains. In Nairobi, the treatment site was located in a designated waste treatment area next to a wastewater treatment plant more than one hour’s drive away from the collection point and accessible through dirt road only requiring specific vehicles to access it.

Process optimisation and robustness

Quality control procedures and schedules were in place in both production sites, ensuring the C^{HEDF} produced was free of weed seeds and pathogens harmful for humans and plants. Pathogen elimination was monitored by regularly measuring temperature in the piles as well as pathogen testing at different stages of the process to ensure product compliance with the WHO guidelines for the reuse of excreta (WHO, 2006). An additional challenge faced for these ventures in LIC was a lack of locally available laboratories that have the capacity or are willing to test HEDF. As a result, both companies had their own in-house labs to carry out these tests following standard international analytical methods.

Given the novelty of composting source-separated human excreta at a large scale, both SOIL and Sanergy put continued efforts into improving their product and optimising production processes with teams dedicated to C^{HEDF} optimisation and agricultural performance of the C^{HEDF}. This involved extensive experiments with minimal production time being a priority. Nutrient analyses (N, P, K) were also carried out weekly on both C^{HEDF} to monitor quality and provide detailed information to customers. Both ventures tested the quality of their HEDF products and their effects on crops in in-house field trials.

The composition of both C^{HEDF}s were clearly labelled, and customers were appreciative of this. Clients valued knowing the nutrient content of the C^{HEDF} and getting guidance on how to apply it:

«With SOIL compost it's different, you have the full composition and you can easily prepare your dosage» SOIL C^{HEDF} client.

One of the clients also voiced appreciating the fact that the quality of the product was constant and recalled how before they had to 'make do' with what was available:

6.3.3 HEDF commercialisation strategies and challenges

Both SOIL and Sanergy were selling their full C^{HEDF} production at the time of the field visits and were scaling up production as they were increasing the number of toilet customers. Both companies chose to sell their product at a premium price, which was seen by some customers as a sign of quality. One of the clients quoted a Haitian proverb that says that *'that which is of good quality is expensive'* (SOIL C^{HEDF} client). Another SOIL C^{HEDF} client however said that if the C^{HEDF} was cheaper they would be willing to buy larger quantities.

The two companies targeted very different customer segments for C^{HEDF} sales. SOIL benefited from the fact that many international organisations are present in Haiti working in reforestation projects as well as with farmers. These organisations can afford to buy C^{HEDF} at a premium price and SOIL were able to secure them as customers from the early stages of production. Additional clients found out about the C^{HEDF} mainly through word of mouth, so few marketing efforts were put into obtaining new C^{HEDF} clients. Sanergy on the other hand used a much more active marketing and sales approach to sell directly to farmers. Their current target was medium-scale horticultural farmers in rural areas of Kenya. A fleet of salesmen covered the rural areas where cash crop farmers are concentrated, they directly approached farmers and provided guidance for C^{HEDF} application. This approach required educating the farmers initially to help them understand the needs of their soil and the benefits C^{HEDF} could have for them.

Neither companies sought distributors for their C^{HEDF} at this time because of the current lack of market for organic fertilisers; it was thought unlikely that farmers would pick the C^{HEDF} from fertiliser shops. The availability and distribution of alternative organic fertilisers both in Kenya and Haiti was very poor. *"the reality is that the distribution of organic fertilisers is very poor so most farmers have never used it before and don't have access to it"* Sanergy

In Haiti the fertiliser market is unstable, it has been heavily disrupted by a history of failed subsidy systems. At present there are no fertiliser subsidies in place and there is a lack of government input or direction in the sector. The landscape for organic fertilisers is also disorganised with few products formally available on the market. Similarly in Kenya the government subsidises the demand of mineral fertilisers but does not intervene with organic fertilisers.

“The fertiliser market here, chemical fertiliser, it’s very chaotic, it’s completely dominated by interventions from the State every now and then depending on their financial ability” IDB Haiti

“I think we’re probably leaders in compost production in Haiti but mostly because there’s hardly anyone else.” SOIL employee

Barriers to accessing a wider range of customers

Several organisations working with smallholders in Haiti were interviewed. These organisations work directly with farmers and aim to promote sustainable farming practices as well as facilitating their access to markets and especially international markets, coffee and cocoa beans mainly. Their target is to produce high-end products and given the traditional farming practices used (no application of chemical fertilises or pesticides), these farms can easily be certified organic. Organisation representatives stated that if their farmers were to apply fertilisers on their fields, they would have to be certified organic. Certifying bodies however do not accept human waste as a valid input for organic fertilisers, so that market segment remains inaccessible for SOIL.

In Kenya, the export of agricultural goods is one of the pillars of the economy. Horticultural farms growing crops for export have more purchasing and investment power than others:

“When we talk about export there’s no problem. Even the smallholders when it comes to export, they have some problems but really, they have no [major] problems.” FAO Kenya.

These exporters could therefore be good potential clients for Sanergy’s C^{HEDF}. Exporters however must abide to international farming standards set by their buyers to be able to export their goods. The most common standard specifying agricultural practices is Global GAP (GlobalG.A.P., 2011), which states that no human sewage sludge can be used on certified fields, preventing Sanergy from accessing farmers producing crops for export as discussed in Moya *et al.* (2018).

Different company strategies

Both companies had different business models and strategies. SOIL's main focus is on sanitation provision with C^{HEDF} sales aiming to recover treatment costs.

"If our goal is to provide sanitation what we want to do is cover as much as we can of our waste treatment costs so we want to sell it at a high price" SOIL

Another long-term aim of SOIL was to turn their different activity areas into private businesses and ideally involve the Haitian government in the operation and maintenance of the waste treatment site.

Sanergy's focus on the other hand was to shift from treating human excreta only to becoming a waste management company. The production of C^{HEDF} was not the aim of the company but rather to extract as much value as possible from wastes and diversify their end-products to include biogas and animal feed in addition to C^{HEDF} to have a portfolio of valuable products in the market.

"only grabbing one source of value from waste isn't going to make this economical" Sanergy

Sanergy would like to integrate sanitation waste into the wider waste management strategy of a city and be able to create a Public Private Partnership (PPP) with municipalities to provide city-wide sustainable waste management solutions. Sanergy also aimed to reduce the cost of production of their C^{HEDF} so they could provide it to a wider range of farmers but challenges remained to access farmers, who often don't have knowledge of soil health management.

Both companies emphasized the importance of having a good team to enable success of the company. When asked about the enabling factors for their success, respondents from both companies answered that the strength and motivation of their team was the main factor for success.

“In general I think our biggest resource and our biggest challenge is human resource. Human resources, finding the right people who are passionate, who can do the job, training them to do the job and bringing in experts.” SOIL

“I think one is a team, a vivid team that's very resourceful. We often have lots of challenges but it's sort of a mindset to approach it, we look at it as “let's figure out how to solve it”.” Sanergy

Involvement of public bodies

Neither sanitation ventures received government support or involvement for the creation or operation of their toilet or waste management activities. Both projects started with donor funds and grants without involvement of the local government and still operate without public funds. This is something that both ventures expressed wanting to change. Sanergy aimed to create a PPP with the Nairobi municipality within the next two to three years. Similarly, SOIL’s aim was to outsource toilet waste treatment in 5 to 10 years, ideally it would be run by the Haitian government in partnership with a private partner.

Both ventures would also welcome local authorities adopting and implementing a regulatory framework for sanitation enterprises, which does not exist presently. Container-based solutions to sanitation and companies taking care of the full sanitation chain are novel and therefore are not currently regulated in Kenya or in Haiti.

“We're sort of like Uber and AirBnB, we work in grey space and we try slowly to work with the government to regularise what we do” Sanergy

The commercialisation of C^{HEDF} is also novel and unregulated. The lack of certifications was perceived as a barrier for wider acceptance and commercialisation. HEDF don’t fit exactly into existing legislation. Currently the best available are WHO guidelines or national regulations on biosolids from other countries but their abidance to those regulations is not controlled. The effectiveness of pathogen reduction achieved in the waste treatment process was based on the honesty of these ventures and trust of the customers given the lack of local regulations on biosolids reuse or lack of regulation enforcement bodies locally.

Local authorities however do not always have the organisational capacity to implement regulations. In Haiti for instance, the local authority responsible for sanitation, DINEPA (National Directorate for Water Supply and Sanitation), is younger than SOIL, founded in 2009 and their capacity is still limited.

Challenges to profitability

Neither of the two ventures made a profit from C^{HEDF} sales at the time when these case studies were carried out. The cost of transport and treatment still outweigh the revenue that could be generated from C^{HEDF} sales, even when sold at a premium.

"if we sell all of our compost at our current cost then we recover about 20% of our operating cost for transport and treatment" SOIL employee

Sanergy's strategy to overcome this was to scale up volumes of waste processed, diversify the types of waste treated as well as the end products sold.

"Sanergy limited need more waste, they don't gather enough waste from the Fresh Life network to produce enough end products to reach certain level of sales so that it's profitable" Sanergy

Challenges to accessing smallholder farmers

The most disadvantaged and largest in numbers are smallholder farmers but they are also the hardest to reach or to sell to. Neither SOIL nor Sanergy currently reached smallholder farmers with their C^{HEDF}. Interviews with international agricultural organisations such as FAO in both countries or the IDB in Haiti highlighted similar issues faced by farmers. Low education level, lack of means to pay for fertilisers, difficulty to access markets and transport were challenges typically faced by smallholders, making them a difficult target for C^{HEDF} sales. Traditional practices are not necessarily good but governments often don't have good extension programs.

"In terms of sustainability, if the project is finished, there's no more market" IDB Haiti

"So much of the agricultural education that's been done over the past few decades is pushing fertiliser usage, chemical fertiliser usage. So how do you get people to realise the value of saving their soils and preserving it for the future?" Sanergy

Local smallholder farmers practice very traditional agriculture with little infrastructure, relying on rainfall for irrigation and with little or no fertiliser input.

"Always the most limiting in most of the cases is water. In many cases is water. Then come other things like good quality seeds, fertilisers and good agronomic practices but mainly water" FAO Kenya

"they're not used in most of the country [fertilisers] […] People here practice almost natural agriculture" FAO Haiti

Lack of appropriate infrastructure is a major barrier for farmers, both for supplying fertilisers to rural areas and for farmers to sell their produce or accessing markets. One of the interviewees quoted what a beneficiary of a farming training program had said *"But my problem is that after two or three seasons, what are we going to do with it? [harvested crops] »* FAO Haiti

"Sometimes the farmers produce but they don't know where to sell or they produce a lot at very low prices" FAO Kenya

6.4 **Discussion**

Results from the two case studies showed that both sanitation ventures faced similar challenges and that there were also similarities in the government and policy contexts between Haiti and Kenya. Both case studies showed that there is a demand for organic amendments, but a larger market needs to be accessed to reach profitability. In treating human excreta and producing C^{HEDF}, the treatment can become more profitable at larger scales (Schroeder, 2011), both companies were still increasing the number of toilet customers and were hoping to reach an economy of scale and be profitable once a certain density of coverage is reached and C^{HEDF} volumes increased. Certain additional market segments either were not accessible because of regulatory barriers or because of a lack of awareness of soil health management.

6.4.1 Challenges to profitability

A considerable amount of resources are currently needed to sell C^{HEDF} because of its relative novelty as a commercial product. The quality of the C^{HEDF} and its positive effect on crops need to be demonstrated through trials to attract customers and a dedicated team of agronomists providing support and advise to farmers is required. It is likely that these efforts will only be needed at the beginning of the commercialisation process to secure initial customers, but they represent a significant investment and effort for a young company. In addition to that initial challenge to breaking even, C^{HEDF} is also a low-value product. In both case studies it was evident that the demand for HEDF existed, but the challenge lay in recovering treatment costs and making a profit from sales. The production of fertilisers derived from organic residues in the formal sector is generally uncommon and that type of fertiliser is often stigmatised because it originates from waste. C^{HEDF} is also bulkier than chemical fertilisers, so transport costs can be significant relative to its value and it is often perceived as less convenient to use than pelletised chemical fertilisers (Niemeyer *et al.*, 2001; Rouse *et al.*, 2008; Schroeder, 2011). Modifying the properties of the final product can also have significant effects on its profitability. Danso *et al*. (2017) showed the potential effect of modifying C^{HEDF} attributes: farmers' willingness to pay (WTP) was highest for certified compost, sold at a price 67 times higher than the cost of providing it, followed by pelletised compost, and compost enriched with chemical fertilisers, which would both be sold at a loss with farmers' current WTP.

The high concentration of pathogens in the initial material required extensive monitoring and testing to ensure health risks are eliminated, also adding to the operational cost of the composting plants. Full cost recovery of biosolids production is also a challenge for wastewater treatment companies. In the Unites

States for instance, a survey of a range of companies selling biosolids compost, showed that on average 1/3 of operation and maintenance costs of the composting facility were covered by compost sales (Datta *et al.*, 2012).

C^{HEDF} also faced barriers in the fertiliser market, with markets for organic fertilisers not being developed. There is a need to 'level the playing field' to create viable competition for organic fertilisers in the wider fertiliser market; incentives for using organic fertilisers need to be provided. Currently many countries provide subsidies to facilitate farmers' access to chemical fertilisers but no incentives are in place for the use of organic fertilisers. Measures to counter this have been put in place in India for instance as part of the "Swachh Bharat Mission" (Clean India Mission), promoting the production and commercialisation of compost derived from waste. The programme provides monetary 'market development assistance' to fertiliser marketing companies that sell 'city compost' (derived from urban wastes). Standards and testing procedures for compost derived from wastes have also been put in place (MoUD, 2016). Such initiatives improve the market prospects of organic fertilisers and encourage their use locally.

Successful production and sales of compost from organic wastes is not impossible. A well-known example of successful production of compost from organic waste from markets is Waste Concern in Bangladesh (Waste Concern, 2018). As Seelos and Mair (2006) explain for this case, a partnership with a chemical fertiliser company allowed the compost manufacturer to sell all its produce at a profit whilst the chemical fertiliser company processed it further. This was also helped by local government's efforts in promoting organic agriculture among local farmers (Seelos and Mair, 2006). Support from the Bangladeshi Ministry of Agriculture was instrumental to the success of this initiative by providing formal approvals and supporting policies for the compost (Zurbrugg *et al.*, 2005; Rouse *et al.*, 2008).

Neither of the treatment systems considered in this study collect or treat the urine fraction of excreta even though it contains the highest concentration of nutrients, 70-90% of N, 70-95% of K and 45-85% of P in human excreta (Drangert, 1998;

Vinneras *et al.*, 2003). This was mainly due to the large volumes of urine produced as compared to excreta, which imply prohibitive transport costs. Nutrients are more concentrated in urine, and struvite production is a well-studied process and common application for urine treatment. Its profitability is variable depending on local contexts and availability of raw materials such as magnesium sulphate (Tilley *et al.*, 2009). Etter *et al.* (2011) for instance reported challenges in making a profit out of struvite, at present only recovering 13% of the potential fertiliser value of urine.

One of the main challenges faced by both sanitation ventures was the low market price of compost. The value of compost could be increased if it is evaluated beyond its market value. If carbon credits or a ‘green tax’ are put in place the sale of compost might become profitable and nutrients can be cycled back to land without revenue losses. In Quebec, Canada, for instance, a ‘green tax’ is imposed to biosolids disposed in landfill or incinerated, promoting their reuse (Hébert, 1997). Carbon credits for the production or use of biosolids could also encourage their application to land. Brown and Leonard (2004) considered the potential carbon credits gains from various biosolids uses. Their analysis showed several configurations where carbon credits could be realised: compost production and application to soil generated positive carbon balance but the highest carbon credit potential lied in powering fuel cells from biosolids biogas (Brown and Leonard, 2004). Through a simulation modelling study Marenya *et al.* (2012) showed that using a carbon payment credit to farmers could be a more efficient driver for increasing fertiliser use than subsidies and promote sustainable agricultural practices.

6.4.2 Government involvement to facilitate business viability

Both companies benefited from minimal government interference at their inception allowing for trial and error and optimisation. Once the process is established and running however, the necessity of additional funds has become clear to ensuring the economic viability of the companies. These private sanitation ventures are providing a public service, efficient sanitation and waste management, which in most parts of the world is publicly subsidised in some way. FSM is also often handled by the informal sector in an LIC, outside regulatory frameworks, especially in urban slums, so local governments often have little experience in regulating or financing FSM and regulatory frameworks for FSM implementation are often weak (Odey *et al.*, 2017; Rao *et al.*, 2017).

When governments are involved however, composting plants for FSM are able to cover operation and maintenance of the plant from compost sales and waste tax and collection fees. In Sri Lanka for instance a FS composting plant runs successfully in a town of 35 000 people, recovering all waste management costs but the main contributors of this cost recovery are the tax and collection fees (Rao *et al.*, 2017). Another example from Ghana shows successful PPP between a private company that produces and markets sludge pellets and the municipality, which provides the production site (Impraim *et al.*, 2014).

Collaboration of local governments can also be significant in facilitating the commercialisation of biosolids compost. In King County in the USA for instance, public opposition was faced after successful initial sales of biosolids had been secured for application of biosolids for forests and soil improvement, forcing them to find new customers. Interest was received from farmers who wanted to use the biosolids for agriculture; collaboration with the local government lead to a change in policy on biosolids to allow its use in agriculture and eventually the demand for King County’s biosolids compost exceeded supply (Newlands and Leonard, 2000)

Smallholder farmers were not viable customer targets for HEDF in Kenya or Haiti, which has also been found in other contexts. Other customers such as landscaping applications, agroforestry or plant nurseries are often more promising for compost sales (Evans *et al.*, 2015; Rao *et al.*, 2017). Government intervention would also be needed for accessing smallholder farmers, through extension programs and training to educate them on soil health management. Subsistence farming smallholders currently lack access to productive assets in East and Southern Africa, finding themselves effectively in a poverty trap.

Government intervention, and policy changes are needed to increase smallholder farmers’ access to the fertiliser market (Waithaka *et al.*, 2007; Barrett, 2008).

6.4.3 Certification to increase product credibility and value

Dealing with materials containing high concentrations of human pathogens, sanitation enterprises have a big responsibility to ensure they achieve adequate pathogen removal and stop any spread of disease. Theoretically these companies have the potential to create significant health and environmental pollution risks in communities. The two sanitation companies considered here set risk-mitigating measures in their treatment plants, carried out extensive analyses on their final products and ensured they achieved the requirements set in international standards, but there were no regulatory bodies locally controlling their activities. This implied that the quality and safety of the HEDF products both companies produce depends entirely on them and on the trust that customers put on them. This is a risky approach for the companies but also for the local governments. Regulating the production of HEDFs would be beneficial both for the companies to provide evidence to clients of the safety of their product and for local governments to preserve the environmental health of the community. In other countries such as Bangladesh and other parts of Asia certification procedures exist albeit they are complex and/or lengthy (Evans *et al.*, 2015).

Certification could be beneficial for improving commercialisation, potentially increasing its market value (Danso *et al.*, 2017). The value in creating certifications and standards for sanitation is currently recognised, with several ISO standard-setting processes currently under way. The ISO’s bimonthly magazine of Jan 2018 for instance was dedicated to water and sanitation and SDG6 in light of the ISO standards for toilet hardware and treatment facilities currently being prepared (ISO, 2018). Similar standards for fertiliser products derived from FS treatment could be developed.

6.4.4 Dividing activities into several companies

Covering the full sanitation value chain might not be feasible for a single company, different incentives and prioritisation strategies are needed for a company, which provides toilets and one that collects and treats waste. As one of the interviewees pointed out, it is important for a venture to have a single business aim or priority and optimise operations to fulfil it. The goal and strategy of a company will determine its business model, which will then determine the activities and tactics to achieve their goal (Casadesus-Masanell and Ricart, 2010). A company whose aim is to provide safe serviced sanitation in a community cannot optimise its processes to produce the best quality HEDF suited for the local market or one that reaches the largest number of farmers. If on the other hand resource recovery is the company's aim, then diversifying organic inputs and the range of treatment processes for those organic wastes is probably more attractive. Globally there is an increasing interest in the concept of 'waste biorefinery', aiming to extract as many valuable components and products as possible from organic wastes, which can be applied to human excreta (Carey *et al.*, 2016; Venkata Mohan *et al.*, 2016). With that vision, it might be more worthwhile to combine different waste streams for treatment rather than just human excreta.

6.5 **Conclusion**

These two studies showed that it is feasible to provide safe and sustainable sanitation in urban slums and produce HEDFs that have an outlet in the local market. The two organisations had different models of production and sales of C^{HEDF}, but similarities could be seen across both cases and contexts. Continuous and rigorous efforts were needed to establish a successful venture producing and selling C^{HEDF}. Investment in extensive R&D for composting was needed initially to obtain a good quality end-product with beneficial effects on soil and crops. Detailed and efficient organisation and management of the production sites along with thorough risk mitigation practices and testing schedules were essential to ensure product integrity and avoid contamination. Both sanitation ventures considered here successfully managed to secure initial customers, but the costs of transport, operation and maintenance however outweighed profits. These CBS ventures would greatly benefit from public financing for providing a service that has a positive impact on public health, reducing the incidence of disease in the communities and producing sustainable organic amendments in the form of HEDFs. Examples from other parts of the world show that financial or government policy assistance are instrumental in the success of C^{HEDF} marketing. Successful public-private partnerships can be established and taxes or government incentives can have positive impact on the economic viability of compost production from organic wastes. Having a range of products in the market is possibly more viable than only producing C^{HEDF}, calling for a wider waste management solution to FSM.

A principal challenge for widespread commercialisation of HEDF was the lack of clear regulations or certifications to accredit the quality and give more credibility to these products. The production and commercialisation of HEDF also requires a different skillset from the provision of sanitation, there is therefore a need for collaboration across sectors to achieve the optimal solution of both sanitation, waste management and agricultural challenges, develop appropriate policies and ensure the adoption of new technologies.

7 CHALLENGES TO THE USE OF HEDFs: THE CASE OF VEGETABLE EXPORTS FROM KENYA TO EUROPE AND INFLUENCE OF CERTIFICATION SYSTEMS

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Abstract

Land degradation and inadequate FSM are two major issues in SSA. The transformation of human excreta into HEDFs and their wide-scale adoption could improve soil health and contribute to solving the sanitation crisis in SSA. There are however perception challenges around these fertilisers because of the potentially harmful components they contain such as pathogens and heavy metals, which can be removed with appropriate treatment such as composting. One of the aims of this research was to evaluate the effects of HEDFs on soil. Soil tests were carried out on fields where HEDF had been applied and showed that HEDF did not increase heavy metal contents in soil or cause microbial contamination. Another major barrier to the wide scale commercialisation of HEDF are the unclear regulations surrounding their use. The other aim of this study was to identify barriers to the use of HEDF by farmers participating in the horticultural export market with Kenya as focus area since horticultural exports are a major contributor to the country's economy. Global GAP is the most widely adopted standard for quality assurance of horticultural crops and the use of human sewage sludge is currently not allowed on certified farms. Interviews with stakeholders along the food export chain highlighted the complex interactions that exist between them and showed that Global GAP certified farmers were not willing to use HEDF on their farms even if local regulations recognise treated sludge as a valid input to agriculture. Several countries (like the UK, Sweden, Australia and the USA) created specific certification or assurance schemes to improve public perception of biosolids. The creation of a similar assurance or certification scheme specific to fertilisers made from source-separated human excreta would be a step into formalising

The formatting of the original published manuscript has been adjusted to fit the format of this thesis.

them as a product, establishing production procedures, limits on contaminants content as well as testing protocols. Such a certification scheme could increase the confidence of regulating bodies in HEDF and lead to their acceptance by global farming standards.

Keywords: compost, sludge, human excreta, fertiliser, export, certification

7.1 **Introduction**

7.1.1 Soil Fertility and Sustainable Sanitation in SSA

Land degradation is a global issue that affects millions of people worldwide by compromising food security, inducing loss of livelihoods and even causing migration (Reed *et al.*, 2011). It is estimated that 25% of all agricultural land is affected by soil degradation (DeLong *et al.*, 2015). Soil degradation in SSA is a major challenge, which is primarily caused by agricultural intensification and expansion (Tully *et al.*, 2015). Limited application of fertilisers in many parts of Africa is the leading cause of reduced crop productivity and depletion of soil fertility (Chauvin *et al.*, 2012; Tully *et al.*, 2015). Soil health can be restored with appropriate measures such as application of organic amendments to increase soil organic matter, essential for maintaining healthy soils (Bationo *et al.*, 2007). An abundant source of organic matter in cities is organic residues such as vegetable wastes or human excreta.

Another issue prevailing in SSA is the safe treatment and disposal of human excreta, especially in urban areas. It is estimated that between 65% and 100% of sanitation in SSA is provided by on-site sanitation systems (Strauss *et al.*, 2000; Blackett *et al.*, 2014), which require emptying and appropriate treatment and disposal to prevent public health and environmental hazards. In areas where safe, effective and appropriate FSM practices are not in place, it is essential to create incentives locally for the collection and treatment of FS.

Human excreta have been shown to have a good fertilising potential, providing essential plant nutrients as well as organic matter contributing towards building soil structure and reducing erosion (Jonsson *et al.*, 2004; Guzha *et al.*, 2005; Begum, 2011). With an appropriate heat treatment such as composting, all harmful pathogens in human excreta can be eliminated to produce HEDFs safe to use in agriculture (Berendes *et al.*, 2015; Piceno *et al.*, 2017).

In SSA the use of HEDFs could solve two problems at once: the issue of low soil fertility as well as the problem of FSM, especially in densely populated areas. However, fertilisers derived from human excreta suffer from significant stigma and unclear regulations create a barrier to their use in agriculture. In Europe, the application of biosolids to land is regulated by the sewage sludge directive, which has been integrated into the member countries' legislations (European Commission, 1986). In the case of source-separated human excreta however, regulations are generally less clear on the reuse of treatment products, which has implications on farming practices and is an obstacle to commercialising HEDF.

7.1.2 Global food trade and its implication on farming practices

In an increasingly globalised world, food production and trade across borders are common practice and customer expectations have evolved accordingly. Changes in dietary habits, especially in high-income countries, have increased the demand for year-round availability and a wider range of fruits and vegetables, which fuel the global trade of fresh fruits and vegetables. Between 2000 and 2012 the volume of global agricultural exports increased by 60% and the value of global food trade tripled in the last decade (WTO, 2014; FAO, 2015).

The international trade of fresh vegetables started through wholesalers. In Europe however, this trend changed when the largest supermarkets gained the majority of shares of the food market in the 1980s and 1990s and hence got more involved in the direct procurement of produce (Dolan and Humphrey, 2000). Supermarkets now dominate the fruit and vegetable market in Europe, between 60 to 90% of produce is sold through supermarkets depending on the country (CBI, 2015). In the UK, the five supermarkets with the largest market share currently capture more than 75% of the grocery market (Kantar, 2017). About 14% of crops imported to the UK originate from Africa (DEFRA, 2007). There is now a tight relationship between large supermarket chains and horticultural exporters, they are dependent of each other and don't want to compromise their relationship (Dolan and Humphrey, 2004).

In many countries of SSA the export of fresh horticultural produce is becoming an increasingly important and lucrative practice. In LICs, it is more profitable for farmers to participate in the global trade of horticultural products than the local market alone (Reardon *et al.*, 2009). In SSA the three main countries exporting horticultural products are Cote d'Ivoire, South Africa and Kenya, together accounting for 90% of the region's fruit and vegetable exports (Diop and Jaffee, 2004; Asfaw *et al.*, 2009). Kenya is the largest horticultural exporter to the EU in SSA, horticultural exports make up 70% of the horticultural earnings, the value of exports rises on average 10% per annum and is the third source foreign exchange from exports after tourism and tea (Kenya Horticultural Council, 2017). Given the importance of horticultural exports in Kenya and the presence of an SME producing and selling HEDF in Nairobi, Kenya was chosen as the focus for this study.

The development of a large horticultural industry in Kenya dramatically changed the agricultural sector, large commercial farms were created, and the number of smallholder farms decreased. These large farms supply the majority of fruit and vegetables to exporters; considering the 4 largest exporting firms, in 1992 about 75% of exported produce was sourced from smallholders whereas in 1998 only about 18% of produced was supplied by smallholders for (Dolan and Humphrey, 2000). The UK is the destination for over 70% of Kenya's vegetable trade (Jaffee and Masakure, 2005).

Producing for export has implications on farming practices and product quality: produce needs to meet specific safety and quality standards. International good agricultural practice standards were created to guarantee the safety of produce traded internationally. A wide range of third-party accredited agricultural production standards now exist worldwide, the 24 major ones are described and summarised in SAI (Sustainable Agriculture Initiative) Platform (2009). The most widely adopted standard for guaranteeing the safety of produce is Global GAP (Global Good Agricultural Practices), which specify farming practices to minimise the risk of contamination in produce and protect farm workers' health. Global GAP is now present in more than 120 countries and has its headquarters in Germany (Global GAP, 2017).

Kenyan standards recognise treated sewage sludge as a valid substance to be used as a fertiliser (KS2290:2011). One of the clauses in Global GAP however states that "no human sewage sludge can be used on accredited fields" (Global G.A.P., 2011), though it is unclear whether this includes compost derived from human sewage sludge. Vegetable exporters therefore usually ban the use of HEDF on fields growing crops for export as a precautionary measure, creating a major barrier to the commercialisation of HEDF and for recycling nutrients to soil in areas with large horticultural export sectors.

7.1.3 Issues of public perception of HEDF

Perception is one of the main challenges with products derived from human excreta (Beecher *et al.*, 2004; Gale, 2007). Farmers generally do not have an issue with the origin of organic amendments if they have a positive effect on soil (Danso *et al.*, 2002; Cofie *et al.*, 2005; Moya *et al.*, 2017). However, customer and regulator perceptions of products derived from wastewater or human excreta is a common barrier to their commercialisation. As a result, several countries have developed assurance schemes specific to biosolids. The Biosolids Assurance Scheme (BAS) in the UK for instance, ReVAQ in Sweden, the National Biosolids Partnership (NBP) in the USA or the Australasian Biosolids Partnership (ABP) in Australia and New Zealand provide a certification scheme for biosolids to increase customers' confidence in biosolids use in agriculture (Gale, 2007; NBP, 2011; L'Ons *et al.*, 2012; BAS, 2016). It is proposed in this study that a similar scheme specific for HEDF could help reduce the barriers to its use.

7.1.4 Concerns with the use of products derived from human excreta on agricultural land

The main concerns over fertilisers derived from human excreta are generally pathogens, heavy metals and other chemical contaminants such as pharmaceuticals. These can be dealt with through appropriate treatment such as composting and safe products can be obtained as presented in Moya *et al.* (2018). Another emerging concern that has been reported beyond the treatment stage of human excreta is the regrowth of pathogens. Ward *et al*. (1999) for instance reported the regrowth of *Salmonella* as well as other pathogens after pasteurisation of sewage sludge digestate. It is believed that if a few pathogens survive in the end-product after treatment, under the right conditions they can start colonising the environment again. Another hypothesis is that pathogens can effectively become inactive or dormant under extreme conditions such as thermal treatment or dewatering but can become reactivated when the conditions become viable for microbial growth and pathogen recolonisation occurs (Higgins *et al.*, 2007). Williams (2014) studied the use of competitive exclusion as a prevention mechanism for the regrowth of *E. coli* on treated sludge from centralised wastewater treatment plants: experiments showed that introducing certain microorganisms that competed with *E.coli* for growth effectively halted the regrowth of *E.coli* colonies and hence stopped recontamination of the treated sludge.

The aim of this study was to characterise the effects of HEDF on soil, identify the barriers along the food chain to their use in agriculture and formulate strategies to overcome them. The research activities were carried out in Kenya and several stakeholders along the horticultural export chain were interviewed. The potential regrowth of pathogens in HEDF and contamination of soil was also evaluated by carrying out pathogen and heavy metal analyses on soil previously amended with HEDF (compost) as well as soil nutrient analyses to characterise the effect of HEDF application on soil properties.

7.2 **Methodology**

Stakeholder interviews were carried out as semi-structured interviews covering the topics of crop production and exports, agricultural certifications, fertiliser use and opinions regarding fertilisers derived from human excreta. These interviews were a means to explore the issues related to crop production, export and regulations. Stakeholders along the whole food chain between Kenya and the UK were interviewed: regulatory bodies, certification bodies, supermarket representatives and horticultural crop exporters as summarised in Table 7.1.

A criteria-based purposive sampling approach was followed to select respondents from exporting companies. The criteria to select respondents were as follows:

- Certified to Global GAP
- Have their own farms and subcontract smallholders as well (these exporters have a more detailed knowledge of farming practices and are familiar with differences between smallholder farmer and large commercial farms practices)
- Export to UK market
- Directly supplying to supermarkets (not via wholesalers) (these exporters are aware of supermarket-specific requirements)
- Supply to large supermarket chains in the UK and Europe.

Table 7.1 Stakeholders interviewed along the food chain, organisation and stakeholder type are indicated

Stakeholder organisation	Stakeholder group
European Commission, DG Grow	International regulator on fertilisers
Biosolids Assurance Scheme	UK-specific biosolids certification
Exporting company 1 **Large exporter (provider to 3 major UK supermarkets)**	Fertiliser user in Kenya, certified to Global GAP
Exporting company 2 **Large exporter (provider to one major UK supermarket)**	Fertiliser user in Kenya, certified to Global GAP
Exporting company 3 **Medium exporter (provider to continental Europe supermarkets)**	Fertiliser user in Kenya, certified to Global GAP
Supplier Relationship Manager for a UK supermarket in Kenya	Large UK food retailer

Six interviews were carried out between December 2016 and March 2017, they were recorded and transcribed when respondents agreed. One of the interviewees did not agree to voice recording so detailed notes were taken throughout the conversation. Interviews were coded manually using the software NVivo (QSR International, 2015), initially using descriptive coding methods which is best suited for identifying the topics emerging from an interview (Saldaña, 2013). Codes describing the topic or principal argument were first applied to conversation sections without considering the connection of codes between different sections. These codes were then analysed and grouped to draw out emerging themes from the interviews and their frequency.

The second part of this research consisted in evaluating the effect of soil amendments derived from human excreta on soil after crop growth. Soil samples from six farms where HEDF (compost) had been applied for different lengths of time to grow a range of crops were taken to evaluate the effect of the compost on soil (Table 7.2). The application of HEDF was localised to plant root areas and done at the time of planting in the direct area, which was possible with the types of crops cultivated on these farms. The fields sampled were divided in different sections and some of them had received no HEDF applications. Samples were taken both from fields where HEDF was applied and those where it was never used, allowing evaluation of the effect of HEDF on soil. The sampling methodology consisted in dividing fields into 3 sections, walking a ‘W’ in each section across the length of the field collecting 5 subsamples of the first 20cm of topsoil taken with an auger and making a composite sample out of them. 6 soil samples were taken from each farm, half from fields where HEDF had been used and half where it had never been used previously.

Table 7.2 Characteristics of HEDF use and crops grown on the farms sampled.

Location reference	Time HEDF compost has been used	Number of seasons HEDF compost was applied	Crops grown
Farm 1	9 months	3	Watermelon Tomato
Farm 2	2 months	1	Tomato
Farm 3	1 year	3	Melon Tomato Maize
Farm 4	6 months	2	Melon
Farm 5	1 year	1	Beans Maize Potato
Trial farm		1	Onion

Faecal contamination was evaluated by testing the presence of *Clostridium perfringens* in soil samples (ISO7937, 2004). Basic soil nutrient analyses were carried out on these samples to compare the characteristics of the different soils in the same laboratories as for the HEDF samples following the same methodologies as outlined in Chapter 3. Statistical analyses were carried out: a t-test with a significance level $p<0.05$ was performed for samples from each field comparing sections with and without HEDF applications using the software Statistica (Statsoft, 2011).

7.3 Results and discussion

The barriers to the use of HEDF by the largest horticultural producers in Kenya, vegetable exporters and in particular those who export to Europe were evaluated. Interviews with vegetable exporters in Nairobi highlighted the challenges faced to meet the existing regulatory and commercial demands for exporting horticultural crops. The main findings and recurring themes are summarised in the following sub-sections.

7.3.1 Accessing the horticultural export market requires compliance with a wide range of regulations and certifications

Imports into the EU are regulated by EU laws for product quality and safety, chemical residues and marketing requirements. Compliance with these regulations is the first hurdle for Kenyan farmers and exporters, and non-compliance leads to market loss for exporters.

"We have a regulating authority, KEPHIS [Kenya Plant Health Inspectorate]. *Because it's the image of the nation, if they don't put regulations strict we will lose on trades with other countries. They are strict on pesticides, on seed materials, seed source, very strict"* Exporting company 1

Access to certain supermarket clients also requires abiding to additional private third-party certified standards. Global GAP dominates as the standard of choice by food retailers in the EU for assuring product safety and traceability and is now effectively a precondition for entering the European market (CBI, 2016). The cost of certification falls on the producers and adherence to Global GAP requires the adoption of specific farm practices and infrastructure, which can have significant cost implications.

"If you want to enter that market, it's up to you to get the certification" Exporting company 1

Certification also requires a yearly renewal, which imposes significant recurring costs (Kariuki et al, 2011). Investment costs related to Global GAP certification can represent up to 30% of the annual crop income for farmers in Kenya (Asfaw *et al.*, 2010). It therefore becomes challenging for smallholders to afford certification as well as apply and comply with all the control points and technical and administrative requirements set out by Global GAP.

Another constraint identified was a trend for increasing the number of certifications required from producers covering farm practices, labour conditions and fairness of trade, increasing certification expenses. One of the exporting companies interviewed reported spending up to 11 million Kenyan Shillings a year on certification costs (about 80 000 GBP) and refusing new clients that required additional certifications. Currently worldwide there exist over 132 standards for the agricultural and fresh fruits and vegetables sector (ITC, 2017). The benefits of these standards are questioned by some: Oya *et al*. (2017) carried out a systematic literature review of studies that had analysed the effect of various agricultural certification schemes on the welfare of farmers and found that certified farmers did improve the income obtained from their produce but the effect on overall household income or children's educational level was not significant. Asfaw *et al*. (2009) on the other hand claim that certification schemes significantly increase farmers' financial performance although they admitted that certification mechanisms can leave out the poorest farmers from participating in lucrative export chains. Growth of the trade in fresh produce has however been highest in countries where the most standards are adopted. The adoption of certification schemes has also been shown to positively impact farmers' health by controlling the application and handling of chemicals on farms (Asfaw *et al.*, 2010; FAO, 2015).

Certain supermarket chains require additional certifications, but all the exporters identified Global GAP as a benchmark for the other supermarket-specific certifications. Respondents saw these partly as a marketing tool for the supermarkets. The most up-market supermarkets are the ones that have the tightest constraints and tests but also offer the highest premium in crop purchase price, so the producers abide to these strict requirements.

7.3.2 Horticultural exporters depend on supermarkets and the criteria they set

Exporters have a close relationship with supermarkets. They both agree at the start of the season on the volumes that will be provided but the volumes purchased sometimes are reduced leaving producers with a surplus. All exporters interviewed said that the produce they grow for export is difficult to resell in the local market because crops such as fine beans or tender stem broccoli are not common in the local consumer's diet so most often these crops go to waste or used as animal feed. Exporters are therefore dependent on the supermarkets buying their produce and have to respect the criteria and standards they set.

7.3.3 Vegetable producers face challenges to increased productivity

Interviewees identified several factors that affected productivity on their farms as well as smallholders. Climate change was seen as a main challenge for smallholders for growing crops and one of the respondents even reported reducing their farm production area from 7-9 hectares to 2-3 ha due to water shortages. The climate conditions in Kenya are favourable to the breeding of pests and interviewees felt that they were running out of options for fighting infestations due to increasing regulatory restrictions.

"the weather has been very erratic. You can no longer plan well. Normally around this time we have heavy rains. The rains have been delayed, volumes have been distorted a lot of quality issues […]. The yields right you can't compare the yields now and ten years ago" Exporting company 3

"Kenya is on the equator so we have a very conducive climate for most pest and diseases and it's almost impossible, it's very difficult to grow crops without using any spray unless you are doing under a controlled environment. Most farmers cannot afford greenhouse cover" Exporting company 3

The reduction in crop productivity was also coupled with high volumes of crops being wasted at the farm level because of cosmetic constraints set by the standards. Such cosmetic restrictions lead to large volumes of crops going to waste with one of the respondents reporting that over 40% of the produce was wasted at farm level. A study carried out on food waste in the horticultural export chain in Kenya Colbert and Stuart (2015) reported that up to 50% of produce was rejected before export.

"it's become a bit ridiculous in Europe like if it's not straight and a certain size and a certain then you can't sell in a supermarket" Exporting company 3

"There is no difference in between the taste of a straight bean and the taste of a bent bean, it's the same taste. But these guys will all have these specifications, they will say that I want bean that are maybe 9-15 cm, if it is longer than that or shorter than that I can't sell it" Exporting company 2

7.3.4 Exporters are pushed to innovate to increase their competitivity but don't want to risk breaching certification terms.

Exporters also expressed concerns with an increasing price of farm inputs, which is not matched by sales price increases, pushing them to innovate. Larger exporters are starting to provide post-harvest processing services or starting to grow new types of crops to keep ahead of competition. One of the exporting companies even had a dedicated innovation team.

The need for improving soil health was expressed by one of the respondents particularly. They expressed the need for additional organic matter and pH regulation on their fields:

"our soils depleted are finished because of continuous use of inorganic fertilisers, they're done, they're tired […] we try to renovate, we try to close some farms and leave it for some time. The soil can't have it, you put an inorganic fertilizer, it doesn't work you go and check the pH is below five you know that's a very acidic and no crop will grow there." Exporting company 2

A company in Nairobi produces HEDF and found that up to 30% yield increase was observed with local application of HEDF to grow French beans. During interviews respondents were informed of this and photos of the HEDF production site were shown, highly mechanised and modern (mechanised mixer and mechanised compost windrow turning and watering). All respondents were interested in finding out more about the product, they however voiced a concern over Global GAP compliance if they used HEDF. Since the standard currently does not allow the use of treated human sewage sludge on fields, all respondents said they were not willing to use HEDF even if it had a positive effect of soil because of the potential loss of contracts.

"*it's something that we cannot engage in. Unfortunately, Global GAP takes preference*" Exporting company 3

The supermarket representative interviewed thought that if the HEDF are made up to standards and safety assurance then maybe it could be allowed, but only if it was approved by Global GAP. One of the respondents also voiced a concern over the perception of HEDF and the willingness of farmers to use them. There is however evidence that local farmers are willing to use HEDF if it has a positive effect on their soil and are affordable (Danso *et al.*, 2002; Cofie *et al.*, 2005; Moya *et al.*, 2017).

The general impression from respondents was that the modification of Global GAP standard is not impossible; the standards are reviewed regularly and open to consultation by technical groups. There seems to be a possibility of dialogue: each country has technical groups who are consulted prior to changes to the standard. Sustainability is a key issue for Global GAP so the use of HEDF could be seen as beneficial. Exporters suggested that lobbying to Global GAP could be possible with appropriate evidence of the safety of HEDF.

7.3.5 The need for more sustainable fertilisers is recognised

Despite reservations and lack of clarity towards biosolids, there is a global recognition for the need to produce more sustainable fertilisers. The EU directive on fertilisers is currently being updated (EPRS, 2017). One of the key drivers for the fertiliser regulation update is to promote the circular economy. The aim of the European Commission is to increase the sustainability of European agriculture and reduce dependency on imports from outside the EU for fertilisers (European Commission, 2015). This is especially the case for P since all the mineral resources are outside the EU and in geopolitically sensitive areas. Another key issue is the accumulation of heavy metals in European soils, especially Cd, which is a by-product from P extraction.

Organic wastes are a valuable source of phosphorus and the EU Commission stakeholder interviewed explained that the aim of the EU is to encourage their recycling to land by increasing the value of organic fertilisers through regulations. They recognised a need to "*create a level playing field between the mineral fertilisers and the organic ones".*

Sewage sludge however is not currently included in the EU's 'end-of-waste' criteria, which define materials that cease being considered wastes and are eligible as inputs for other processes. A report in 2014 recommended sludge not to be included in the EU end of waste criteria, creating a barrier to the production and commercialisation of composts derived from sewage sludge (Mininni *et al.*, 2015). The EU interviewee recognised that there is a fear of contamination with persistent organic compounds from sewage sludge, which are not regulated yet so currently sewage sludge is not listed as a potential input for fertilisers. The view for source-separated human excreta however was different, they admitted that HEDF didn't fit into a specific category at the moment and perhaps could be included as an animal by-product. This highlighted the grey area which HEDF fall into with regulations. The respondent from the EU Commission also recognised that private standards are often more efficient at achieving specific outcomes and more powerful than regulations with stricter implementation checks. Their opinion echoed that of the Kenyan exporting companies: unless private certification schemes such as Global GAP change their stance on the use of HEDF, it is very unlikely that farmers trading with supermarkets will adopt them.

7.3.6 Soil properties of fields treated with HEDF

Several respondents thought that the current exclusion of "human sewage sludge" in Global GAP farming standards was related to uncertainties of their quality and their potential to contaminate soils. An evaluation of the effects of HEDF on several fields was therefore carried out to quantify the potential benefits to soil and contamination risks of HEDF. Soil sampling was carried out on six different farms, which grew a range of different crops as summarised in Table 7.2. Results from the soil analyses carried out on soil from the different farms are detailed in Table 7.3 and results from statistical analyses summarised in Table 7.4.

Table 7.3 Results of soil analyses from the different farms sampled and results of the t-test performed (significance value taken at $p<0.05$). Significant differences are highlighted

	Farm 1			**Farm 2**			**Farm 3**			**Farm 4**			**Farm 5**			**Trial farm**		
	Sections never treated with HEDF	Sections treated with HEDF	p value	Sections never treated with HEDF	Sections treated with HEDF	p value	Sections never treated with HEDF	Sections treated with HEDF	p value	Sections never treated with HEDF	Sections treated with HEDF	p value	Sections never treated with HEDF	Sections treated with HEDF	p value	Sections never treated with HEDF	Sections treated with HEDF	p value
pH	5.71	5.55	0.71	5.79	6.10	0.446	5.62	5.45	0.651	5.56	5.93	0.382	6.35	7.02	0.071	**6.51**	**6.77**	**0.040**
P (mg.kg^{-1})	15.4	10.4	0.15	**5.80**	**39.2**	**0.000**	79.5	27.9	0.063	**3.48**	**12.90**	**0.002**	**120**	**81.4**	**0.012**	150	103	0.749
K (mg.kg^{-1})	440	444	0.899	457	586	0.082	614	488	0.059	389	486	0.195	876	1.12 .10^{3}	0.254	890	498	0.484
Ca (mg.kg^{-1})	664	645	0.754	1.07 .10^{3}	1.06 .10^{3}	0.963	873	698	0.093	550	716	0.168	2.08 .10^{3}	4.15 .10^{3}	**0.005**	5.02 .10^{3}	5.16 .10^{3}	0.837
Mg (mg.kg^{-1})	258	304	0.129	375	333	0.143	267	227	0.063	264	321	0.159	230	321	0.115	623	587	0.372
Na (mg.kg^{-1})	97.5	74.9	0.141	66.7	92.9	0.226	64.3	80.2	0.280	95.9	131	0.133	111	212	0.479	481	528	0.631
Organic Matter (%)	2.59	2.41	0.790	2.79	2.35	0.345	2.35	2.66	0.058	2.35	2.86	0.196	**1.98**	**3.50**	**0.015**	2.98	3.14	0.497
Total N (%)	0.17	0.15	0.628	0.160	0.14	0.158	**0.16**	**0.14**	**0.013**	0.15	0.19	0.078	**0.08**	**0.16**	**0.019**	0.12	0.12	1.00
C.E.C (meq.100g^{-1})	9.93	11.6	0.465	14.2	12.6	0.510	12.6	11.5	0.403	9.71	11.01	0.405	**17.63**	**29.2**	**0.012**	39.6	37.4	0.554

Table 7.4. Summary of results from t-tests between fields sections where HEDF had been applied and those never treated with HEDF

Location reference	Time HEDF compost has been used on field	Significant differences in t-test for nutrients between fields treated with HEDF and those where no HEDF was applied
Farm 1	9 months	None
Farm 2	2 months	P higher with HEDF
Farm 3	1 year	Total N lower with HEDF
Farm 4	6 months	P higher with HEDF
Farm 5	1 year	P lower with HEDF Ca, Organic Matter, Total N, CEC higher with HEDF
Trial farm	1 crop season	pH higher with HEDF

In Farm 1, no significant differences were found in any of the parameters analysed between fields treated with C^{HEDF} and those that had not received HEDF. Overall, K, Mg and Na concentrations did not experience significant changes between any of the fields treated with HEDF and those that had not received any C^{HEDF} applications. Significant differences in P between untreated fields and those that had received HEDF were found in 3 of the farms sampled: the P concentration increased more than 6 times with HEDF application in Farm 2, it was almost quadrupled in Farm 4 whereas in Farm 5 it was reduced by about 40%. Similarly, significant changes in Total N concentrations were found in two of the farms, one experiencing a reduction of about 15% whereas in the other farm Total N concentrations doubled with the application of HEDF. These differences in the effect of HEDF on soil nutrient concentrations across the different fields sampled could be due to different soil types, differences in types of crops grown as well as differences in soil fertility management between the farms. Additional fertilisers were applied during crop growth in each farm, each farmer having their own practices and using different fertiliser mixes, making it impossible to directly compare changes in soil nutrient concentration between farms. It is difficult to draw conclusions from analytical results from soils originating from different geographical regions and undergoing different crop culture practices. It is also difficult to see the effects of HEDF on the soil overall when the C^{HEDF} was applied locally to the plant root area, therefore a change in the overall soil properties was not detectable.

Most significant differences between control and plots where HEDF was applied were found in samples from Farm 5: Ca and Total N concentrations doubled, and organic matter and CEC also increased with the application of HEDF during one season. Several types of crops were grown in this farm including beans, which are nitrogen fixers and hence could have contributed to higher N concentrations in soil after applying HEDF for 1 year. N fixation also facilitates aggregation of soil particles and contributes to build-up of organic matter. In this farm, the manager stated having specifically chosen to apply compost to improve soil organic matter content; this was a large-scale commercial farm with planned and controlled crop management practices and more financial means than the other smaller farms sampled. C^{HEDF} on farm 5 was applied in higher quantities and N fixers were part of the crop rotation, which translated in more benefits to soil health from HEDF application than in the other fields. These results suggest the effects of HEDF can be magnified by certain farming practices.

The longest period of application of HEDF was 3 seasons, which is not long enough to draw conclusions on the long-term effect of the C^{HEDF} on soil. Other similar studies comparing the effect of soil amendments derived from sewage sludge had longer time frames of 4 years (Odlare *et al.*, 2008), 16 years (Mantovi *et al.*, 2005) or 22 years (Zaman *et al.*, 2004) for instance. After 4 years of crop trials with different fertiliser applications, Odlare *et al* (2008) found few trends or significant differences in soil chemical and biological properties between plots treated with a range of fertilisers: Municipal Solid Waste (MSW) compost, digestate from MSW anaerobic digestion, digestate from sewage sludge digestion, cow and pig manure and chemical fertilisers. They did however see differences in soil microbial processes such as ammonia oxidation rate and N mineralisation capacity and suggest these as better indicators for short term effects of fertilisers derived from organic wastes on soil. Mantovi *et al.* (2005) saw significant increases in organic matter, N ($p \leq 0.01$) and available P ($p \leq 0.001$) in soil as well as significant increases in N ($p \leq 0.01$), P ($p \leq 0.001$), Zn ($p \leq 0.001$) and Cu ($p \leq 0.01$) content in the wheat crops grown in plots treated with three different fertilisers derived from sewage sludge as compared to plots treated with chemical fertilisers only. They found a significant build-up of Zn and Cu in top soils of plots treated with the fertilisers derived from sewage sludge but concentrations remained below regulatory limits. Zaman *et al.* (2004) found that fields that had received sludge-derived composts had significantly higher concentrations of Total N and carbon as well as soil microbial biomass than fields treated with chemical fertilisers.

7.3.7 Assessing the presence of contaminants in soils treated with HEDF

The presence of *Clostridium perfringens* was analysed to test for faecal contamination on the fields and all results were negative; *Clostridium perfringens* concentrations were below the detection limit of 10 $cfu.g^{-1}$ in all samples. This result is in accordance with the pathogen tests carried out on the compost samples discussed previously in Moya *et al.* (2018), showing that the treatment of human faeces by thermophilic composting eliminated harmful pathogens.

The concentration of heavy metals in the soils sampled was also measured and no significant differences were found between soils treated with HEDF and those that weren't. All soils were compliant with regulatory heavy metal concentration limits as shown in Table 7.5. It should be noted that soil Cd concentrations, which were reported as being one of the main concerns for the EU, remained below the EU limit for soils in all farms as well as those set out in the UK's Biosolids Assurance Scheme.

Table 7.5 Heavy metal concentration in soils tested compared with regulatory limits

Heavy metals	Mean concentration (n=4) without application of HEDF in (mg.kg^{-1})	Mean concentration (n=4) soil with application of HEDF in (mg.kg^{-1})	p value from t-test analysis	EU Heavy metal concentration limits in soil in (mg.kg^{-1}) [(a)]	BAS strictest heavy metal concentration limits in soil in (mg.kg^{-1}) [(b)]
As	1.58	1.63	0.92	5	3
Cd	0.83	0.80	0.50	1	
Cr	33.3	32.8	0.70	100	
Cb	11.9	11.0	0.28	20	
Cu	9.76	9.92	0.91	100	130
Ni	11.8	12.4	0.52	50	80
Pb	14.6	14.3	0.84	60	300
Zn	100	93.9	0.61	200	200

(a) limits taken from the finish ministry of environment, which are considered a good representation of the mean values of European regulatory limits

(b) limits for soil from arable lands with pH >5 that have received biosolids applications

7.3.8 The value of biosolids-specific assurance schemes

In the UK, nearly 80% of biosolids are applied to soils following Safe Sludge Matrix guidelines, 75% of which are applied to agricultural land (UKWIR, 2015). Nevertheless, challenges remain in terms of perception and risk to the produce which resulted in development of the Biosolids Assurance Scheme (BAS) to ensure that its recycling into land is transparent and subject to external controls (Water UK, 2013). This initiative came from the Water Utilities to increase customers' confidence by compiling regulations, codes of practices and best practice guidelines to provide evidence and assurance of the quality of biosolids they produce. Several stakeholders along the food chain were actively involved during the creation of the BAS to ensure their concerns were addressed and produce a scheme that met their requirements and provided the assurance they need.

"It's about direct reassurance to the people who matter" BAS creator

The creators of the BAS admitted that there are still major barriers for widespread use of biosolids in agriculture. In the UK currently biosolids are only applied to 1.3% of the total agricultural land (though this is mainly limited by sludge availability) and to combinable crops, not to any vegetable crops.

“almost nothing goes anywhere near any vegetable crop by a long mile.“ BAS creator

The use of biosolids directly onto fields growing vegetables is still controversial and not accepted at present. Respondents were of the opinion that food retailers would not allow the use of biosolids on farms that they purchase from.

“Really is more about a perception issue than a science issue.” BAS creator

The creation of BAS seems to have had a positive effect on the acceptance of biosolids for agriculture in the UK but their application remains limited to certain crops. It is suggested that a similar scheme could be developed for HEDF to increase confidence in the quality and safety of these products and therefore increase their acceptance from farming standards and regulatory bodies. Certification of HEDF could also increase the willingness to pay for compost as Danso *et al.* (2017) found in Ghana.

7.4 **Conclusion**

The production of HEDFs for use in agriculture provides an incentive for collecting and treating FS as well as an addition of organic matter to soil, both of which are needed in many low and middle-income countries. The production and use of HEDF in Kenya could help solve the issue of sludge management in urban slums and improve the fertility of organic matter depleted soils. Several barriers were however identified in this study for the adoption of HEDF in Kenya. The largest agricultural producers are oriented towards exporting crops and are required to abide by international certifications to be able to trade with most supermarkets, Global GAP being the most widespread standard. Interviews revealed that vegetable exporters face issues of crop productivity and decreasing soil health but can’t innovate outside the boundaries set by the standards. It is unclear whether the use of HEDF on certified farms is allowed at present so producers of horticultural exports are not willing to use them on their fields. Local regulations in Kenya recognise sewage sludge as a valid input for organic fertilisers but private standards have more weight in defining farmer practices. Unless the standard-setting body, Global GAP, explicitly allows the use of HEDF, it is unlikely that these fertilisers will be adopted by farmers producing for export.

Interviews with regulators highlighted their main concerns with the application of biosolids: soil contamination with heavy metals (especially Cd), pathogens and pharmaceuticals. One of the recurring opinions that was found throughout the interviews carried out in this project was that not enough was known about HEDF and their effects on soil and additional tests and experiments were needed. The soil analyses carried out on fields that had been treated with HEDF showed no evidence of heavy metal contamination or of pathogen contamination. The long-term effect of HEDF on soil however could not be evaluated as part of this project since they had been applied for maximum three crop seasons. Analyses on soils treated with HEDF for longer periods and further analyses testing the presence of pharmaceuticals or other organic compounds will be required to provide further evaluate the safety of HEDF use in agriculture.

The use of biosolids commonly faces prejudices and negative public perception. Standards specific to biosolids have been developed in several countries to improve the perception of HEDFs and increase their use. A similar scheme specific for fertilisers derived directly from human waste from dry toilets could be beneficial for lifting a barrier to their use and provide a safety and quality assurance for this type of soil amendment. This assurance would be achieved through a set of requirements and controls ensuring product safety along the whole production chain and provide evidence to all stakeholders along the food chain of the safety using HEDF. The creation of a certification scheme would give more legitimacy to HEDF as a product and would help in lobbying for the inclusion of HEDF in regulations and standards.

8 THESIS DISCUSSION

The provision of safely managed sanitation is a challenge in urban areas in most LICs, particularly in urban slums. In cities of LIC, almost two thirds of sanitation is provided through OSS and only 22% of these are safely managed (Blackett *et al.*, 2014). Traditionally OSS are pit latrines that fill up over time and their emptying is problematic, especially in densely populated urban slums (Parkinson and Quader, 2008). The need for alternative systems is widely recognised and in the last several years there has been a surge of interest in developing alternative toilet systems that do not rely on pits encouraged by initiatives such as the Reinvent the Toilet Challenge launched in 2011 by the Bill and Melinda Gates Foundation (BMGF) (Gates Foundation, 2011). Interest in sanitation has also grown in a wide range of stakeholders including within the large multinational businesses that created the Toilet Board Coalition in 2014 to 'accelerate the sanitation economy' (Toilet Board Coalition, 2017). The need for resource recovery is recognised as a requirement for achieving sustainable sanitation solutions as well as increase the economic viability of sanitation businesses (Diener *et al.*, 2014; Andersson *et al.*, 2016; Rao *et al.*, 2017). Recovering resources from sanitation systems would help realise a circular sanitation economy, in alignment with the recognised need to shift production systems from linear to circular systems (Ellen MacArthur Foundation, 2013).

CBS is a new type of sanitation system and model which has been implemented by a small number of organisations over that past few years. CBS is based on an alternative system of excreta management where excreta are collected in portable sealable containers, which are then collected and transported to a treatment facility several times per week. Resource recovery is usually a part of these systems, typically nutrients, energy or water are harnessed (Tilmans *et al.*, 2015). The lack of permanent infrastructure in CBS systems makes them highly attractive for densely populated informal settlements where space is limited, and where dwellers do not usually own the land. So far, these organisations have functioned as private entities recovering costs through user fees and resource recovery from the excreta collected.

Resource recovery through nutrient harvesting is an attractive solution that several CBS organisations have adopted for producing sustainable HEDFs. However, issues related to the characteristics and quality assurance of nutrient reuse from human excreta remain key challenges (Rao *et al.*, 2016). The characteristics of HEDFs (as opposed to sewage sludge) have not been studied extensively in literature and neither has their effect on soil and crops. Research in this area is in its infancy and this research provided novel data characterising and evaluating the effect of HEDFs derived from CBS systems, namely D^{HEDF}, C^{HEDF} and V^{HEDF}. The properties of the HEDFs produced by two different CBS organisations were initially characterised for their nutrient, pathogen and heavy metal content. The sludge from CBS systems has had a much shorter storage time than pit latrine sludge and it has been shown that the properties of sludge change over time (Niwagaba *et al.*, 2014), it was therefore hypothesized that sludge from CBS systems would have different properties to those from conventional OSS sludge. One of the systems studied used a staged treatment process allowing for tracing the nutrient evolution through the different treatments. The effects of D^{HEDF}, C^{HEDF} and V^{HEDF} produced by one CBS venture in Madagascar were investigated for the first time through a field study and a pot trial in order to quantify the effect of these HEDFs on soil and crops.

Since the profitability of marketing fertilisers derived from organic residues is known to be challenging (Rouse *et al.*, 2008), another aspect of this research focused on the commercialisation potential and challenges associated with HEDF marketing. Two case studies from CBS ventures revealed that both organisations were selling their full C^{HEDF} stock, but neither were recovering treatment costs through fertiliser sales. Several barriers to reaching a wider range of C^{HEDF} customers were identified. One of these barriers was studied in more detail, namely, the ban of products derived from human excreta in private international agricultural practice standards. A stakeholder analysis along the horticultural export chain in Kenya and the import chain in the UK highlighted the weight that these private standards have in defining agricultural practices. A lack of clarity in regulations regarding the use of products derived from treated human excreta was also identified, suggesting that schemes certifying the quality of HEDFs treated to an appropriate standard would be beneficial for establishing their acceptability and value.

8.1 The quality of HEDF and their effect on soil and crops

A range of HEDF types from different CBS organisations were characterised in this project. The results of this characterisation showed that the quality of the end products obtained was dependent on the type of production process from which they originated. The production of HEDF can be achieved through different processes, including anaerobic digestion, composting and vermicomposting. These treatments are all biological processes, which are inherently sensitive to changes in environmental and processing parameters (Campitelli and Ceppi, 2008). This was highlighted by the significant differences in nutrient content identified between different HEDF batches (Chapter 3).

Comparison between C^{HEDF} from three different CBS organisations showed differences between those obtained from faeces only (CA and CX) and those that treated urine as well as faeces in their system (CB) (Chapter 3). The two C^{HEDF} derived from the faeces fraction of urine-diverting toilets shared similar properties in terms of pH (ranging between 5.5 and 5.7), EC (between 8.5 and 9.13 $mS.cm^{-1}$), P (between 0.73 and 0.83%) and K (between 0.71 and 0.87%). Slight differences in carbon (17.34 and 27.3% for CX and CA respectively) and Total N concentration (between 1.93 and 1.17% for CX and CA respectively) could be attributed to the differences in compost processing: CA mixed the faeces and cover material with other agricultural wastes at the treatment site whereas CX did not add any additional material to the contents of the buckets (faeces and cover material). CB HEDFs had different properties from those of CA and CX: the pH was higher, ranging between 7.9 for D^{HEDF} and 9.5 for C^{HEDF}, EC was also higher, between 25.7 and 72.8 $mS.cm^{-1}$, which could be due to the urine fraction of excreta also being treated in this process since urine has a higher concentration of salts. These results suggest that similar types of toilets and treatment systems can yield HEDFs with similar properties across geographical locations, which is encouraging for establishing quality benchmarks for this type of fertiliser. Comparison with sludge-derived composts reported in literature show variabilities similar to those measured in the CBS C^{HEDF} analysed in Chapter 3, suggesting that source-separated ‘fresh’ excreta produce similar fertilisers to those obtained from conventional centralised sanitation systems.

Evidence was gathered from CBS organisations of the iterative optimisation processes that are required to obtain good quality HEDF attractive to the local market (Chapter 6). There is a direct link between the quality of the production process and that of the resulting HEDF obtained, indeed, the production of HEDF needs to be planned and optimised from the start of a sanitation venture to optimise product quality. Considerable time and research need to be invested to develop a product with positive effects on soil and crops. All the CBS organisations considered in this research underwent phases of compost optimisation and had teams specifically working on improving process efficiency.

It is also essential to plan the treatment facility in accordance with the Sanitation Safety Planning tool developed by the WHO to minimise the risk of contamination (WHO, 2016). The importance of establishing HACCP principles along the whole production process became evident in the pathogen tests carried out on HEDF from different ventures, in that contamination issues were found in the process facility where testing protocols were still being developed. The results presented in Chapter 3 highlighted both the opportunities and challenges in HEDF production. It is possible to produce HEDFs that are safe and do not pose a risk to the environment but there are also risks of spreading pathogens if treatment processes are not closely monitored. None of the countries where these CBS ventures produce fertilisers have regulations for sludge products or law-enforcing bodies so there is no formal way of monitoring or guaranteeing the quality of the product.

This research was undertaken over three years and the D^{HEDF}, C^{HEDF} and V^{HEDF} used for all the different experiments reported in Chapters 3 to 5 were produced with the same types of materials treated through similar treatment processes at a time when the HEDF production process was still undergoing optimisation. Significant differences were observed between these HEDFs over time as shown in

Table 8.1, highlighting the effect production process has on the quality of the final product. Observations between batches of C^{HEDF} and V^{HEDF} from 2014 and 2017 are contradictive for certain parameters. Total N concentrations for instance were halved between C^{HEDF} and V^{HEDF} in 2014 whereas they had similar values in 2017. Similarly, the concentration of organic carbon was reduced between the compost and vermicompost process in 2014 whereas values were similar in 2017. The concentration of available P was ten times higher in V^{HEDF} than C^{HEDF} in 2014 whereas in 2017 the difference was less pronounced, it had less than doubled through the vermicomposting process. Between 2014 and 2017 the processing layout for vermicomposting was modified and could have had an effect on the end product. Watering of the vermicompost piles can also lead to nutrient leaching as Frederickson *et al.* (2007) showed; differences in management of the piles could have led to differences in the final product composition. These differences further highlight the variability between batches identified in Chapter 3 and the sensitivity of these biological processes to changes in processing parameters or input materials.

Table 8.1 Variation in HEDF properties between batches taken at different times from Loowatt's system in Madagascar (mean values ± 1 SE)

	D^{HEDF}		C^{HEDF}		V^{HEDF}	
Parameters	**Jul-14 (n=3)**	**Jan-17 (n= 5)**	**Jul-14 (n=3)**	**Jan-17 (n=3)**	**Jul-14 (n=3)**	**Jan-17 (n=7)**
pH	8.5 ± 0.05	7.91 ± 0.02	8.7 ± 0.1	9.54 ± 0.05	7 ± 0.1	8.47 ± 0.07
Total N (g.kg^{-1})	0.88 ± 0.06 (g.L^{-1})	2.51 ± 0.16 (g.L^{-1})	23 ± 4	20.75 ± 1	11 ± 0.1	21.6 ± 0.6
Conductivity (mS.cm^{-1})		25.7 ± 0.3		27.82 ± 1.58		26.4 ± 0.5
Ammonium N (mg.kg^{-1})		2.27 ± 0.13 (g.L^{-1})	210 ± 27	489 ± 95	32 ± 1	92.8 ± 7.9
Nitrate (mg.kg^{-1})			7 ± 3		977 ± 36	
Organic C (g.kg^{-1})		2.75 ± 0.11 (g.L^{-1})	393 ± 17	348 ± 17	175 ± 8	333 ± 4
C/N ratio		1.14 ± 0.05	17	17.2 ± 1.4	16.6	15.4 ± 0.5
organic matter (%)		0.47 ± 0.02		59.8 ± 7.9		57.3 ± 0.7
Total P g.kg^{-1}	42 ± 3 (mg.L^{-1})	163 ± 5 (mg.L^{-1})		2.93 ± 0.19		4.70 ± 0.07
Extractable P (mg.kg^{-1})			21 ± 1	757 ± 75	212 ± 6	1287 ± 17
Total K (g.kg^{-1})	1.4 (g.L^{-1})	1.33 ± 0.04 (g.L^{-1})		34.6 ± 0.9		32.4 ± 0.7
Exchangeable K (g.kg^{-1})			26.4 ± 2.8	32.1 ± 0.83	5.07 ± 0.2	28.9 ± 0.3
Exchangeable Ca (g.kg^{-1})			0.35 ± 0.12	1.30 ± 0.09	0.88 ± 0.02	2.83 ± 0.2
Total Ca (g.kg^{-1})	22 (mg.L^{-1})	6.53 ± 0.33 (mg.L^{-1})		4.84 ± 0.26		7.70 ± 0.25
Exchangeable Mg (mg.kg^{-1})			0.252 ± 0.060	0.65 ± 0.04	0.95 ± 0.02	1.62 ± 0.08
Total Mg (g.kg^{-1})	6.5 (mg.L^{-1})	7.57 ± 0.28 (mg.L^{-1})		1.34 ± 0.06		2.16 ± 0.12
Total Mn (g.kg^{-1})		1.36 ± 0.03 (mg.L^{-1})		6.93 ± 0.63		11.3 ± 0.6
Total Fe (g.kg^{-1})		9.37 ± 0.22 (mg.L^{-1})		2.12 ± 0.4		2.80 ± 0.21
Exchangeable Zn (mg.kg^{-1})			3.5 ± 0.8	65.28	0.9 ± 0.2	274

Nutrient transformations were characterised during the three different treatment processes. During the hydrolysis and acidogenesis phases of anaerobic digestion, polymers are broken down into soluble forms of their constituent parts, the mass or nutrients is not reduced but they are mineralised and therefore present in more plant-available forms in digestate (Möller and Müller, 2012). These nutrients are however very diluted as compared to their concentration in compost or vermicompost. Composting resulted in an increase in organic matter and concentration of nutrients and vermicompost further modified nutrient composition. Despite the differences between batches from different years, the effect of the action of the worms' digestive system on organic matter could be observed: a nitrification process reflected by a decrease in pH, increase in P concentration and increase in concentration of exchangeable micronutrients. Concentrations of exchangeable Zn between C^{HEDF} and V^{HEDF} decreased in 2014 but increased in 2017, echoing the varied results of the effects of *E. Fetida* worms on heavy metals reported by Mohee and Soobhany (2014). Mineralisation of organic matter can be the reason for an increase in P concentrations, which is also reflected in the concentration of available nutrients. These are in accordance with those reported in literature from composts and vermicomposts with similar origin materials (Alidadi *et al.*, 2005). The properties of vermicompost have been shown to vary depending on the origin materials, these results cannot therefore be generalised (Tognetti *et al.*, 2005; Pramanik *et al.*, 2007; Campitelli and Ceppi, 2008).

The field and greenhouse experiments reported in chapters 4 and 5 showed that HEDF do not have a detrimental effect on soil. The results of soil tests from farms that had used HEDF presented in chapter 7 showed that there was no evidence of pathogen or heavy metal contamination from HEDF application and results from certain farms suggested beneficial effects on soil such as an increase in organic carbon content. The pot experiment suggested that HEDF had a positive effect on soil health by increasing soil organic matter and that V^{HEDF} could have a more significant effect than C^{HEDF} by increasing the concentration of micronutrients. Grain yields from maize cobs were highest from pots treated with V^{HEDF} in the pot experiment and lowest in those treated with chemical fertilisers only. The concentration of soil micronutrients also significantly increased with the application of V^{HEDF}, suggesting an improvement in soil health. An increase in soil organic matter and in soil pH were observed with both C^{HEDF} and V^{HEDF} application, showing the benefits of these amendments on soil health. However, differences between the effects of HEDF applications on plants were not visibly striking. Final plant heights between different treatments were similar in the field and pot trials (Chapters 4 and 5). Even where HEDF had been applied for two or three crop rotations the effects of localised C^{HEDF} application on soil properties were not clear (chapter 7). This implies that potential HEDF customers would need to have longer term plans for the management of their soil health, which is unlikely to be the case for smallholder farmers given their limited resources. The effects of D^{HEDF} could not be quantified during this project given that results from the field trials reported in chapter 4 did not yield significant differences between the different HEDF treatments applied because initial soil conditions were not optimal for fertiliser testing. It has been shown however that nutrients in digestate are present in mineralised form, so it is anticipated that the effects of D^{HEDF} are closer to those of chemical fertilisers and the risk of nutrient pollution is therefore higher with D^{HEDF} as Lu *et al.* (2012) highlighted.

The quality of the HEDFs and their effect on soil do not however directly translate into their commercial value. In producing HEDF for cost recovery through resource recovery, organisations aim to maximise their revenue from final products while keeping production costs to a minimum. The different factors that come into play for determining the profitability of each potential HEDF is summarised in Table 8.2. In Loowatt's staged treatment process, V^{HEDF} is the most expensive product to produce and D^{HEDF} the cheapest. The advantage of selling D^{HEDF} is that the processing effort and cost are reduced but this can be outweighed by high transport costs; given its dilute nature, high volumes of D^{HEDF} are needed to meet crop demands. A pasteurisation step also needs to be added to the anaerobic digestion process to ensure pathogen elimination. Composting can therefore be a beneficial step after anaerobic digestion for volume reduction, nutrient enrichment and pathogen elimination but it is a long and labour-intensive process. Processing time is another major contributing factor to production cost: V^{HEDF} has a shorter production time than C^{HEDF}, which allows for higher throughput. In the case of vermicomposting however, worms need to be purchased initially, which can be a significant investment. The vermicomposting process also does not reach temperatures high enough to ensure pathogen elimination, so an initial thermophilic composting stage is still required. V^{HEDF} has higher concentrations of elements contributing to soil health and its market value is also considerably higher than C^{HEDF}. This higher value however needs to be recognised in the local market: interviews with farmers in Madagascar for instance gave an indication that small holder farmers were not aware of the properties of vermicompost. Similarly, it was found that the use of liquid fertilisers was not habitual in local farming practices in Madagascar.

Table 8.2 Factors determining profitability of the different HEDF considered in this study + indicates low, ++ medium and +++ high

HEDF type	Capital investment	Labour require -ment	Processing time	Nutrient value	Pathogen elimination	Product market value
D^{HEDF}	++/+++ Medium to high, depending on type of digester and level of automation	+	+ Short	+ Nutrients are dilute in liquid digestate, concentrations are low	+/+++ (if pasteurisation stage included)	+ Dilute nature of digestate incurs high transport costs
C^{HEDF}	+ Minimal, depending on type of processing chosen	+++	+++ Long	++ Composting concentrates nutrients and increases organic matter concentration	+++ Thermophilic stage sustained for several days eliminates pathogens	+ Bulky material and slow release nutrients
V^{HEDF}	++/+++ Medium to high, depending on worm purchase needs	++	++ Medium	+++ Nutrients in more mineralised forms and higher micronutrient concentration	+ Temperatures of vermicomposting are not high enough for pathogen removal	++ Higher concentration of micronutrients increases the value of vermicompost

Planning and design of the HEDF production process and characteristics of the final product are essential for ensuring successful HEDF commercialisation. As a wide range of parameters come into play for each process, including for instance, additional organic matter or local regulations, product development should be carefully planned and tailored to each location. Therefore, the optimal process and end-product from human excreta are dependent on specific local conditions and will result from trade-offs of product quality and production costs to make a product that will fit the potential customers available locally. Product appearance is important for end users; this was highlighted in the interviews carried out in Chapter 3: peri-urban farmers in Madagascar stated they preferred V^{HEDF} over C^{HEDF} without being aware of its properties or of the vermicomposting process. Preferences in product appearance have also been reported in other contexts: in Ghana for instance farmers had a preference towards pelletised products over loose compost from human excreta (Danso *et al.*, 2017).

8.2 Market potential of HEDF

A potential market for HEDF does exist, indeed, all organisations considered in this research had commercial outlets for their end-products and sold their full production volumes. None of the organisations however made a profit from these sales, as the cost of transport and treatment outweighed the revenues generated from HEDF sales. Finding customers for HEDF was not a difficulty for any of the CBS ventures, as farmers and other fertiliser users are often willing to use fertilisers regardless of their origin if they have a positive effect on soil (Danso *et al*., 2002; Moya *et al*., 2017). There was a scarcity of organic fertilisers on the market in the three countries considered in this research, HEDF users therefore welcomed a new product to increase organic matter content in their soils; the effect of HEDF on soil and crops was more important to them than its origin.

The market for organic fertilisers is, however, less organised and more informal than that of chemical fertilisers, making it more difficult to find channels to target new customers. In addition to this, fertilisers derived from organic residues are perceived as lower value products than chemical fertilisers. This is despite organic matter-rich fertilisers being necessary for maintaining soil health and reducing soil degradation. HEDF can have a positive environmental impact and contribute to a circular economy, which should be valued. The need for establishing circular economy solutions and the importance of resource recovery from residues is now recognised globally and included in future policy plans (European Commision, 2015). Significant systemic changes in nutrient management will be needed to achieve a circular economy in the agrifood industry and recycling human excreta into soil could be instrumental in this: it is estimated that 28% of the N, P and K consumption worldwide could be covered by human excreta if all nutrients were recovered (Ellen MacArthur Foundation, 2013). The value of HEDF could be increased through adopting alternative value systems or incentives such as carbon credits or green taxes. A new system of “phosphate rights” was recently approved by the European Commission for dairy farmers in the Netherlands giving farmers tradeable phosphate rights to limit the production of dairy cattle manure and reduce the associated risks of environmental pollution (European Commission, 2018). A similar scheme encouraging the use of fertilisers containing recycled nutrients could be put in place to promote circular economy initiatives in farming. Incentives are needed for promoting the use of fertilisers derived from wastes and create a market for them.

Another option explored to increase the value of HEDF is their combination with chemical fertilisers (Nikiema *et a.l* 2014). The benefits of mixing both types of fertilisers were highlighted in the pot trial experiment presented in Chapter 5. Grain yields were higher in pots treated with mixes of HEDF and chemical fertilisers than chemical fertilisers alone. These pots showed combined positive effects of nutrient availability from mineralised nutrients as well as gradual release of nutrients during crop growth and had higher soil organic matter concentrations. It could be envisaged that a company producing chemical fertilisers could integrate HEDF in their processes to produce enriched compost, as in the case of Waste Concern in Bangladesh (Zurbrugg *et al*., 2005). Another viable option for nutrient enrichment of C^{HEDF} could be using the urine fraction of urine-diverting toilets, which was not harvested by the two CBS organisations installing this type of toilet (Tilley *et al.*, 2014).

8.3 **Regulatory barriers to HEDF commercialisation**

Stakeholder interviews and reviews of local and international regulations identified the lack of clear regulations as the main challenge for achieving widespread adoption of HEDF rather than regulations that go directly against their use. One of the main concerns with HEDF is the presence of contaminants such as pathogens, heavy metals and chemical contaminants. The risk of pathogen transmission can be significant if treatments are not appropriately carried out as highlighted in Chapter 3 but successful pathogen elimination can be achieved by establishing appropriately monitored treatment processes. Heavy metal analyses carried out on different types of HEDF (Chapters 3, 5 and 7) gave evidence that the risk from HEDF for heavy metal contamination is not significant. Heavy metal concentrations in HEDF tested in Chapter 3 were lower than those in biosolids from centralised wastewater treatment plants.

In an increasingly globalised world, international regulations and private certification schemes can have a significant weight and in certain cases over-rule local regulations through indirect market regulation. This is the case of international horticultural exports, which are effectively regulated by international bodies setting standards for good agricultural practices that farmers need to abide to in order to access the market. The ban of use of HEDF in the Global GAP standard, which interviewed farmers defined as a pre-condition to enter the horticultural export market, is a main barrier to accessing additional customers for HEDF in countries with large horticultural export sectors such as Kenya, as discussed in Chapter 7. Changes in these standards would be needed for a wider adoption and use of HEDF. Evidence gathered as part of this research demonstrated that HEDFs produced according to WHO guidelines do not pose a risk of heavy metal or pathogen contamination to soil. Wastewater treatment companies in several countries try to overcome negative perception of biosolids by developing their own assurance schemes, which go further than the local regulations. The application of the British Biosolids Assurance Scheme protocol to test HEDF was a novel approach adopted in this research and proved valuable for ensuring product quality by identifying contamination issues (Chapter 3). This highlighted the potential and importance of quality assurance schemes. The creation of a certification scheme or standard for HEDF would be beneficial for providing assurance of their quality and increasing confidence in these products. It has been shown that farmers are willing to pay a higher price for HEDF that are certified (Evans *et al.*, 2015; Danso *et al.*, 2017). The creation of certification systems involving third-party auditing can require significant investment, which could be a barrier for establishing HEDF-specific certifications. International organisations such as the BMGF have recently been financing sanitation-related standardisation efforts, so similar financing from international organisations could be sought.

8.4 Reflections on CBS and HEDF production

The different case studies developed in this research highlighted that CBS companies produced HEDF to eliminate pathogens and recover costs from sales, but their principal goal was to increase and improve sanitation coverage. Production of high-quality HEDFs requires a different set of skills and a variety of organic inputs. The case of Sanergy provided a good example of the division of the sanitation provision and resource recovery activities. CBS organisations recognised that it was a challenge for a single organisation to increase sanitation coverage and produce outputs with commercial prospects. Covering the full sanitation value chain involves different disciplines and skillsets as well as a wide range of stakeholders and is therefore a challenging goal to achieve for a single small organisation. A multidisciplinary approach is required to make full sanitation value chain systems viable. All CBS companies required additional material for the different treatments of human excreta to maximise the quality of outputs (biogas volume or fertiliser quality) and procuring these was a challenge for all organisations. Co-composting has been shown to have benefits and is promoted in many places (Cofie *et al.*, 2016). Co-composting could be facilitated at the municipal level by collecting human excreta and municipal solid waste simultaneously. In fact, in the case of CBS systems, the logistics involved in collection and transport of toilet waste are very similar to those of Solid Waste Management (SWM), taking materials from point sources and transporting them to treatment sites. Logistics and high transport costs were found to be one of the main challenges for recovering costs from HEDF production, combining transport of human excreta and solid wastes could therefore help reduce these costs. Removal of solid waste is another major issue in urban slums and appropriate collection and management would improve the health of communities too (Wilson *et al.*, 2012). Collecting several sources of organic matter would also increase the value extraction potential from residues: a wider range of products could be obtained in addition to reducing transport costs. This resonates with the biorefinery concept that has been gaining interest in recent years, aiming to maximise resource extraction from organic wastes (Carey *et al.*, 2016; Venkata Mohan *et al.*, 2016).

To be economically viable, CBS ventures need to collect user fees that allow for partial cost recovery for the services they provide. This requires users to have a certain amount of disposable income and therefore means the lowest economic tier of slum dwellers cannot currently afford CBS systems. There is evidence that the cost of CBS provision could be reduced by economy of scale if sanitation coverage in an area is increased (Remington *et al.*, 2016). This would increase the portion of the population that can access CBS systems, but in current models toilet users bear the majority cost of sanitation. It has been shown that with OSS, households bear a higher cost for sanitation than those served by sewerage systems, where utilities bear most of the operation and maintenance costs of the networks (Dodane *et al.*, 2012). In practice this translates to the poorest urban dwellers spending more on sanitation than richer residents who are connected to the sewerage network, raising ethical questions. *Dodane et al*. (2012) for instance showed that in Dakar OSS users paid on average 5 times more than customers connected to sewerage systems. To achieve universal sanitation coverage, access to sanitation will need to be provided for the poorest segments of the population, which will require public funding. CBS systems have been shown to be extremely effective at increasing sanitation coverage fast thanks to the lack of permanent infrastructure required. The logistics of CBS have also proven to be efficient, managing to remove human excreta safely from households and therefore reducing health and environmental threats of poor sanitation in communities. Investing in CBS solutions would be an attractive way for local governments to increase sanitation coverage fast and ensure its sustainability. Municipalities are also responsible for waste management, so they could greatly benefit from partnering with CBS organisations and combining SWM and sanitation operations.

With current food production systems cities are nutrient sinks: food is produced outside the city, consumed in the city but the nutrients that result from food consumption are not returned to the areas producing food (Drechsel *et al.*, 2010). This trend is not sustainable and will only be exacerbated with increasing rates of urbanisation if systemic changes are not put in place. The need for peri-urban agriculture will also increase with rising urban populations and with limited access to organic matter sources, maintaining soil health in these areas is a challenge (N'Dienor, 2006). The use of HEDF in these areas would provide a true circular city nutrient management system. Farmers in peri-urban areas of LIC however are often smallholders. HEDF customers in the CBS organisations considered in this study are organisations, landscapers or farmers who can afford to pay the premium price currently established for these HEDFs. Smallholder farmers on the other hand often have low purchasing power, currently preventing them from accessing these fertilisers (Marenya *et al.*, 2012). Soil degradation in SSA is mainly due to poor soil health management practices such as insufficient soil organic matter and nutrient replenishment after crop harvest, most likely the case of most smallholder farmers' practices (Chauvin *et al.*, 2012; Wanzala and Groot, 2013). HEDF could therefore have a significant impact improving soil health if used by smallholders but this would require extension programs and policies facilitating smallholders' access to organic farming inputs.

CBS and the resulting HEDF could have a major impact increasing sanitation coverage in urban areas and could prevent further soil degradation by increasing soil organic matter. However, external financing is required for reaching the most vulnerable parts of the population with these resources.

9 CONCLUSIONS

This chapter presents the main conclusions from the research presented in this thesis and the original contribution to knowledge realised. Several limitations of this research are also outlined along with suggestions for further work on this topic.

9.1 Research conclusions

The research aims and objectives were presented in Chapter 1 and addressed through the different research activities carried out in this research. Quantitative research methods were used to explore the agronomic potential of soil amendments produced by CBS organisations and qualitative methods were applied for addressing the research objectives related to the marketing potential of HEDF and associated challenges. This transdisciplinary approach allowed evaluating the value of HEDF in various dimensions, from their chemical and biological properties to their market acceptability and the influence of various stakeholders. The wide range of activities allowed the provision of a rounded answer to the research question.

The objectives set out in Chapter 1 were addressed as follows:

1. Characterise the nutrient content of 3 different types of soil amendments derived from human excreta, namely pasteurised digestate from anaerobic digestion of toilet excreta, compost and vermicompost from AD digestate and straw.

   - The properties of HEDFs depend on the materials and process used to produce them. Nutrient content of C^{HEDF} is different in systems that only treat faeces (pH 5.5-5.7, electrical conductivity 8.5-9.13 $mS.cm^{-1}$) and those that treat both urine and faeces (pH 7.9-9.5, electrical conductivity 25.7-72.8 $mS.cm^{-1}$).
   - Composts from similar sources also share similar characteristics (pH 5.5-5.7, P concentration 0.73-0.83%, K concentration 0.71-0.87%, Total N 1.17-1.93%) for C^{HEDF} from CBS systems treating only faeces.

- Operational variations in treatment process have an effect on the properties of the final product. This was shown by the variability between HEDF samples in 2014 and 2017.
- The type of production process affects the characteristics of the HEDF obtained. Nutrient evolution was characterised in the staged treatment process of digestate, compost and vermicompost. Nutrients are transformed in each stage: nutrients released from the original material through anaerobic digestion and are most dilute in digestate, composting concentrates nutrients and increases organic matter content, vermicomposting mineralises nutrients and increases organic matter content.

2. Demonstrate fertiliser potential and environmental and health safety of HEDFs.

- HEDF does not have a detrimental effect on crops. All crops treated with D^{HEDF}, C^{HEDF} or V^{HEDF} had a similar or better effect on crops than control plots in both field and glasshouse trials.
- C^{HEDF} and V^{HEDF} can provide higher organic matter to soil than chemical fertilisers. Final organic carbon concentrations in pots treated with V^{HEDF} and C^{HEDF} were 1.13% and 0.42% respectively compared to 0.22% for pots that received chemical fertilisers only.
- Vermicompost provides higher concentrations of micronutrients to soil than compost. Mg concentrations are higher in V^{HEDF} than C^{HEDF}, reflected in final concentrations of exchangeable magnesium in pots treated with V^{HEDF} (36.9 mg.kg^{-1}) compared to those treated with C^{HEDF} (20 mg.kg^{-1})
- Mixing chemical fertilisers and HEDF can combine the benefits of mineralised nutrients with the addition of organic matter to soil: pots treated with mixes of HEDF and chemical fertilisers had higher organic matter content, K, Mg and pH than soils treated with chemical fertilisers alone.

- Vermicompost can have an effect on the concentration of heavy metals but the results are mixed, concurring with reports in literature. Heavy metals concentrations of Cd and Pb were reduced whereas concentrations of As, Cu, Ni and Zn increased through vermicomposting.
- There is no evidence of heavy metal contamination potential from HEDF use or application. HEDF from two CBS systems did not comply with the Netherland's strictest 'very clean compost' limits but they did comply with a wide range international regulations of heavy metal contents for compost except for Cd limits in Europe, which are especially restrictive.
- Pathogens can be safely eliminated from excreta if an appropriate treatment system such as composting with rigorous quality control protocols. The risk of pathogen contamination is however significant if HACCP procedures are not put in place in the HEDF production system as shown by a helminth contamination identified in one of the treatment sites.

3. Identify the barriers and enabling conditions to widespread use of treated human excreta as fertiliser

- The case study approach used in this research proved valuable for identifying common challenges that CBS organisations face. The production of HEDF is a resource-consuming process that requires optimisation and careful monitoring to achieve safe and good quality products.
- Characterising the nutrient content and quantifying the effect of HEDF on crops is needed to attract potential customers. In the absence of certification schemes, guarantees of HEDF quality are currently based on customer trust so the reputation of CBS organisations is essential for facilitating HEDF sales.
- It is important to develop a product that is adapted to the local market and responds to fertiliser requirements locally. Vermicompost for instance has a higher market value but if potential customers are unaware or don't value

the benefits of vermicompost over compost they will not be willing to pay a higher price.

- The market for organic fertilisers was undeveloped in both countries considered in the case studies and the benefits of HEDF on soil and in providing a circular solution to FSM are not reflected in their commercial value.
- Finding customers for HEDF was not difficult in either locations studied but recovering treatment costs from C^{HEDF} sales is a challenge for CBS organisations at present because of the low market value of compost.
- Smallholders might be the largest farmers in number, but they are currently unlikely to be the main customers for HEDF given their low purchase power, lack of long-term investment strategies and limited farming training. Other fertiliser users with higher investment capacity are more likely to be HEDF customers (for example landscapers, cash crop farmers or larger organisations running farming extension programs).
- Barriers exist to accessing certain significant markets such as horticultural exporters. The ban of human sewage sludge use on Global GAP certified farms currently creates a major barrier to accessing a large segment of potential HEDF customers.
- In both countries studied, the sanitation services provided by the CBS ventures had a very high social value but didn´t receive any public financial support. Public policies were weak and incentives for treatment do not exist.

4. Investigate the potential role of certification and self-regulation for enabling the widespread commercialisation of human FS derived fertilisers.

- Applying the testing protocols and schedules set by the Biosolids Assurance Standard from the UK was a novel aspect of this research and helped identify contamination issues in the fertiliser production process of one of the CBS organisations. This highlighted the value in adopting a certification or assurance scheme for HEDF for guaranteeing their quality and increasing customer confidence.

- The adoption of certification or assurance schemes for biosolids in several countries lead to their wider acceptance. Similarly, a scheme specific to HEDF could also have a positive effect on their commercialisation

A multidisciplinary approach is required to increase sanitation coverage and provide sludge management and valorisation solutions. It became evident that covering the full sanitation value chain is a challenge for a small private enterprise. Similarities can be drawn between the logistics of CBS solutions and municipal solid waste management, so it is suggested that municipalities could integrate these two activities or create public private partnerships to provide both services. The findings from this research suggest that the involvement of public bodies will be instrumental in enabling the success of CBS solutions and the commercialisation of HEDF providing a circular solution to FSM.

9.2 Contribution to knowledge

This thesis set forth to use a transdisciplinary approach to explore the value of HEDF and link their soil nutrient value to their economic value and commercial potential. This novel approach using both soil sciences and qualitative research methods created a holistic study on the potential of HEDF.

This thesis complements the limited number of academic studies available on the properties of fertilisers derived from source-separated human excreta and their effect on soil and crops. This was achieved through the initial field trial completed in Madagascar followed by the pot trial at Cranfield University using HEDF to grow maize. One of the unique features of these studies is that the HEDFs used for the crop trials were obtained through a staged process allowing tracing soil nutrient transformation through the different treatment processes in addition to comparing their effect on soil.

The case study approach adopted for part of this research was a novel approach to compare and contrast barriers and enabling conditions faced to commercialise HEDF. This type of comparative study is the first type of its kind as far as we are aware.

The application of an assurance scheme specific for biosolids to HEDF was also novel and proved valuable for identifying product contamination issues.

This research also explored for the first time the interaction of HEDF market acceptability and private certification schemes, which have a strong influence on international markets.

9.3 Research limitations

Field and pot trials were limited to one season, one crop type and the HEDFs applied originated from the same CBS venture. Several repetitions of each treatment are required to obtain statistically valid results from crop trials, requiring large volumes of fertilisers for carrying out an experiment. This can be a challenge for a small company that is developing their production capacity and was a limitation during this research. The results from these trials gave indications of the effect of the different HEDF on crops and soil but cannot be generalised.

Practical limitations were experienced for the field trials and experimental work in Madagascar especially. Limits in infrastructure and analytical capacities available are constraints often encountered in LICs and this project was affected by such limitations in several situations. The lack of certified laboratories for carrying out pathogen analyses on HEDF in Madagascar hindered the testing planned for this project. Pathogen results obtained were not reliable, but it was not possible to send samples for testing overseas because of challenges with storage conditions and customs permits. Limitations in infrastructure were also experienced during the field trials, the trial site in Antananarivo became inaccessible for two weeks when the a strong tropical storm hit the area with very heavy rains.

Crop trials were carried out in 2014 and 2015 with HEDFs from different batches, which were found to have different properties as discussed in the previous chapter. This created a limit for comparing and contrasting the results from the field and the glasshouse trials.

The findings from the case studies were limited to two CBS organisations since they were the only ones fulfilling the defined selection criteria at the time. Many organisations produce HEDFs, but few manage to produce and commercialise them at scale. The generalisations that can be made from these two case studies are therefore limited but proved valuable for indicating common challenges faced in different contexts.

The case studies developed in Haiti and Kenya involved a series of interviews with stakeholders, which proved useful for obtaining unpublished information as well as stakeholders’ views and perspectives. It is however known that biases occur during interviews, these can originate from the researcher’s or the interviewees ‘world view’ or from ‘social desirability bias’, driving the interviewee to adapt their responses according to their perceived social desirability (Creswell and Plano Clark, 2011; Bryman, 2012). The interviewer sought to maintain neutrality during interviews to minimise the risk of bias. Interviews were also complemented with observations and field notes wherever possible.

9.4 **Further work**

The research activities carried out in this study highlighted the value of HEDF from CBS systems on crops however, the results from the field and crop trials were limited. The effect of HEDF on crops and their market potential require further research:

- Additional field trials with HEDF are required, over several crop seasons to evaluate the long-term effect of HEDF on soil and crops.
- Crop trials with different types of crops would be beneficial to characterise the effect of HEDF on different types of crops such as legumes, grains for example to understand the safety implications and develop recommendations about which crops are best suited for HEDF application.
- The results on CBS and HEDF in this study were limited to three organisations and their corresponding locations. Additional research in other countries and other contexts would be beneficial to draw more general conclusions.
- A full economic assessment should be undertaken to establish the costs the whole sanitation value chain of CBS systems and quantify revenue potential from HEDF to allow return on investment assessment.
- One of the salient points of this research is the need of certification for HEDF, which could help establish HEDF formally in the market, increase their commercial value and remove barriers to commercialisation. It is recommended that a standard or assurance scheme is developed, similar to those developed by wastewater treatment companies in many countries.
- Given the mixed results obtained on the effect of vermicomposting on heavy metal concentrations, further characterisation of the effect of *E. Fetida* worms on heavy metals in human excreta is needed.

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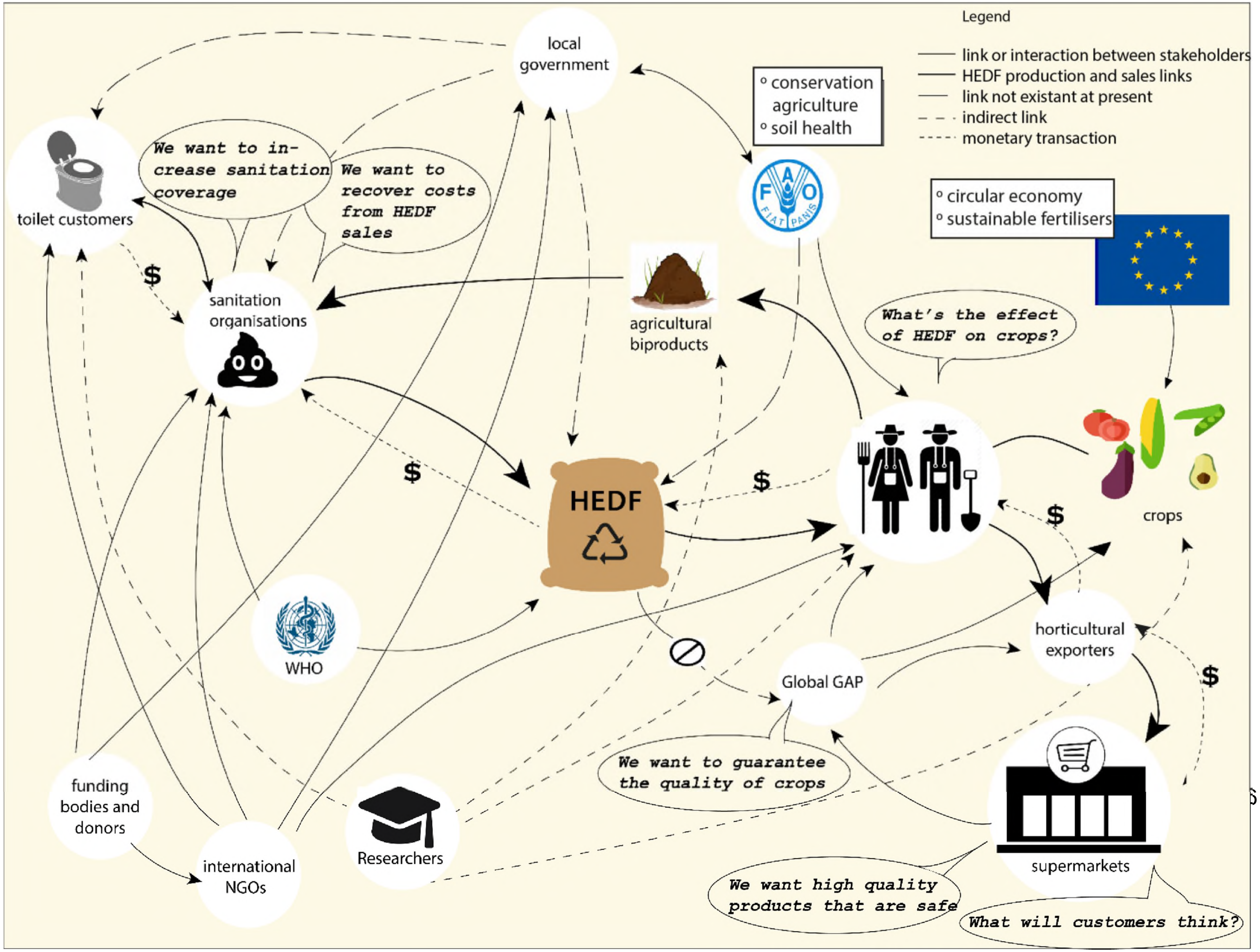
APPENDICES

Appendix A Rich picture of the research problem developed using Soft Systems Analysis principles

Figure_Apx A-1 Rich picture of the problem situation regarding the commercialisation of fertilisers derived from human excreta

See overleaf


Legend
link or interaction between stakeholders
HEDF production and sales links
link not existant at present
indirect link
monetary transaction
local government
toilet customers
We want to increase sanitation coverage
We want to recover costs from HEDF sales
sanitation organisations
$
° conservation agriculture
° soil health
° circular economy
° sustainable fertilisers
agricultural biproducts
What's the effect of HEDF on crops?
HEDF
$
$
$
crops
WHO
Global GAP
horticultural exporters
$
We want to guarantee the quality of crops
funding bodies and donors
international NGOs
Researchers
supermarkets
We want high quality products that are safe
What will customers think?

Appendix B Images of Field Trial 1

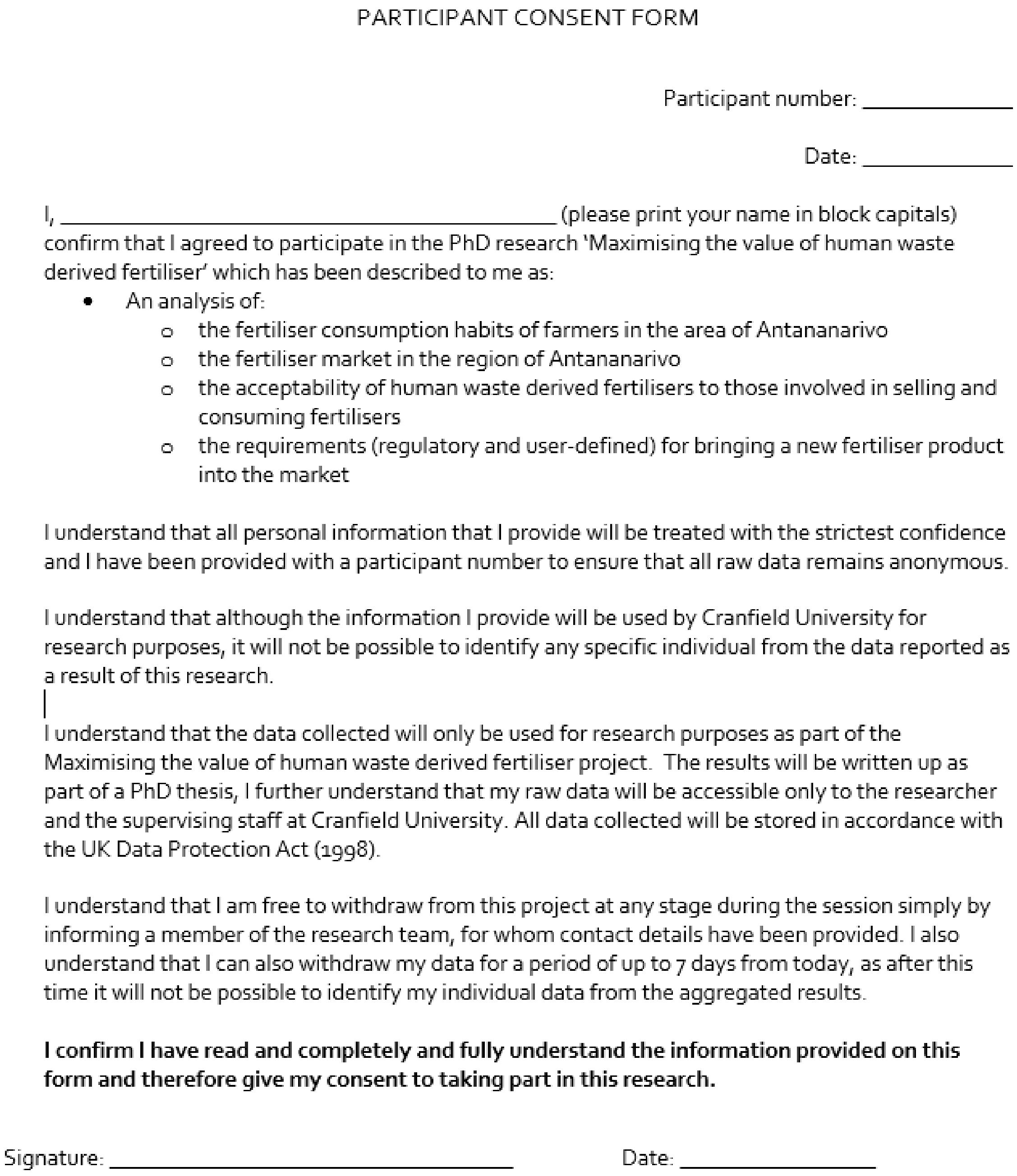
Figure_Apx B-1 Field trial site in Antananarivo before planting

Figure_Apx B-2 Maize crops grown during field trial

Figure_Apx B-3 Set up for pot trial at Cranfield University

Figure_Apx B-4 Maize crops grown in the glasshouse at Cranfield University

Appendix C Participant Consent Forms



PARTICIPANT CONSENT FORM

Participant number: ____________

Date: ____________

I, ____ (please print your name in block capitals) confirm that I agreed to participate in the PhD research 'Maximising the value of human waste derived fertiliser' which has been described to me as:

- An analysis of:
    - the fertiliser consumption habits of farmers in the area of Antananarivo
    - the fertiliser market in the region of Antananarivo
    - the acceptability of human waste derived fertilisers to those involved in selling and consuming fertilisers
    - the requirements (regulatory and user-defined) for bringing a new fertiliser product into the market

I understand that all personal information that I provide will be treated with the strictest confidence and I have been provided with a participant number to ensure that all raw data remains anonymous.

I understand that although the information I provide will be used by Cranfield University for research purposes, it will not be possible to identify any specific individual from the data reported as a result of this research.

I understand that the data collected will only be used for research purposes as part of the Maximising the value of human waste derived fertiliser project. The results will be written up as part of a PhD thesis, I further understand that my raw data will be accessible only to the researcher and the supervising staff at Cranfield University. All data collected will be stored in accordance with the UK Data Protection Act (1998).

I understand that I am free to withdraw from this project at any stage during the session simply by informing a member of the research team, for whom contact details have been provided. I also understand that I can also withdraw my data for a period of up to 7 days from today, as after this time it will not be possible to identify my individual data from the aggregated results.

I confirm I have read and completely and fully understand the information provided on this form and therefore give my consent to taking part in this research.

Signature: ______________________________ Date: ______________

PARTICIPANT CONSENT FORM

Date: ____________

I, ____ (please print your name in block capitals) confirm that I agreed to participate in the PhD research 'Maximising the value of human waste derived fertiliser' which has been described to me as:

- An analysis of:
    - The barriers and enabling conditions for commercialising human waste derived fertilisers
    - The fertiliser consumption habits of farmers of the region of Port au Prince and Cap Haitien
    - the acceptability of human waste derived fertilisers to those involved in selling and consuming fertilisers
    - the requirements (regulatory and user-defined) for bringing a new fertiliser product into the market

I understand that all personal information that I provide will be treated with the strictest confidence and I have been provided with a participant number to ensure that all raw data remains anonymous.

I understand that although the information I provide will be used by Cranfield University for research purposes, it will not be possible to identify any specific individual from the data reported as a result of this research.

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I confirm I have read and completely and fully understand the information provided on this form and therefore give my consent to taking part in this research.

Signature: ________________________________ Date: ________________

Contact number: ______________________

PARTICIPANT CONSENT FORM

Date: ____________

I, ____ (please print your name in block capitals) confirm that I agreed to participate in the PhD research 'Maximising the value of human waste derived fertiliser' which has been described to me as:

- An analysis of:
    - The general regulatory context for recycling treated waste products to soil and more specifically policies surrounding the use of human waste derived fertilisers
    - The resulting barriers and enabling conditions for commercialising human waste derived fertilisers
    - The requirements (regulatory and user-defined) for bringing a new fertiliser product into the market
    - The acceptability of human waste derived fertilisers to those involved in selling and consuming fertilisers.

I understand that all personal information that I provide will be treated with the strictest confidence and I have been provided with a participant number to ensure that all raw data remains anonymous.

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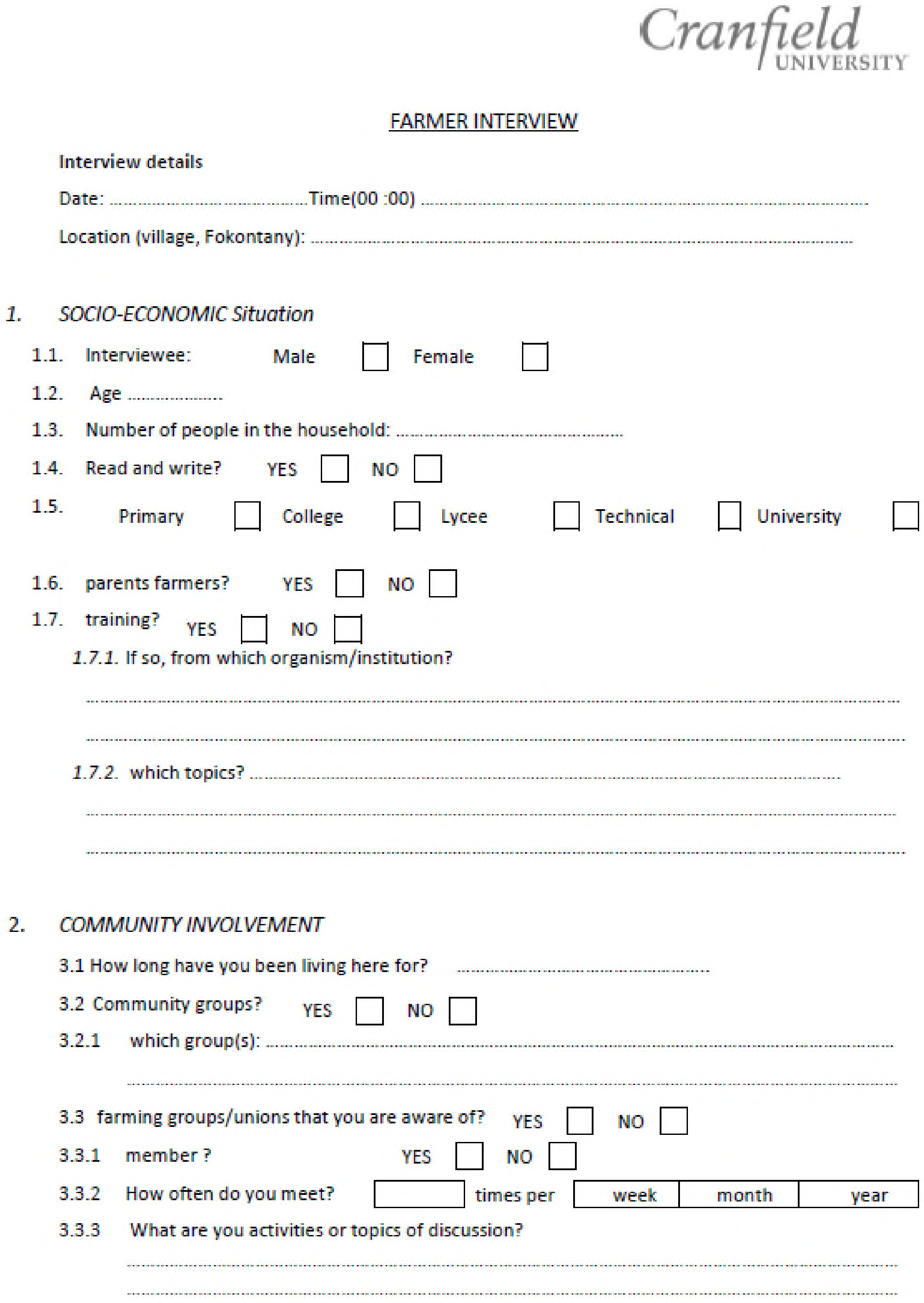
Appendix D Template for Surveys of Peri-Urban Farmers of Antananarivo



Cranfield UNIVERSITY

FARMER INTERVIEW

Interview details

Date: ……………………………Time(00 :00) ……………………………………………………

Location (village, Fokontany): ………………………………………………………………

1. *SOCIO-ECONOMIC Situation*

1.1. Interviewee: Male ☐ Female ☐

1.2. Age ……………

1.3. Number of people in the household: ……………………………

1.4. Read and write? YES ☐ NO ☐

1.5. Primary ☐ College ☐ Lycee ☐ Technical ☐ University ☐

1.6. parents farmers? YES ☐ NO ☐

1.7. training? YES ☐ NO ☐

1.7.1. If so, from which organism/institution?

……………………………………………………………………………………

……………………………………………………………………………………

1.7.2. which topics? ……………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

2. *COMMUNITY INVOLVEMENT*

3.1 How long have you been living here for? ……………………………

3.2 Community groups? YES ☐ NO ☐

3.2.1 which group(s): ……………………………………………………………

……………………………………………………………………………………

3.3 farming groups/unions that you are aware of? YES ☐ NO ☐

3.3.1 member ? YES ☐ NO ☐

3.3.2 How often do you meet? ☐ times per ☐ week ☐ month ☐ year

3.3.3 What are you activities or topics of discussion?

……………………………………………………………………………………

……………………………………………………………………………………

3. *FIELD INFORMATION*

3.1. Do you own this land? YES ☐ NO ☐

3.1.1. If NO, mode of agreement with the owner? ....

3.2. Average size of your field? ....

3.3. What types of crops do you grow?

....

....

....

3.4. Topography of the field: ....

3.5. Change crops with the season? YES ☐ NO ☐

3.5.1. How many cycles per year? ....

3.6. Livestock? YES ☐ NO ☐

3.6.1. How many? ....

3.7. Crops produced? ....per month/season/ year

3.8. Are you satisfied with the productivity of your land? YES ☐ NO ☐

3.9. Is your production for personal use or for selling? Personal use ☐ Sale ☐

3.10. Farm ☐ Market ☐ Shop ☐ Supermarket ☐ Other ☐

4. *FERTILISER USE*

4.1. Do you use any fertiliser on your land? YES ☐ NO ☐

4.1.1. If NO, why not? Is your land fertile enough or are fertilisers too expensive? ....

....

4.1.2. If YES, what type(s) of fertilisers?

4.1.2.1. Chemical fertiliser

Urea ☐ Compost ☐ NPK ☐ Other (specify) ☐

4.1.2.2. Organic fertiliser

Animal manure (zebu, chicken) ☐ Compost ☐

4.2. Organic fert different price to chemical fertilisers? YES ☐ NO ☐

4.3. Have you ever used liquid fertiliser? YES ☐ NO ☐

4.4. When in the crop cycle do you apply fertiliser? ....

4.5. How much fertiliser do you apply? ....

....

....

4.6. Fertiliser from where? ....

4.7. Does your provider offer you advice about which type of fertiliser to use? YES ☐ NO ☐

4.8. Do you trust your provider? YES ☐ NO ☐

4.9. How do you find out about new products or the quality of the products? ....

....

....

4.10. How much does the fertiliser cost? (per bag/ per kg) ....

....

....

....

4.11. Fair price for fertiliser? YES ☐ NO ☐

4.12. Payment cash ☐ in kind/exchange ☐

4.13. How much do you usually buy?.. kg/bags

.... kg/bags

4.14. How long do you store it for?..days/weeks/months

4.15. What is a good fertiliser in your opinion? ....

....

....

4.16. Do you feel the fertiliser you use is efficient? YES ☐ NO ☐

4.17. If you could, would you like to use more or different fertilisers? YES ☐ NO ☐

4.17.1. If yes, why are you not able to do so? ....

....

....

5. *REACTION TO LOOWATT'S FERTILISERS*

5.1. colour?

5.1.1. Compost ....

5.1.2. Vermicompost ....

5.1.3. Digestate...

5.2. texture?

5.2.1. Compost ....

5.2.2. Vermicompost ....

5.2.3. Digestate ....

5.3. smell?

5.3.1. Compost ....

5.3.2. Vermicompost ....

5.3.3.Digestate ………………………………………………………………………………………………………

5.4. Would you be willing to use any of these products on your land? YES ☐ NO ☐

5.5. opinion change? YES ☐ NO ☐

5.6. Would you still be willing to use it? YES ☐ NO ☐

5.6.1.Would tell customers? YES ☐ NO ☐

5.6.2. If NO, why? What makes you not want to use it? ……………………………………………

………

5.6.2.1. idea disgusts? YES ☐ NO ☐

5.6.2.2. don't know efficacy? YES ☐ NO ☐

5.6.2.3. fear people won't buy produce? YES ☐ NO ☐

5.6.2.4. health concerns about the products? YES ☐ NO ☐

5.7. More expensive ☐ cheaper ☐ than chemical fertiliser

5.8.Above which price would you definitely not buy the product? …………………………………

5.9.Below which price would you say you would not buy ? ……………………………………………

5.10. different if the fertiliser used to grow fruit, flowers or ornamental plants? YES ☐ NO ☐

5.11. What format would be the most suitable? Bag of 1Kg to 5Kg/10Kg to 15kg/20 to 25Kg/More

5.12. What kind of information would you like to have on the package? ……………………………

………

………

………

5.13. prefer using vermicompost ☐ compost ☐

5.14. Why? ……………………………………………………………

6. *REVENUE*

6.1.Do you have any other occupation aside from farming? YES ☐ NO ☐

6.2.What is your average income? ……………………………………………………………………………

6.3.How much of your income comes from selling crops? ………………………………………………

6.4.What revenue do you get from selling your crops? …………………………………………………

Appendix E Images of HEDF Production Sites

Figure_Apx E-1 Loowatt anaerobic digestion site

Figure_Apx E-2 Box composting at SOIL treatment site

Figure_Apx E-3 Windrows after box composting at SOIL treatment site

Figure_Apx E-4 Loowatt composting site (rice straw storage area and small windrow composting below. The blue drums contain digestate

Figure_Apx E-5 Vermicomposting drawers in Loowatt treatment site

Figure_Apx E-6 Worms in Loowatt treatment site

Figure_Apx E-7 Loowatt final vermicompost

Figure_Apx E-8 Sanergy composting site, mechanically turned windrows

Figure_Apx E-9 Compost windrow turner

Appendix F Images from Farms Using HEDF Sampled in Kenya (chapter 7)

Figure_Apx F-1 Example of sample collection method (with an auger)

Figure_Apx F-2 Trial farm sampled

Figure_Apx F-3 Farm 1 sampled

Figure_Apx F-4 Farm 2 sampled

Figure_Apx F-5 Farm 3 sampled

Figure_Apx F-6 Farm 4 sampled

Figure_Apx F-7 Farm 5 sampled