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INVESTIGATING THE COMPOSTING METHODS FOR ENHANCEMENT OF THE FERTILIZING VALUE OF DESICCATED HUMAN FAECES PRODUCED BY THE MOBISAN FACILITY FOR AGRICULTURAL APPLICATION

by

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Declaration

I, **REMY MUALABA TSHIBANGU**, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Remy Mualaba Tshibangu

Signed **Date: August 2015**

Abstract

Agriculture in rural communities of South Africa is negatively affected by the poor quality of soils with low fertility. With limited financial resources, non-commercial farmers are not able to purchase chemical fertilizers or other products necessary for plant production. Alternatives such as composting of human excreta and animal manure have found favour in many regions of the world for improving soil fertility for sustainable crop production.

Human faeces contain nutrients and have potential to be used as fertilizer in agriculture. Faeces should not be regarded as waste, but rather as a product that can be used for the provision of an affordable agricultural fertilizer. The MobiSan facility is a urine diversion toilet installed at Pooke se bos informal settlement, where the disposal of waste is difficult for number of reasons such as lack of space, inadequate infrastructure and no access roads.

However, the lack of safe disposal of desiccated human faeces from MobiSan facility has created a detrimental effect within the settlement that lead to unwanted conditions. The alternative means of reducing the pollution loads within the settlement areas is to look at localized on-site treatment of composting methods that can treat desiccated human faeces from MobiSan facility to meet standards for agricultural applications.

Faeces can be treated and stored under controlled process called composting to enhance the nutrients value for plant production. Without composting, human faeces usually have a low initial fertilizing value. Analysis of the studies done in Uganda showed an enhancement of the composted faeces-to-food waste from 78-litre reactors attained 19% N, 34% P and 28% K; and also E. coli and total coliforms were found lower than the detected value with high temperatures exceeding 50°C and pH (4.5-8.7).

Given the initial low fertilizing value of human faeces, further treatment method is required to make it suitable for agricultural use. Several methods are used to enhance the fertilizing of human excreta, amongst these is the composting. In this line, three composting methods, namely Co-composting, Skyloo-composting and Bio-process composting were piloted with great importance in the settlement for reasons such as: Low O&M costs, Use of locally available materials, and no energy needed to treat human faeces…The application of the three composting methods could provide the community within the settlement with work opportunities and also improving soil fertility using locally-available fertilizers.

The initial characteristics of desiccated human faeces from the MobiSan facility were determined by sampling and testing quality parameters namely pH, Oxygen, temperature, moisture content, Carbon, Nitrogen, Phosphorus, Potassium, Faecal coliform and E. coli. The initial results of desiccated human faeces from the MobiSan facility showed a low fertilizing value when compared to previous literature, with values of Nitrogen, Phosphorous and Potassium being respectively 4.7%, 3.4% and 1.5%, while those of E-Coli and Faecal coliform being $5.9x10^3$cfu/g and $7.8x10^3$cfu/g respectively.

Results on the composted faeces using the Co-composting method were as follows: Nitrogen: 22.2%, Phosphorus: 25.4%, Potassium: 31.1%. Skyloo composting method results were found with Nitrogen: 16.2%, Phosphorus: 19.6%, Potassium: 15.2% and results obtained from Bio-process composting method were: Nitrogen: 25.3%, Phosphorus: 28.6%, Potassium: 33.2%.

Results of the study showed that the three composting methods were suitable for treating human faeces from the MobiSan facility. Results indicate that the enhanced fertilizing value and reduction of pathogens in composting process could make the compost safe for agricultural application. Bio-process composting was found to be the most suitable method as it enhanced the fertilizing value of desiccated faeces to 83% N; 88% P and 95% K. The composting process also significantly reduced the concentration of E.coli and Faecal coliforms.

Results of this study intended to address the issue for the disposal of desiccated human faeces from MobiSan by assessing the potential of composting in enhancing the fertilizing value of human faeces for agricultural application. Results provided also an understanding of the fertilizing value of human faeces and assisted subsistence farmers (small scale) with valuable knowledge of the fertilizing value of desiccated human faeces from Mobisan and the potential of composting in enhancing it for safe use in agriculture.

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Dedication

To my mother Ntumba Mutombo

To my wife Jeanne Ndona

To my sons Graddy and Joy Mualaba Tshibangu

To my sister Bibi Musawu

To my brothers Mutombo and Kabongo

To all assisted me during my study and lastly to the Almighty God

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Abbreviations and variables

APHA	American Public health Association
CHF	Composted human faeces
C/N Ratio	Carbon to Nitrogen Ratio
DWAF	Department of Water Affairs and Forestry
FC	Faecal coliform
HF	Human faeces
DHF	Desiccated human faeces
G	Gram
K	Chemical symbol of Potassium
L	Litre
l/s	Litre per second
m^2	Meter square
m^3	Cubic meter
N	Chemical symbol of Nitrogen
NPK	Nitrogen Phosphorous Potassium
NH^3	Ammonia
P	Chemical symbol of Phosphorus
WHO	World Health Organisation
%	Percentage

Glossary of terms and acronyms

Terms and Acronyms	Definition/Explanation
Aerated static pile	The circulation of forced aeration or controlled aeration into the organic matter rather than through frequent agitation (turning).
Bacteria	A member of a large group of microorganisms capable of causing disease in humans.
Colony forming unit (cfu)	Measure indicating the number of microbes that can multiply in a sample.
Compost	Solid mature product that can be used to improve the soil structure with nutrients.
Composting	Product resulting from a managed process of bio-oxidation of organic matter under controlled conditions.
Contaminant	Element or compound, which through its presence or concentration can adversely affect living organisms on the natural environment.
Escherichia coli (E-Coli) expressed in cfu/g	Is a species of bacterium present in water or food indicating faecal contamination and can make sickness to human being.
Eutrophication	Excess nutrient concentration in water caused by runoff. The productivity of nutrients in water with elevated temperatures causes the growth of algae plant and reduction in fauna and flora variety.
Faecal coli forms	Is a group of bacteria that can be found in soil; in human's intestines or warm-blooded animals; its presence indicates the faecal contamination.
Foreign matter	any matter over 2 mm in dimension that results from human intervention and has organic or inorganic components such as metal, glass, synthetic polymers (for example plastic and rubber) and that may be present in the compost but excluding mineral soil, woody material and pieces of rock.
Helminth	A worm or worm-like animal, especially parasitic worms of the human digestive system, such as the roundworm or hookworm.
In-vessel composting	Diverse group of composting methods in which composting materials are contained in a reactor vessel; the purpose is to

	maintain optimal conditions for composting.
Mature	Term used to designate a compost that, when used as an organic soil conditioner, does not have phytotoxic effects arising from, for example, nitrogen immobilization or anaerobioses.
Micronutrient	Plant nutrient (for example boron, copper, molybdenum, manganese, iron and zinc) required in lesser quantities than major (for example nitrogen, phosphorus and potassium) and secondary (for example calcium and magnesium) plant nutrients, having essential physiological functions in plant metabolism.
Microorganisms	Species of unicellular or multi-cellular organisms that is not visible with open eye. They are classified in protozoa, algae, fungi, viruses and bacteria.
Nutrients	Essential substances or elements needed for human body or for plant growth. The most important are nitrogen, phosphorus, and potassium).
Pathogen	A disease-causing microorganism.
pH	A symbol for the degree of acidity or alkalinity in a solution, ranging in value from 1 to 14. Below 7 is acidic, above 7 is alkaline, 7 is neutral.
Organic material	Referring to a material from an animal or vegetable source, such as refuse in the form of manure or food scraps; also a form of agriculture which employs fertilizers and soil.
Urine Diversion	These are ecological sanitation systems that separate urine component from faeces.

Chapter one: Introduction

1.1 Background

Human faeces have been applied in agriculture as soil fertiliser in many developed countries, such as China, Holland and Japan. Despite the fertilising value, farmers are facing difficulties in improving productivity through the use of human faeces, mainly due to the unknown properties of faeces extracted, resistant cultural beliefs and potential health concerns. Despite the established fertilising value of human faeces, inappropriate and improper use does lead to health and environmental problems (WHO, 2006).

The study site for this research is situated at Pooke se bos, an informal settlement which was provided with only one communal dry sanitation system, called a MobiSan facility. The MobiSan is a urine diversion toilet installed on private land, generating a volume of solid waste that requires safe disposal to the localised treatment facility. The waste disposal in this settlement is difficult for a number of reasons, such as lack of space, no access roads, no electricity, flooding during the rainy season and high population density.

Recycling nutrients from human faeces affords the possibility of re-using the waste products and preventing direct pollution, but opinions remain divided regarding the characteristics of desiccated human faeces produced by the MobiSan in terms of their fertilising values and their potential pollution effect in the soil.

The study investigated three composting methods (co-composting, Skyloo composting and bio-process composting) for the treatment of desiccated human faeces to meet the necessary standards for agriculture and to assist subsistence farmers with an understanding of the fertilising value of desiccated human faeces from the MobiSan and the potential of composting method enhancement.

1.2 Statement of the research problem

The use of human faeces in agriculture is still posing problems in informal settlements due to its unknown properties, its unknown fertilizing values, health environmental issues and lack of information on how the faeces can be used in agriculture. The inadequate infrastructure and lack of sanitation services for the disposal of desiccated human faeces from MobiSan the facility have a detrimental effect within the settlement that leads to unwanted conditions, such as contamination of ground water and environmental degradation. Often, the Mobisan site suffers

from problems such as waterborne diseases, attraction of mosquitoes, flies, insects, domestic animals, and rodents that spread diseases. These cause health hazards, especially during the rainy season. Due to several factors named above, the correct application of human faeces can contribute to the restoration of soil fertility in settlements where the loss of soil organic matter and nutrients is prevalent.

1.3 Research questions

The key question addressed by the study includes the following:

Can the composting methods used to treat desiccated human faeces produced by the MobiSan facility be able to enhance the fertilizing value and meet agricultural standards?

- What are the characteristics of desiccated human faeces produced by the MobiSan facility in terms of fertilizing value and pollution in agriculture?
- Do the characteristics of desiccated human faeces from MobiSan meet the applicable standard for use in agriculture?
- To what extent the Co-composting; Skyloo composting and Bio-process composting can enhance the fertilizing value of desiccated human faeces from MobiSan?
- Do the characteristics of composted human faeces comply with agricultural standards?

1.4 Aim and objectives

The aim of this study was to investigate three composting methods used to treat desiccated human faeces produced by the MobiSan facility for agricultural application in order to assess methods for the enhancement of the fertilising value of human faeces. These composting methods are co-composting, Skyloo composting and bio-process composting. Objectives of the study were as follows:

- To determine the characteristics of desiccated human faeces produced by the MobiSan facility in order to assess the fertilising value and understand its application in agriculture.
- To compare the characteristics of desiccated human faeces to the accepted agricultural standards in order to assess its compliance for safe use.
- To investigate three composting methods that could enhance the fertilising value of desiccated human faeces in order to determine the treatment level of human faeces and their applicability.

- To compare the three composting methods in terms of their effectiveness with regard human faeces enhancement capabilities in order to select the most suitable for the MobiSan context and complies with agricultural standards.

1.5 Scope of the report

The scope of the report is presented in steps regarding how the structure of the study was described and objectives assigned. The literature review and experimental studies are combined in this work. The outline of the work consists of background and its significance and is presented as follows:

- *Introduction:* the first part of this report introduces the study by outlining the background, research problem and objectives, outcomes, research question, significance of the study, and delineations.

- *The literature review in Chapter 2* comprises of desktop study of accumulated knowledge regarding the fertilising value of human faeces and methods of enhancing it for crop production. The literature review explains in details the characteristics of human faeces, the fertilising values of human faeces, and the treatment methods of human faeces. This section of the study includes also the impact of excreta on the environment and the methods used to enhance the fertilising value of human faeces. In addition, the literature review includes the mechanisms of composting treatment methods and guidelines established for human faeces in agriculture.

- *The experimental work in Chapter 3* describes the design portion of the study and how the research was outlined. The materials and equipment used during the experiments is also discussed. The chapter consists primarily of a description of the process of building and monitoring the three lab-scale plants of composting, which were designed based on existing features, constructed and then appropriately manned.

  Laboratory experiments were mainly conducted by collecting samples and conducting analysis for selected relevant parameters, within the confines of a laboratory. This phase of the study was achieved by determining the characteristics of desiccated human faeces collected from the MobiSan facility and the enhancement of desired characteristics through various composting methods. Samples of composted human faeces from the pilot-plants

were collected and tested for quality parameters such as temperature, pH, moisture content, oxygen, carbon, nitrogen, phosphorus, potassium, E. coli and faecal coliform.

- *The presentation of results in Chapter 4* highlights the results obtained from experimental works undertaken, as discussed in the Chapter 3.

- *Discussion and analysis of results in Chapter 5* comprises a report on the results collected before and after the composting treatment of desiccated human faeces collected at the MobiSan facility. Results obtained for the three composting methods identified above were compared for their efficacy in treating human faeces, as well as confirming their measure in accordance with the standards applicable in agriculture.

- *Conclusions and recommendations in Chapter 6* offer an overview of the three methods used for the composting methods of desiccated human faeces from MobiSan facility. A particular method is recommended as the most suitable.

1.6 Delineation of the study

The study was limited to the investigation of composting methods used to enhance the fertilising value of desiccated human faeces produced by the Mobisan facility, as well as monitoring and testing of relevant parameters of importance for the composting process, with emphasis on agricultural use and environmental health issues.

These parameters include temperature, oxygen, pH, moisture content and major nutrients, such as carbon, nitrogen, phosphorus and potassium, as well as E. coli and faecal coliform. Other aspects, including the design of the MobiSan, operation and maintenance, different types of crops, vegetation and soil properties that can be adapted to the use of human faeces, and environmental factors such as soil pollution, were beyond the scope of the study.

1.7 Relevance and benefits of the study

The study was conducted to address the issue of the disposal option of desiccated human faeces from dry sanitation systems such as MobiSan by assessing the potential of composting in enhancing the fertilising value of human faeces. The intention was to provide an understanding of the fertilising value of desiccated human faeces from a MobiSan facility and the potential of composting processes in enhancing this fertilising value.

The outcomes of the study were to assist farmers who have adopted the re-use of composted human faeces by providing them with knowledge of the fertilising value of desiccated human faeces from Mobisan systems and the potential of composting processes for enhancing human faeces for safe use in agriculture.

Chapter 2: Literature review and theory

2.1 Introduction

For many decades, human faeces have been applied in numerous developing countries as fertiliser for both household gardens and agriculture, in order to increase production and to save on expensive inorganic fertiliser. The need for a safe, domestic supply of fertiliser should be addressed by recovering nutrients from human faeces, rather than allowing faeces to be discarded as waste and flushed out into the rivers (Winblad, 2004).

Human faeces need to be treated before use in agriculture (Esrey *et al*., 1998). Thus, composting is the preferred method for municipalities and industries to sanitise human faeces and recycle a variety of organic by-products to apply them as soil conditioners and amendments (WHO, 2006).

This section of the study presents a literature review pertaining to human faeces and its characteristics. It further presents the treatment of human faeces, and its fertilising value. The impact of using human faeces in agriculture is presented. Furthermore, methods of enhancing the fertilising value of human faeces and the composting treatment technologies are also described. In addition, relevant literature for the compost quality guidelines set for human faeces in agriculture is summarised.

2.2 Characteristics of human faeces

Human faeces is characterised by certain physical conditions (temperature, moisture content, oxygen availability and pH); as well as type and number of microorganisms and available nutrients (N, P, K). Human faeces has specific characteristics, as summarised below (Chaggu, 2004).

2.2.1 Raw human faeces

Raw human faeces contains a potential of danger in the form of disease pathogens. In a low-temperature compost pile with adequate retention time, diseases such as cholera, hepatitis, typhoid and intestinal parasites are destroyed by composting, and the process produces biological heat that may destroy other species of bacteria in a certain period of time (Chaggu, 2004).

According to Chaggu (2004), the agricultural use of raw human faeces can facilitate the spread of various diseases and it is therefore considered not hygienically safe for use in the fields. Human faeces should always be treated prior to its use in agricultural applications. Proper composting of organic matter results in a pleasant-smelling material and destroys possible pathogens in the compost pile. The following factors influence the survival times of pathogens in soil.

2.2.1.1 Physical characteristics

The physical characteristics of relevance are temperature, pH and moisture content (Haug, 1993). These are described as follows:

a) Temperature

According to Feachem et al. (1983), the temperature of human faeces may be considered as an important factor in the effect of activities of microorganisms. The same authors suggest that, at temperatures lower than 10°C, each microbial species survives well, but are rapidly killed at temperatures above 45°C. Therefore, temperatures around 55-65°C are required to destroy different species of pathogens (except bacterial spores), and can do so within hours in the composting processes (Vinneras & Jonsson, 2002).

Temperature impacts on the treatment process of human faeces and has an effect on chemical reactions and reaction rates. Biological treatment processes will perform optimally at temperature between 25-30°C, as this is considered favourable a favourable range for microbial life (Tchobanoglous & Franclin, 2003). Microorganisms' survival in faeces and soil within an ambient temperature are presented in the following table.

Table 2.1: Organism survival within an ambient temperature in faeces and soil (adapted from Nielsen *et al*., 2004)

Microorganism	**Survival at 20-30°C (days) in:**		**Time needed for 90% inactivation of pathogen (days)**		**Maximal survival**
	Faeces	**Soil**	**Faeces**	**Soil**	**Soil**
Bacteria Thermo. coliforms	< 90 < 60	< 70 < 70	E. coli: 15-35 10-50	E. coli: 15-70 15-35	1 year/2 months
Viruses	< 100	< 100	Rotavirus: 20-100	Rotavirus: 5-30	1 year/3 months
Protozoa	< 30	< 20	Giardia: 5-50	Giardia: 10-50	2 months
Helminthes	Several months	Several months	Ascaris: 50-200	Ascaris: 15-100	2years

b) pH

The pH of human faeces is a measure of the acidity or alkalinity relating to pathogens' survival and destruction (Esrey *et al*., 1998). At a pH ranging between 7.0-8.0, the majority of micronutrients are found to be soluble. When the pH of organic matter is too low or too high, micronutrients are not soluble (Srivastava, 2002).

The alkalinity of human faeces is important, especially for destroying pathogens and causing many species of viruses to die off (Haug, 1993). The denaturation of enzymes or hydrolysation of cell components have an inactivating effect on most microorganisms because of high acidic and high alkaline conditions (Hellstrom *et al*., 1996).

Baiphethi and Jacobs (2009) also observed a pH below 9.0 in their study of source-separated faeces. Austin *et al*. (2006) confirmed the total coliforms and faecal coliforms were reduced by 1 log at pH values between 9.9 and 10.1 and at 12.1 for pathogen destruction in urine diversion sanitation systems.

c) Moisture content

Moisture contents of between 30% and 40% were found to be important for the survival of pathogens in human faeces and for a reduction of microorganisms to be achieved (Feachem *et al*., 1978). At moisture contents below 10%, the biological activity comes to a halt that may be caused by the critical aeration in the application of material agitated during the process. Thus, the process is slowed, and when it drops below 35%, it may begin to be a limiting factor for microorganisms (Austin and Dunker, 2002).

Moisture content is mainly applicable to the survival of microorganisms in faeces and soil. Anaerobic conditions are produced when moisture content exceeds about 60% through water-logging, which inhibits aerobic compost degradation and may result in odour problems (Bouhoum and Amahmid, 2000).

2.2.1.2 Chemical characteristics

The relevant chemical characteristics for plant growth are macro-nutrients, namely nitrogen, phosphorus and potassium. The chemical characteristics are generally divided into two groups: primary and secondary macro-nutrients (Strauss *et al*., 1994). They are presented below in Table 2.2

Table 2.2: Composition of Human Faeces (adapted from Chaggu, 2004)

Approximate Quantity	Faeces
Moisture content (%)	66-85
Nitrogen (N) (%)	5.0-7.0
Phosphorus (as P_2O_5) (%)	3.0-5.4
Potassium (as K2O) (%)	1.0-2.5
Potassium (K) (%)	0.80-2.1
Carbon (C) (%)	44-55
Calcium (Ca) (%)	2.9-3.6
C/N ratio	5.0-10
Protein (g) (%)	4-12

a) Primary macro-nutrients

Primary macro-nutrients of human faeces include nitrogen, phosphorus and potassium, which are required by plants in order to grow properly (Carolina, 2007). As these are the major fertilising elements, they are described as follows:

- ***Nitrogen (N)***

Human faeces contain nitrogen, which is largely responsible for plant growth, production of fruit, the growth of leaves and an increase in the seeds of the plant (Pescod, 1992).

Fernandez et al. (2007) confirmed that nitrogen from human faeces are recycled by plants as ammonia and nitrates in the soil that are absorbed by most of the plants at 30% of nitrogen concentration in the soil and through several mechanisms such as volatilization; the rest of nitrates are lost during the transformation (Girovich, 1983).

Human faeces contains the amount of nitrogen in the form of organic compounds such as ammonium (NH_4^+) ion and nitrate (NO_3^-) ions which are absorbed by plants from the soil in large quantities. Thus, these ions move easily toward plant roots when the roots absorb water (Haug, 1993).

- ***Phosphorus (P)***

Phosphorus is a plant macronutrient that is being added to soil by using human faeces as fertiliser and is often scarce in soils in a form that is bio-available to plants (Strauss et al., 1994). Phosphorus is found stable and can be found accumulated in the soil surface when added with human faeces. Human faeces contains low amounts of phosphorus and does not negatively impact the environment when used for irrigation (Girovich, 1983).

Phosphorus is one of the key essential elements in the process of photosynthesis, transporting nutrients and energy transfer for seed production (Hellstrom and Karrman, 1996). Phosphorus is a necessary and beneficial input for crop production system by functioning and increasing root growth and promoting resistance to root diseases as the major nutrient player (Slob, 2005).

- ***Potassium (K)***

Thirty percent of Potassium from faecal matter is recovered in the form of ion which many chemical fertilizers dissolve in an ideal form for uptake by plants (Esrey et al., 1998). Potassium is recognised as an essential nutrient for promoting good fruit and flower development in plants (Girovich, 1983).

Strauss et al. (1994) suggested that Potassium may plays the role of enhancing crops quality and improving the physical quality that can resist to root diseases and shelf life of fruits and vegetables used for human consumption.

Potassium is absorbed by plants through its roots in ionic form (K^+). If plants do not have adequate amounts of potassium they become less resistant to drought, high and low temperatures and excess water (Pescod, 1992). Plants may be easily contaminated by diseases and grow very slowly and their roots might be very poor if they lack potassium. This nutrient is generally absorbed by plants while they are still young (Bole and Bell, 1978). About 30% of the 1.8 kg potassium excreted by a human body in a year is found in faecal matter (Hellstrom and Karrman, 1996).

b) Secondary macro-nutrients

The essential secondary macro-nutrients for plant growth are calcium (Ca), magnesium (Mg), and sulphur (S). These nutrients are found in human faeces in lower amounts and large quantities when added to soil (Slob, 2005). These macro-nutrients are each described as follows:

- ***Calcium***

Calcium is an essential part of plants cell wall structure and is largely made up of other minerals which are responsible for the transportation of nutrients as well as strengthening the plant. Calcium is responsible for counteracting alkali salts and organic acids within the plant (Haug, 1993).

- ***Magnesium***

Magnesium is an essential nutrient needed for photosynthesis by plants and is the component of the chlorophyll in all the green plants. Plant enzymes absorb magnesium through the root (Slob, 2005).

- ***Sulphur***

Enzyme and vitamins in plants are developed when sulphur is present in soil, and it facilitates the production of nutrients in plants for the production of protein and promotion of plant life or activity. The development and growth of root from the plant is mainly improved by the presence of Sulphur element and assists the plant in withstanding cold weather (Slob, 2005).

2.2.1.3 Microbiological characteristics

The microbiological characteristics of human faeces refer to the presence of pathogenic micro-organisms such as protozoa, bacteria, viruses, helminths, ascaris and salmonella (Vaz da Costa Vargas, Bastos & Mara, 1996). Following are the indicator organisms that have been used to assess the risks associated with the use of human faeces in different situations:

a) Bacteria

According to Schonning (2001), bacteria is a large domain of single-celled organisms that have been found in environments such as water, soil, organic matter, and the bodies of multi-cellular animals. Twenty five percent of aerobic bacteria in human faeces often require oxygen and grow best at a high oxygen tension. Therefore, a reduction tension below 10% may be needed for a number of bacteria, called microaerophilic, for a better growth of anaerobic bacteria (Teunis and Havelaar, 2002).

Infectious diseases in humans are always caused by bacteria when they are living in spoiled food (causing food poisoning) although some are regarded as beneficial as they are used in various industrial processes, especially in the food industries and manufacturing for a variety of enzymes and hormones (Austin and Duncker, 2002).

According to Singleton, (1995), species of bacteria in human faeces cause disease in the environment. Among them are the shapes, spheres and spirals bacteria. They are distinguished in part by their morphological and genetic features as follows:

- ***Salmonella***

These microorganisms are generally found in human faeces at populations of 10^4 to 10^8 per gram of faecal matter (WHO, 2006). Faecal matter from ecosan toilets in Kwazulu-Natal was characterised as having a concentration of 10^6cfu/g. When sawdust was mixed with faeces in another study, Salmonella was found to be10^2cfu/g after 10 months of storage, which is quite low (Austin and Vuuren, 2002).

- ***Faecal Streptococci***

In a case study in India, Faecal Streptococci had a concentration of about 2.1 x10^6 per gram of human faeces (Austin and Duncker, 2002). These microorganisms also manifest resistance to an increase of pH values, surviving up to pH values between 10.1 and 12.1, where they showed only 1 log reduction.

- ***E. Coli and Faecal coliform***

Micro-organisms namely e-coli and faecal coliform are considered as indicators of human contamination. These pathogens can transmit communicable diseases present in human faeces. They are also introduced into wastewater from different sources (Ottoson et al., 2003).

E. coli has concentrations of between 10^2 and 10^3 in human faeces (WHO, 2006). The number of E.coli in a given volume of human faeces can indicate the level of risk to human health where there is contact with human faeces; the presence of faecal coliform indicates faecal contamination, used to assess the presence of pathogenic bacteria and specific organisms (Schonning, 2001).

The transmission of infectious diseases is often associated with faecal coliforms and E. coli which are the most common bacterial indicators of faecal pollution, with 97% of bacteria in fresh human faeces (Sami, 1998).

b) Helminthes

Schonning (2001) confirmed that helminthes are parasite worms that cause organism disease on a human or another animal externally. Morbidity and mortality are a primary caused in developing countries by Helminth infections, and they are pathogens that are considered as the hardiest in faecal matter intended for handling and re-use. An estimation of one billion cases in 1983 has been reported for Ascarias as caused by helminth infections (Feachem et al., 1983).

c) Protozoa

Protozoa are often passed as cysts in the faeces and can infect humans and cause diseases when ingested. Three species of human intestinal protozoa, Balantidium coli, Giardia lamblia and Entamoeba-histolytica, are frequently pathogenic (Teunis and Havelaar, 2002).

Slob (2005) reported that protozoa are mostly around 0.01-0.05 micrometres and the smallest of all animals which can be seen with the naked eye, living in a cell where they can breathe, move, and reproduce like multi-celled animals in water or in faeces. Protozoan parasites are harmful and cause serious diseases to humans, and are identified as agents of waterborne epidemics, though some are helpful for fish and other animals,

d) Virus

Viruses are also considered the smallest infectious organisms that can replicate only inside of cells. Many types of organisms from animals and plants can be infected by viruses from human faeces (Teunis and Havelaar, 2002).

Human faeces may contain 10^9 infectious virus particles, regardless of whether the individual is experiencing any discernible illness, and human faeces can excrete several types of viruses that can cause diseases. The most common viruses found in human faeces include poliovirus, rotaviruses, hepatitis A virus, enteric viruses and diarrhoea-causing viruses (WHO, 1989).

e) Ascaris

Ascaris is generally excreted at a rate of 10^4 per gram of faecal matter produced by a person (WHO, 2006). Ascaris eggs have been observed as the most resistant of the pathogens; they can withstand low moisture contents up to just above 5% (Austin and Duncker, 2002). Ascaris can survive up to a period of 155 days in faeces, and up to 625 days in soil, or 60 days in crops. This longer storage times is needed with low moisture contents and with high temperatures to kill different species of these microorganisms (WHO, 2006).

Ascaris die-off in faecal matter from solar dried ecosan toilets have been reported in El Salvador, with temperatures between 34 and 44°C when human faeces were stored for two months (Strauss and Blumenthal, 1994). Similarly, in a case study in South Africa, there were

no Ascaris after storing faeces from ecosan toilets in plastic containers for a period of six months (Austin and Duncker, 2002).

2.2.2 Desiccated human faeces

Desiccation and recycling nutrients from human faeces is the first approach of Ecological, focusing mainly on the treatment of human excreta as a resource (Esrey et al. 1998). A study conducted by Havas (2007) indicated that when the source of human excreta is separated, correctly managed, stored and used, can be considered safe and sustainable fertilizer for agricultural application. The use of compost from toilets and source-separated urine may not have an impact on the human health and environment, or cause any significant microbiological risk for the user of the fertilizer the consumer of the crops, as pathogens are killed more effectively than other commonly used methods (Feachem et al., 1983).

The high phosphorus contained in desiccated faeces can be applied prior to planting or sowing because this is beneficial for root formation of young plants. The degradation of organic matter in soil may be utilised by the plants as nutrients are available (Winblad et al.; 2004).

Austin and Duncker (2002) confirmed important parameters for the degradation of desiccated human faeces, including temperature, moisture, and pH, as these contribute to die-off of microorganisms. Singleton (1995) revealed that the time taken by microorganisms to die-off can be increased or decreased, depending generally on the storing time taken under natural conditions.

A case study from India revealed that 97% of faecal coliforms (bacteria commonly found in faeces) in soil died in about two weeks in the hot season and in about three weeks in cold season. The reason, Srivastava (2002) reported, was that temperature impacts on the process of desiccated faeces and has an effect on chemical reactions and reaction rates. Pathogens can begin to die at a faster rate when the temperatures are increased.

2.2.3 Dehydration of human faeces

Dehydration is considered by Esrey et al. (1998) as the more effective method of destruction of pathogens than the wet methods (flush-and-discharge). The destruction of microorganisms is caused by the combination of low moisture, low amounts of organic matter / nutrients, and high pH.

Dudley (1996) confirmed that the contents of the processing vault used for the dehydration of human faeces are dried with ventilation, heat. When adding dried material, the moisture content may be brought down less than 20%. Studies by Winblad et al. (2004) indicated human faeces are dehydrated when there is removal of water and excretion of microorganisms from it; eventually there is a rapid rate of pathogen destruction without smell and fly breeding.

Generally, excreta is dehydrated without urine diversion, although in extremely dry season this is possible, as illustrated in the study by Winblad et al. (2004) in Ecuador resulting in the following findings from dehydrated human faeces:

2.2.3.1 Factors contributing to dehydration of human faeces

Factors that are recognised to the contribution of survival of microorganisms include the following:

- Temperature.

Feachem et al. (1983) revealed that most of microorganisms survive well at temperatures less than 10°C and are destroyed at temperatures above 45°C. This is the case for various types of media including, faeces, crops, soil, sewage and water.

Temperatures ranging between 50-65°C are needed to kill off all types of pathogens in the composting process to ensure a complete destruction (except bacterial spores) within hours (Bertoldi et al. 1988; Haug 1993).

- pH.

Many microorganisms are generally adapted to a neutral pH, and at pH value of 7, enteric pathogens still survive in human faeces. Some microorganisms need to withstand the acidic conditions in the stomach to cause an infection (Ekelund et al., 2007).
Hydrolysation of cell components and denaturation of enzymes can be done within high acidic or high alkaline conditions for the inactivation effect of microorganisms (Caraban, 2007). At pH values ranging between 3 and 5, microorganism survival may be shorter in acid soils than in alkaline soils (Feachem et al. 1983).

Studies by Firman (1994) and Cotton (2001) confirmed the inactivation of enteric viruses found at lower pH value of about 3-5 and at higher pH value of about 10. In dry latrines, the pH may

be increased to 12 when sawdust is added to human faeces and this may affect the survival of microorganisms (Gandhi et al., 1997).

- Moisture

Moisture content is relevant to microbial life of many species of microorganisms in soil and faeces as this favours the life of microorganisms. Under moist conditions in the composting system the virus survival can be prolonged while protozoan cysts are highly sensitive to desiccation which may also affect their survival on plant surfaces (Cooperband, 2000). Ascaris eggs need moisture content lower than 5% for them to be inactivated (Feachem et al. 1983).

2.3 Fertilizing values of human faeces

Human faeces are considered as valuable resources with nutrients capable to be used as fertilizer in agriculture. Using human faeces for agricultural application can reduce the need of chemical fertilizer and improve food production, especially for subsistence farmers. The valuable resources of excreta from both animals and humans, if properly managed, can replace significant amounts of chemical fertilizers due to its beneficial fertilizing values (Rosemarin, 2004).

Esrey et al. (1998) argue the same: that human faeces have a positive effect with macronutrients for plant production and should not be regarded as a waste, but rather as a product that can be used given its fertilizing values in agriculture.

Others have found the same. Human faeces are considered as valuable sources of nitrogen, potassium and phosphorus and other nutrients necessary for plant growth (Vinneras et al., 2002). Human faeces develop small organisms in the soil; these microbes are responsible for changing minerals to forms that are easily utilised by the plants.

Morgan (2003) described a number of experiments utilising human faeces for plant production as a source of nutrients in Zimbabwe; he compared growth of the plants in the local poor quality sandy topsoil with that from urine-diverting toilets (a mixture of human faeces, soil and wood ash).

The excreted amounts of plant nutrients are about the same as the amount eaten for adults who maintain approximately the same mass during their lifetimes. This fluctuates according to

people's diets, and according to the age, sex and societies (Vinneras and Jonsson, 2002).The quantity of human faeces produced per person depends eventually on the composition of consumed food with meat and other foods low in fibre when producing smaller volumes than food high in fibre (Vinneras and Jonsson, 2002). The addition of sawdust used in the treatment of faeces contributes to the total content of nutrients and organic matter of treated faecal product (Austin and Dunker, 2002).

Human faeces contribute to plant production by its fertilizing effect and by its soil-improving effect (Girovich, 1983). Due mainly to the varying proportion of nutrients in mineral form in faeces, the fertilizing effect of faeces is significantly higher than the fertilizing effect of urine (Schonning, 2002).

According to Vinneras and Jonsson (2002), the estimation excretion of nutrients compared in different countries can be assumed by the loss between the food supplied and the food actually consumed. The characteristics of human faeces are variables from one region to another; it depends mostly on diet and local cultures. Their concentration varies depending on diet; age; sex and societies.

Following the study by Drangert (1998), the amount of human derived nutrients was found to be 5.2% for nitrogen content, 4.8% for phosphorus and 3.1% for potassium content. Baiphethi and Jacobs (2009) also confirmed that the macronutrients value of human faeces were found for nitrogen content at 5.5%, while 4.5% and 3.5% were recorded for phosphorus and potassium content respectively.

Table 2.3: Comparison of human faeces according to various authors (adapted from Chaggu, 2004)

Authors	**Raw human faeces**					**Biodegradability** %	**Country**
	TMW (g/day)	MC %	N %	P %	K %		
Chaggu (2004)	70-520	66-85	5.0-7.0	3.5-5.65	0.8-2.1	80	Ghana
Palmquist and Jonsson (2003)	199	86	7.0	3.5	2.8	74	Uganda
Lopez Zavala (2007)	205	81.8	6.0	4.45	2.5	80	Kenya
Sanitised human faeces							
Niwagaba (2009)	-	43-63	19	34	28	90	Uganda
Strauss and Blumenthal (1994)	-	40-65	16	28	24	95	Sweden
Desiccated human faeces							
Wang (2005)	-	40-60	8	14	17	80	Sweden
Sanders (2001)	-	35-55	12	18	26	85	Tanzania

TMW: Total mass wet; MC: Moisture content.

A study by Cooperband (2000) and others around the world revealed a number of sources in literature that provided information on the enhancement of raw human faeces, sanitised and desiccated human faeces. Results show that the concentration of nutrients in faeces varies with diet between countries and individuals. The comparison values are presented in table 2.3 from different countries.

2.4 Treatment of faeces

Faeces need to be stored and treated under highly controlled conditions, as their presence is considered as high risk to the environment because of the concentration of pathogens (EcoSanRes, 2003). There are various methods of treating faeces and the quality of the end product depends on the choice of treatment method. Treatment methods of faeces are outlined below and described as follows:

2.4.1 Incineration

Incineration of faeces is a compact and rapid process that can achieve pathogens destruction quickly, and the remain of organic material can be re-used in form of ashes as cover material in the toilets, thereby solving the often encountered problem of odours, flies after defecation. In order to burn the material, the moisture content of less than 10% is required at sufficiently high temperatures (Esrey et al. 1998).

Incineration process may increase the level of temperature able to destroy any pathogens present in human faeces, and high level of temperatures above 500°C can be achieved when the faecal material is incinerated with dioxin material capable of destroying the number of pathogens with the possibility of transmission of diseases (Dudley, 1996).

A case study done by Jönsson et al. (2004), confirmed that ash from incineration of faeces contains large amount of nutrient that can fertilise the soil for agricultural purposes. However, the results on the case study done by Partridge and Hodgkinson (1977); suggested that the content of Nitrogen, Sulphite and Carbon were lost at 85 to 100% during the burning of different types and sources of straw.

2.4.2 Chemical treatment

Different chemicals such as acids (phosphoric acid), oxidising agents (chlorine) and bases (ammonia and lime) can be used for the treatment of human faeces in order to reduce

pathogens. The use of chemicals for disinfection such as $Ca(OH)_2$, NH_3, KOH and PO_4^{3-}isalso considered as preferable treatment process to increase the fertiliser value of the product for agricultural purposes (Vinneras et al., 2002).

According to Vinneras et al., (2002), the mixture of urea with human faeces dosed at thirty gram (3% ammonia nitrogen) is able to reduce pathogens after 2 months at 20°C.In the same study, it was also found that the addition of urea to the faeces increased the pH above 9, and an efficient disinfection of E. coli, and Salmonella spp. were observed within 3 weeks while inactivation of Ascaris eggs in faeces by ammonia with different ambient temperatures were recorded between 20 to 30°C. Study conducted by Feachem et al., (1983), concludes that both temperature and time can achieve the thermal inactivation level of pathogens in the system.

2.4.3 Storage

At temperatures slightly above 30-50°C, numbers of microorganisms, bacteria and pathogens in faeces are usually considered to decrease as a result of natural die-off. This happens during a period of 1 to 2 years storage time where most bacterial pathogens are eliminated under the toilet vault, faecal material is kept dried, and will effectively reduce viruses, protozoa and other bacteria (WHO, 2006). The completion of the same result can be achieved during one year storage period, by killing pathogens faster than higher temperatures above 30°C (Schonning et al., 2004).

Oxygen, pH, moisture, temperature, nutrients, ammonia concentration and UV exposure are the most factors that are contributing to the extent of pathogens decrease in numbers during storage of human faeces (Peasey, 2000). However, certain types of bacteria can be increased in numbers when conditions of their growth are favoured in their storage. They are Salmonella, E. coli and Enterococcus spp (WHO, 2006).

2.4.4 Burying faeces

The treatment method of burying faeces in eThekwini Municipality in South Africa was adopted as simple and lower cost in order to reduce number of pathogens in the environment; this can decrease also faecal-related diseases amongst users of human faeces reuse. The method may be used with more space in rural areas. The topsoil of 20-30cm should be applied to cover human faeces from urine diversion dry toilets (Guness et al., 2005).

According to Niwagaba (2009) confirmed that the contamination of groundwater is minimised with trees, bushes and other plants that are closer to buried faeces areas. Therefore, water infiltration will be less to groundwater as plants use a large amount of water preventing it from taking up water and nutrients.

2.4.5 Composting

Composting is the biodegradation of organic material under control conditions. However, sustainable alternatives such as composting toilets, urine diversion toilets, chemical toilets and dehydration toilets involve treating human faeces as a resource by recycling their nutrients for agricultural application (Esrey et al., 1998). These technologies are described as follows:

2.4.5.1 Composting Toilets

The composting treatment can take place in a double vault toilet or somewhere else when the collection period of faeces is over. The composting objective is mainly to make faecal material usable and safe in agriculture from various species of microorganisms. The faecal matter from composting process is transformed into an odourless state and free from flies (Feachem et al., 1978). A composting toilet is considered as an aerobic process that can produce heat from the decomposition of organic matter to reach the desired temperature over 55^{o}C during a period of time to ensure safe reduction of pathogens (Vinneras et al., 2002).

Austin and Duncker (2002) confirmed that composting toilet is an aerobic process that may treats human faeces under control condition to reduce pathogens and benefit land with nutrients for plant production and organic matter for soil improvement. Complex organic compounds are broken-down by different species of microorganisms while producing heat into the system. (Esrey et al.1998).

2.4.5.2 Urine diversion toilets (UDT)

A urine diversion toilet is a sanitation system that separates urine and human faeces through a pedestal design as presented in Figure 2.1. Urine and human faeces are collected separately in order to be used in agriculture as a fertilizer. Urine diversion toilets may be used with a composting and dehydration processes (WHO, 2006).

Vinneras et al. (2002), revealed that moisture content is the only factor that makes difference between urine diversion and composting toilets as urine is not mixed with human faeces. Ash,

sawdust or dry soil are added over the faeces after using the toilet in order to absorb the moisture and also to decrease odours, flies and high risks contained within the faeces. Desiccation of human faeces in urine diversion toilets is caused by dry conditions and can make it fertiliser or good soil conditioner.

Winblad (2004) confirmed that the new approach to waste water management and reuse is the principle of treating human waste as a resource that can be characterised with the following:

- Separation of waste streams
- Recycling of nutrients and its recovery
- Diminution of water
- Pathogens destruction
- Sustainability

Liquids from human faeces are diverted in urine diversion toilets to keep the processing chamber contents dry. Thus, wood ash, lime or sawdust are added to faecal matter in order to get a lower moisture content, help raise the pH and allow time for pathogen die-off (Winblad et al., 2004). Urine diversion toilets depend on storage time, drying agents and bulking materials mixed in the chamber to reduce moisture and increase aeration (Winblad, 2004).

Figure 2.1: Pedestal of dry urine diversion toilets (Winblad, 2004).

Collection of separated urine from human faeces is advantageous as the treatment can be tailored to the specific composition and needed treatment of each organic matter fraction as well as to protect the environment from pollution (Vinneras et al., 2002).

Esrey et al. (1998) confirmed that urine diversion sanitation systems have been developed and adapted over many years in many developing countries successfully using human faeces for the enhancement of plant production. This toilet can be based on either the single vault or double

vault to find ways of reducing faecal pathogens. The two types of urine diversion sanitation are presented as follows:

a) Urine diversion single vault

Single vault toilets contain faecal material that needs to be collected in such a way that facilitates storage and easy removal. Faeces may be collected either in a suitable container or in a heap on the floor of the vault and urine may be collected in a container for direct use or stored as well (Esrey et al., 1998).

Figure 2.2: UDT Single vault (Wafler, 2009)

b) Urine diversion double vault

Two separate containers are used in urine diversion double vault system where the faecal material is moved to one side when the first container gets full, and the second one is moved into place beneath the pedestal. By the time the second container is full, faecal material is removed from the container and stored in a sack for a certain period of time (Austin and Duncker, 2002).

Figure 2.3: UDT Double vaults (Crepa, 2007)

The design of urine diversion toilets with double vaults allows for a covering of metal sheet, inclined by 45 degrees, to speed up the decomposition of faecal matter from the sun. This

system is considered safe from longer period of storing material before handling can take place depending on the number of users and size limitation of the vaults (Epstein, 1997).

b) Urine diversion toilets MobiSan

- ***Definition and Operation of MobiSan***

The MobiSan facility was defined by Castellano et al. (2009) as a type of urine diversion toilet where the system separates human faeces from urine. The MobiSan consists of two separate compartments to store faeces mixed with sawdust. The faecal matter ends up in the first collection chamber and is mixed manually through a mechanical device (Castellano et al., 2009).

Figure 2.4: View of MobiSan toilets facility (Castellano et al., 2009).

MobiSan toilet is much less of a problem as faeces are mixed to sawdust absorbing moisture within the faeces and keep the chamber free from odour and flies are not attracted. Faeces is dehydrated to some extent through ventilation systems which depend also on ambient temperature and humidity. Practical experience showed that they will not be attraction of flies if the urine diversion is well operated and maintained (Esrey et al., 1998).The faecal matter in the first chamber is transferred to the second chamber when the vault is full using a mixing device as presented in Figure 2.6, while the first one remains in use. Therefore, the faecal matter in second chamber is stored for further hygienisation and improvement of the end product quality (Mels et al., 2008).

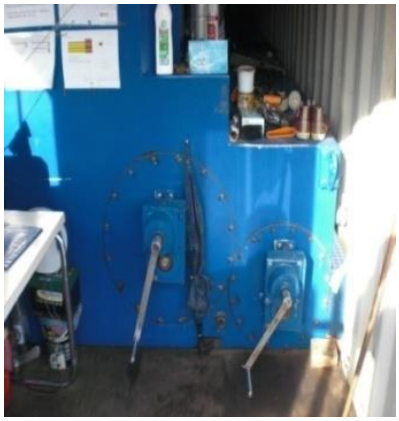

Figure 2.5: Mixing device 1 and 2 of MobiSan (Castellano *et al*., 2009)

Emptying the MobiSan Unit requires that the upper steps under urinals must be removed to unlock and open the doors and the compost can be removed by turning mixer two anti-clockwise (Castellano et al., 2009).

- ***Storage of faeces in MobiSan***

Faeces are contained in the first chamber for a certain period where there is reduction of pathogens as the result of storage time during six to twelve months. Dehydration and decomposition of organic matter occurs, as well as ventilation and the addition of dry material into the first chamber of MobiSan facility (Castellano and Kraaijvanger, 2009).

Schonning at al. (2004) confirmed the number of pathogens reduction in faecal material during storage time, without further treatment. The type of microorganisms and storage conditions governing the time for reduction or elimination are presented in Table 2.4

Table 2.4: Die-off of selected pathogens in faeces and soil during storage period (adapted from Nielsen et al., 2004)

Pathogens	Faeces storage (days)	Soil storage(days)
Salmonella	8-30	6-35
Rotavirus	16-60	6-25
Hepatitis A virus	18-55	10-75
Giardia	9-28	4-30
Cryptosporidium	20-70	182-495
Ascaris	30-125	150-625

2.4.5.3 Dehydration toilets

Dehydration is similar to composting toilets where faeces are stored in a chamber or vault. The main objective of the operation of these systems is to reduce moisture and dry the faecal matter (Esrey et al., 1998).

A reduction of moisture is achieved when adding sawdust. Sawdust is alkaline which absorbs all liquids found in faecal matter and also raises the pH levels of the faeces thereby resulting in pathogen destruction if raised to over 9.5 (Carban, 2007). The absorbent is introduced into the chamber after defecation to ensure that the faecal matter remains dry. Air is also introduced to assist the drying process and drawn out through the ventilation pipe (WHO, 2006).

2.5 Impact of excreta

The use of excreta for agricultural application can be both positively, as fertilizer for growth production, and negatively, as high environmental risk to the community (Schonning, 2001). Environmental impact of excreta associated with health risks in agriculture are described as follows:

2.5.1 Human health

There are many excreted infections of public health importance which are from human faeces and wastewater re-use schemes (Franceys, 1992). The main objective of sanitation system is to protect health; as such any symptom of illness must eventually be minimised and the capability to destroy pathogens is maximised. The complete destruction of disease can only be achieved with the common understanding of hygiene teaching among the community (Kale et al.; 1986).

Studies on the treatment of excreta showed that untreated excreta are considered high risk of infectious disease for contaminating both people and animals, mostly in many developing countries where outbreaks of cholera and typhoid are frequent in urban and peri-urban areas (Schonning, 2002).

2.5.2 Agricultural

Murphy (2006) confirmed that if untreated faeces are mixed to the top soil for irrigation during an extended period, high levels of biological activity may occur and result in poor soil and potential damage to plant production.

Synthetic organic compounds in irrigated soil are adsorbed and biodegraded through the mixture of excreta with the soil; therefore persistent organic compounds are often reduced by biodegradation, adsorption, and volatilisation during the treatment of faeces before its use in agriculture (Cordy et al., 2003).

2.5.3 Environmental

Investigations into the use of excreta regarding its impact on the health of the community have been conducted in many regions where endemic parasites are persistent in the environment (Marilyn et al., 2005).

The high concentrations of pathogens commonly found in untreated excreta such as bacteria, viruses, protozoa and helminths can cause serious diseases to human, known as protozoan parasites that are harmful and very unsafe to the environment (Gunnes et al.; 2005).

According to Phillips (1998) the disposal of faecal matter has a detrimental effect in the surrounded area, especially where the pollutants is discharged into the natural water resources. The general environment, the water resources and human health are mainly affected by the use of excreta and uncontrolled discharge (City of Cape Town, 2004).

2.6 Methods of enhancing the fertilizing value of human faeces

Human faeces can be enhanced through composting method. This may be processed together with organic household residues under controlled condition to make humus. Sufficient oxygen is needed to increase microbiological life and to maintain aerobic conditions into the pile heap within weeks while producing a material as rich as true compost (Vinneras et al., 2002). The following section gives an overview of composting treatment technologies, Mechanisms and category of composting methods.

2.6.1 Overview of composting treatment technologies

2.6.1.1 Definition of composting

Composting may be defined as a biological degradation of organic waste where heat is released in the oxygen consuming microbial metabolism, resulting in high temperatures. The biological activity is intensive in active compost and the oxygen is consumed and makes easier the survival of microorganisms (Liang et al., 2004).

According to Austin et al. (2006), composting may be defined as a process where compostable waste is biologically decomposed to a complex and stable material that is very useful for agricultural application.

2.6.1.2 Goals of Composting

The main goal of composting is the capturing of nutrients from human faeces and to recycle them back for agricultural purposes. In this way the destruction of pathogens contributing to the health and environmental risks is an important aspect of composting system. The understanding of the composting goal is considered as the enhancement of soil fertility for the purposes of plant production (Kirchmann and Vinneras, 1998). The types of composting are introduced below:

2.6.1.3 Types of composting and Operational requirement

There are three types of composting namely aerobic composting; anaerobic composting; and vermicomposting. These are described as follows:

a) Aerobic composting

Aerobic composting can be defined as a process where environmental conditions and aerobic organisms are controlled with the amount of oxygen for the degradation of in organic matter (Haug, 1993). Aerobic composting refers to composting treatment with the presence of oxygen where microorganisms require oxygen for survival (Ndayegamiye and Cote, 1989). The biological decomposition of organic material in the composting process depends on maintaining the activity of decomposer microbes. The most factors that contribute to the decomposition of organic material in the composting process are described as follows:

- Aeration

According to Sanders (2001), aeration is indispensable for aerobic composting and considered as the source of oxygen. The growth of aerobic micro-organisms is limited where the supply of oxygen is not sufficient, resulting in slower decomposition. Moreover, Franceys et al. (1992) revealed that gases from the pile heap and excessive heat can be removed by aeration through perforated pipes.

The composting process needs regular control during the decomposition of organic material to ensure that factors such as ventilation may remove the overheating of the pile and reduce the moisture content (Ndayegamiye and Cote, 1989).

- Temperature

Mesophilic and thermophilic stages are the two different temperatures that are involved in the composting process where the first stage involve the temperature lesser than 35°C and the second stage involves the temperature above 50°C. The complete destruction of pathogens is achieved at the highest temperature ranging from 60-80°C (Mason &Milke, 2005).

- Moisture

To support the metabolic activity of microorganisms, it is important to use the moisture content from 35 to 60% for the composting process. The compost can become anaerobic if it contains more water and can dry if there is less water and necessary microorganisms can die (Strauss and Blumenthal, 1994). Results of practical case study done in Uganda showed that a good composting process begins with a moisture content of 40% to 60% and 15% as the moisture of final product (Niwagaba, 2009).

- pH Control

The pH needed for the growth of bacteria is ranged between 6.0 to 8.0. The nitrogen concentration is lost through volatilization of molecular ammonia when the pH goes up to 9.0; the microorganisms cannot survive when the pH is in the range less than 5.0, and this is very acidic (Lopez, 2002). In some cases, pH may reflect process malfunction; if, for example, however, the composting will turn anaerobic if the pH decrease to 4.5 owing to the accumulation of organic acids. At the pH range of 7.0, the composting process approaches stability shifts toward neutrality (Letitia et al; 1999).

- Nutrients

Microorganisms need to use major nutrients of organic matter for their survival. During the decomposition process, microorganisms use Nitrogen (N) to produce protein and use Carbon (C) for their energy (Murphy, 1990). Thus, the C:N carbon ratio between 25:1 and 30:1 is required for raw materials to decompose faster. If this ratio is over than that required the raw material will take long to decompose and can result in odour problem (Liang et al., 2004). The table below gives the Nitrogen level and the ratio of C:N in the wastes.

Table 2.5: Nutrient level within the wastes (adapted from Liang et al., 2004)

Waste	Nitrogen	Carbon
Fish scraps	6.5 - 10	5.1
Fruits waste	1.5	35
Kitchen waste	6.5 - 10	40 - 100
Garden soil	10	500 - 750
Vegetables wastes	2.4 – 4	11 – 12
Sawdust	5	200 - 500
Human faeces	5 -10	50 - 100

b) Anaerobic composting

Anaerobic composting refers to composting without air and results in fermentation where microorganisms cannot function in the presence of oxygen (Miller, 1993). Anaerobic composts create the awful smell within the composting process and there are very slow working bacteria and growth; thus, the compost may take years to break down (Baker, 1997).

The advantage of anaerobic compost is that it is less labor-intensive, the levels of oxygen are limited, and it does not require turning of the pile. In anaerobic composting, the biodegradable materials are converted to produce methane gas (CH_4) and other gases such as hydrogen sulfide (H_2S) which smell like rotten eggs (Franceys et al., 1992).

c) Vermicomposting

Sanders (2001) defined Vermicomposting as a heterogeneous mixture of organic materials such as vegetable, food waste with earthworm worms called white worms and red worms. These species of worm breakdown the organic matter in the confines that can be made up in old plastic container or metal container.

2.6.2 Mechanisms of composting treatment methods

According to Marylin et al. (2005), many traditional composting treatment methods are used throughout the world, but the most acceptable, simple and commonly used are Co-composting, Skyloo-composting and Bio-process composting. The following overview highlights the working principles, favourable conditions of parameters to deal with and efficient decomposition of the methods used. It also discusses the strength and weaknesses of each system as well as typical application by Niwagaba (2009).

2.6.2.1 Co-composting (Aerobic)

Following the studies by Kone& Strauss (2004) and Niwagaba (2009), Co-composting can start with the mixture of desiccated faeces to food waste and sawdust under aerobic conditions. At the beginning of the process, oxygen plays the important role for the microorganisms to decompose the organic materials with the following:

a) Favourable conditions (Niwagaba, 2009)

- Oxygen and aeration: microorganisms need oxygen and aeration to survive.

The chemical equation of the composting process is presented as follows:

Glucose + Oxygen = Carbon Dioxide+water +Energy

$C_6H_{12}O_6 + 6O_2 = 6C0_2 + 6H_2O + Energy$ (1)

- Moisture content: Moisture content is expected in the range of 40-60%
- pH: 4.5-7.5
- C:N ratio: The C:N ratio of the material should be from 20:1 to 30:1
- Temperature: The temperature should be in the range of: ambient temperature (mesophilic range): 20-40^{o}C and progresses to and through a thermophilic phase (above 55^{o}C), followed by a descent to the mesophilic level.

b) Strength and weaknesses of the system (Niwagaba, 2009)

- Efficient decomposition: Ninety percent of degradation of organic matter in 42 days. Key operations consisted of the mixing of organic material, the sprinkling of water and the turning frequency.

- Strength: high destruction of pathogens and increased level of nutrients NPK. The process allows inactivating excreted pathogens considerably and to achieve a reasonably safe “compost” at a short time period.

- Weaknesses: nitrogen losses during thermophilic composting which requires frequency turning.

Typical application: the pilot co-composting scheme was successfully implemented in Uganda, Ghana, Zimbabwe and many other developing countries including China, Vietnam and Japan.

2.6.2.2 Skyloo-composting (Anaerobic)

The Skyloo-composting is the scale composting treatment done in Zimbabwe. The study by Morgan (2003) revealed the system entails digging the pit, the size of which may vary depending on amount of waste. Garden soil was used on top of organic material that was filled in the pit to avoid smells. The living microorganisms grow in the absence of oxygen, producing energy for themselves through the process of fermentation (Sanders, 2001).

a) Design and material of Skyloo - composting

Human faeces are mixed with kitchen food scraps for the lab-scale of aerobic composting using a 44 x 34 x39 cm^3 bucket. The materials used for the composting were properly mixed in the plastic bucket and allowed to decompose for five weeks (Morgan, 2003).

- Fermentation: The living organisms grow in the absence of oxygen, producing energy through the process of fermentation.
- Reduction of nitrogen: nitrogen is transformed to organic acids and ammonia gas. Carbon that is released from organic mainly produces the Methane gas (CH_4) and Hydrogen sulfide (H_2S).

The chemical equation of the process is presented as follows:

Carbon Dioxide + Hydrogen = Methane + Water

$CO_2 + 4H_2 = CH_4 + 2H_2O$ (2)

b) Favourable conditions (Morgan, 2003)

- Carbon to nitrogen ratio: when mixing material, the C:N ratio have to reach 20:1 to 30:1
- Moisture content: 70% to 90% moisture is needed.
- pH: 4.5-12, very high pH due to addition of sawdust and fermentation.
- Temperature: the highest is in the range of 50-60 due to the absence of oxygen and no turning of pile.
- Time: the quality compost should be accomplished within three to six months.

c) Strength and weaknesses of each system

- Efficient decomposition: 90% of degradation of organic matter.
- Strengths: with low level of temperature, anaerobic composting has a capability of killing pathogens at 99%.

- Weaknesses: no clear design guidelines available and odour nuisance. Length of time is too long.

2.6.2.3 Bio-process composting

Mane et al. (2009) defined Bio-process composting as a decomposition of recycled plant matter for agricultural application. Bio-process composting contains rich nutrients and is mainly made up with holes around the bucket for aeration to reduce excess moisture in the system.

Mane et al. (2009) experienced the use of human faeces mixed to the kitchen food scraps, fruit wastes and dead leaves for the lab-scale of aerobic composting using a 44 x 34 x39 cm^3bucket. The materials used for the composting were properly mixed in the plastic bucket and the composter was also provided with proper aeration and allowed to decompose for five weeks.

a) Favourable conditions (Mane et al., 2009)

- Temperature

The different temperatures during decomposing of materials for the composting process were maintained between 40-60^oC

- Aeration

Aeration was the important parameter provided for the aerobic organisms, supplied by turning or mixing of organic material periodically to ensure homogeneity in the system. This also helped remove any excess moisture and gases in the system. In addition, aeration was maintained through piping system into the pile.

- Moisture content

The moisture content of the compost was determined weekly and adequate quantities of water (500ml to 1000ml) were sprinkled during the composting process for maintaining the moisture content. The percentage moisture content of composting materials ranged from 40% to 60%.

- pH

The pH of the decomposing materials was between 6.37 and 7.55. The pH of the compost was 7.4(slightly alkaline).

b) Operation and maintenance requirements

The operation and maintenance of small treatments systems do not require skilled operators and the design is not expensive (Mane et al., 2009). The Bio-process composting may produce odour if not properly managed and may become inhibited when the moisture content is below 40%.

During the operation process, the moisture content tends to its diminution with high level of temperatures and presence of oxygen. However, sufficient water should be added to the heat pile. If water is not released from the compost pile, this may result in anaerobic composting (Mukama, 2006).

c) Practical performance of Bio-process composting

The efficiency of the Bio-process composting depends on the condition and quality of end product; a well-designed and well-operated aerobic composting should be able to produce compost of good quality (Sanders, 2001).

Very promising results have been observed from different studies on the Bio-process composting of human faeces with the thermophilic temperatures (over 55^{o}C) which are desirable in the composting materials and come up with pathogens destruction efficiencies of more than 90% of weed seeds and fly larvae (Andy, 2000).

The performance of Bio-process composting of human faeces depends strongly on the environmental factors such as temperature, pH, nutrients, and toxicants (Wang, 1994).

2.6.3 Different composing methods

Winblad et al. (2004) confirmed that the three main categories of composing methods are namely Windrows composting, Aerated static composting; and In-vessel composting. Each of these categories has its working principles, described as follows:

2.6.3.1 Windrows composting

Windrow composting has a design of triangular shape and a little longer row of about 5m. The operation of the system comes forth by rotation frequency and allows the penetration of oxygen in the raw material. The rotation of this material favours a good mixing of the waste, where the

outer part replace the inner part each other in the system for the mixing of materials (Winblad et al.; 2004).

Windrow composting is carried out in piles of 2-3 metres high, 3-5 metres wide and up to a hundred metres long so as to keep the temperatures high and also allow some oxygen flow to the centre core All conditions must be met to enable the production of microorganisms to survive freely in the system (Beck-friis et al., 2003).

2.6.3.2 Aerated Static composting

The aerated static composting is the method, which air is injected or forced into the raw material through perforated pipes. The perforated pipes play a more important role of turning the heap pile with a necessary temperature for the aeration of the pile in the system. The agitation of raw material is done with appropriate machines that dispense a good amount of oxygen into the system allowing better running of the process (Miller, 1993).

2.6.3.3 In-vessel composting

In-vessel composting refers to a system where a 4m rotary drum is used, and is called chemical reactor because the system is capable of providing oxygen and moisture trough the composting process. The air is blown in the system while same drum from turns the pile after making 1tour to 10 revolutions per minute to speed up the composting process (Van Haaren, Nantucket trip notes, 2009).

When the rotary drum rotates, the material start also to decompose after 6 days and get to final quality product for at least 2 months (Mels et al.; 2010).

2.6.3.4 Choice of the three composting methods

The three composting treatment methods were chosen with regard to desiccated human faeces produced by the MobiSan facility taking into account of criteria suggested by Ritz as presented below (2001); Morgan (2003) and Mane et al.; (2009).

Ritz (2001) and Niwagaba (2009), suggested that a useful and safe end-product is generated through the composting methods that may combine nutrients and organic material. The choice of a good composting should include the following criteria:

- The concept design is simple

- Can be built with local materials
- A great benefit in the settlement and availability of mixing materials
- Agriculture and food production are provided with local materials
- Total destruction of helminth eggs (< 1 egg viable egg/g TS)
- Maintenance and operation is low cost.

2.6.4 Design and principles of selected composting methods

2.6.4.1 Co-Composting method

Three perforated barrels of 200 litres were used for the composting process as showed in figure below. Each barrel was covered with a cone lid to protect the pile from rainwater and other domestic animals into the barrel (Ritz, 2001).

According to Niwagaba (2009), he confirmed that wastes in the container have to be mixed on a regular basis with frequent turning to provide aerobic bacteria within the system. Sundberg (2005) also suggested that the oxygen is much needed into the container for the survival of microorganisms to speed up the decomposition of organic materials. High temperatures, from 32º to 60ºC can be achieved when the pile is turned for every 5-10 days.

Moisture content is of great importance for the microbial life and a steady decomposition of the pile is periodically seen within the right range of 20-50%. Thus, when the material gets dry within the composter, enough water should be added to protect aerobic conditions. The end quality product can be identified with slow down decomposition process and black colour of material in the composter (Niwagaba, 2009).

Figure 2-6: The experimental view of Co-composting (Rytz, 2001)

2.6.4.2 Skyloo Composting method

30 litres of plastic bucket that contains human faeces was fitted inside of the single small vault with dimensions1.35m long x 0.9m wide x 60m deep, made of bricks and cement mortar. The bucket was collected when it was full, from this vault built above the ground. Thus, the bucket and its contents were transferred to a “secondary composting site” for further treatment (Morgan, 2003).

The organic materials used for composting were mixed with organic vegetables in the 30 litres steel bucket and buried half way in the ground as showed in the figure below. The bottom of the bucket was perforated with holes to allow worms from garden soil to pass through the bucket, while the top layer of the bucket was added also with garden soil. The Skyloo composting doesn’t require a turning of material once the pile is formed. The process was outdoors during the fermentation of material for 6 to 8 weeks (Morgan, 2003).

The same method was experienced again by Morgan (2003) by digging a pit (100 cm long x 100 cm wide x 90 cm deep) where desiccated faeces was mixed with different kinds of organic residues. Thereafter turning of pile, the pit was buried with organic soil for a period of 2 to 3 months. The decomposition of organic material is faster with the absence of oxygen, where the fermentation of the pile is also developed by anaerobic conditions under a moisture content that produce odour in the fully closed composter.

Figure 2-7: The experimental view of Skyloo-composting (Morgan, 2003).

2.6.4.3 Bio-process Composting method

A rotating composting drum had the capacity of 60 litres and was used for the composting treatment of organic waste which consists of vegetables like cabbage, flower, potato, tomato, fruits like pineapple and lastly desiccated human faeces. In addition, charcoal powered was also added to ensure that the faecal matter remains dry and to keep it free from flies. (Mane et al.; 2009)

The Bio-composting process is focused on breaking down the organic materials by frequency turning using a mixture device placed within the pile. The variability of temperature in the rotating drum allow the process to start with fast biodegradation of waste and efforts are made to maintain temperatures above 40º to 60º C. The composting process may take anywhere from 4 to 6 weeks to get matured (Mane et al.; 2009).The 60 litres drum composter for the experiments was hinged on a wooden stand as presented in the figure below.

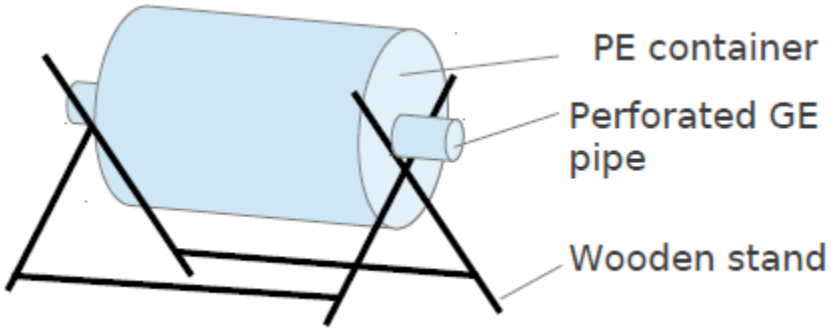

Figure 2-8: The experimental view of Bio-process composting (Mane et al.; 2009).

2.6.5 Summary of the three selected composting methods

Table below 2-6 presents the composting process as the second method that can combine desiccated human faeces with other organic materials. The composting process is achieved by controlling physical factors such as temperature, pH; moisture content and aeration. The decomposition of materials within the process is characterised with variability of temperature that include:

- Ambient temperature range from 0ºC to 20ºC.
- Mesophilic temperature range from 20-40ºC, for survival of microorganisms
- Thermophilic temperature takes place over 65ºC, microorganisms are eliminated

The temperature of Skyloo composting depends on changes in the climate, as shown in the table below. The designer found the temperature was lower than anticipated, and may be

attributed to the wet condition of the soil due to rainfall. A study undertaken by Tchobanoglous and Franclin (2003) confirmed that anaerobic composting is a low-temperature process, mostly operated in the range between 20-40^{o}C.

Table 2.6: Enhancement of human faeces according to various authors (adapted from Sanders, 2001)

Design of the composting methods			
	Co-composting	Skyloo composting	Bio-process composting
Case study:	Uganda, Kampala by Niwagaba, 2009	Zimbabwe by Morgan, 2004	India by Mane et al., 2009
1st Treatment	UDT	UDT	UDT
2nd Treatment (composting + combination of organic materials)	• Kitchen waste • Sawdust	• Raw vegetables • Garden soil	• Organic waste: (cabbage, potatoes; tomatoes and pineapples) • Charcoal powder(Biochar)
Parameters	***0perational Design***		
Temperature Mesophilic: Thermophilic:	 20-40^{o}C 40- 65^{o}C	 10-20^{o}C 25-37^{o}C	 20-40^{o}C 40- 65^{o}C
Moisture content	40-60%	70-95%	40-60%
pH	4.5-7.5	4.5-12	4.5-7.5
Carbon ration C:N	20:1 to 30:1	20:1 to 30:1	20:1 to 30:1
Oxygen	>10 mg/l no limitation	No oxygen	>10 mg/l limitation
Gas produced	NH_3	CO_2; H_2S; CH_4 (Fermentation)	NH_3
Frequency Turning	Yes	No Turning	Yes
Nutrient (NPK)	Enhanced	enhanced	Enhanced
Odor	Yes or not	Yes	Yes or not
pathogens destruction	80-95%	80-85%	80-95%
Duration	6 weeks	8 weeks or more	6 weeks

2.7 Guidelines for the use of human faeces in agriculture

Guidelines that are recommended for the use of human excreta in agriculture are presented as follows:

The WHO (2006) stated that the quality of the human faeces used in agriculture should comply with the legal requirements presented in regulations and guidelines. The compliance with these regulations and guidelines is meant to ensure safe use of human excreta, both with regard to the receiving environment and to the humans that might be in contact with human excreta, either during application, when using plants that were human excreta-fertilised, or when they come in contact with the receiving environment. Guidelines for the characteristics of human faeces are described as follows:

2.7.1Physical characteristics

Table 2.6 gives the recommended storage temperatures for dry excreta, temperatures that are effective in destroying bacteria and pathogens in human excreta (WHO, 2006).

Table 2.7: Recommendations on the storage of human faeces (WHO, 2006)

Treatment	Criteria	Comment
Storage: ambient temperature 2-20^{0}C	1.5 – 2 years	• Pathogens and bacteria are destroyed • Faecal coliform and E. coli are reduced • Viruses and parasitic protozoa are lower risk levels.
Storage: ambient temperature > 20 – 35^{0}C	>1 year	• Bacteria and protozoa are inactivated • Viruses and schistosome eggs (< 1 month) are inactivated. • Ascaris eggs (> or = 4 months) are inactivated
Alkaline treatment	pH > 9 during > 6 months	• Higher temperatures above 35^{0}C, Moisture content less than 20%, and lower pH can eliminate pathogens

2.7.2 Chemical characteristics

The important chemicals in human faeces that are required for plant production are nutrients N, P, and K. If nutrients are available and other conditions are favourable, bacteria may grow in the environment. The high level of nutrients in human faeces is attributed to the fact that it is a better source of N, K and P for plants production (Schonning e*t al.,* 2004). The table below presents the minimum application level needed to maintain fertility in agriculture.

Table 2.8: NPK nutrients level of different crops (adapted from Swedish Food Authority, 2004)

Crop	Water content %	Nitrogen (%)	Phosphorus %	Potassium %
Maize dry	10	15.1	6.8	4.6
Maize fresh	69	12.6	7.4	5.3
Millet	14	18.5	7.2	5.2
Rice unpolished	12	14	6.4	4.6
Sorghum	14	18	7.5	4.8
Green beans	90	4.7	3.7	2.6
Irish potatoes	80	6.3	5.2	3.5
Lentils dry	20	38.4	16.5	12.5
Onions	91	8.9	6.6	5.3
Pumpkin	95	5.3	4.4	2.6
Spinach	94	7.5	3.9	4.9
Tomatoes	92	6.3	4.2	3.1
White cabbage	94	6.1	3.2	2.5

2.7.3 Microbiological characteristics

Microbiological characteristics are the most critical parameters considered in terms of safety of human excreta. The WHO (2006) gives a guide as to the values or amounts of bacteria that human excreta may contain for it to be safe for use in agriculture, as per Table 2.9.The guideline values show that treated faeces should contain very low levels of E. coli.

Table 2.9: Guidelines of faecal matter for use in agriculture (adapted from WHO, 2006)

Helminth eggs (number of E.coli)		
Treated faeces	<1/g total solids	<1000 g/total solids
For crops	<1/g	$<10^3$ Relaxed to $<10^4$ for high-growth leaf crops

2.8 Summary

It is obvious from this review that human faeces are a major source of plant nutrients in the form of nitrogen (N), phosphorous (P) and potassium (K).The concentration of nutrients in human faeces depends mostly on diet; age and society. Human faeces contains large amount of nutrients able to fertilise the soil for agricultural purposes.

The literature review suggests that each country has its own standards for using human faeces in agriculture. The use of human faeces in agriculture is restricted and a number of considerations in terms of environmental pollution and human health need to be observed. The most common parameter referred to is the presence of pathogenic organisms (E. coli, faecal coliform, salmonella, ascaris, etc.). Standard limits ranges according to WHO (2006) are presented as follows:

- ✓ Temperature of storage: 40-60^{o}C, complete inactivation of bacteria, ascaris, protozoa, etc.
- ✓ pH: a level of 9 will prolong the time for absolute elimination of organisms.
- ✓ Faecal Coliform: a concentration of 10^3 per 100 ml is required.

Several methods are used for the treatment of human faeces worldwide, but most were found to be of limited utility to enhance the fertilising value. Composting of desiccated human faeces is preferable, due to fewer problems encountered with urine diversion toilets. However, the composting process is an effective secondary treatment method capable of rendering faeces safe for re-use in agriculture, with high degradation of organic materials under the controlled conditions of factors such as pH, moisture content, temperature and aeration.

Chapter 3: Experimental work

3.1 Introduction

This chapter deals with the research design and methodology. The materials and methods used for the collection of data needed to meet the objectives of the study are discussed in this chapter. The description of laboratory instruments and apparatus used is included. In addition, the chapter contains a description of the experimental methodology and analytical procedures used to analyse the important quality parameters of desiccated human faeces from the MobiSan facility.

The chapter is divided into five sections: 1) the research design; 2) the materials and equipment used to conduct the study; 3) the research methodology that describes the type of data needed; 4)the methods of collecting data and analytical procedures; and 5) the presentation of results and how results were analysed in order to achieve the study objectives.

3.2 Research design

The study is designed in line with the objectives of the study, which were discussed in Chapter One. The work is subdivided as follows:

- *Literature review:* an overview of literature consulted was presented and relevant information pertaining to this study was discussed. This section of the study presents a literature review covering desiccated human faeces and its composting methods. In addition, sampling and testing methods and quality standards applicable to the South African context and standards recommended by the World Health Organisation (WHO) are included.

- *Experimental work*: consisting mainly of constructing, mounting and setting up the lab-scale composting and monitoring of control parameters in the field.

- *Laboratory experiments:* consisting of collecting samples and conducting analysis for the selected quality parameters in the laboratory.

- *Analysis and comparison of data* to the previous literature.

3.3 Equipment and materials

3.3.1 Equipment

The equipment used for the study was selected based on the specific need for achieving the objectives set, and equipment available in the laboratory. Each parameter analysed required specific equipment for its analysis. Some of the equipment used included a thermometer, oxygen meter, pH meter, weighing scale, autoclave, sampling bottles (glass and plastic), storage tanks and an electric oven. The purpose of each piece of equipment is described as follows:

- Composter*:* plastic buckets of 30 litres were used for the experiment of the lab-scale co-composting, Skyloo composting and bio-process composting presented in figure 3.1, 3.2 and 3.3.
- Garden sprayer: used to sprinkle water in the lab-scales composting.
- Sampling bottles: 150 ml plastic bottles were used for the collection of samples.
- Thermometer*:* the temperature of the compost was measured using a mercury thermometer graduated in degrees centigrade.
- Oxygen meter: used to measure the concentration of oxygen in the composter.
- pH meter*:* used to measure the level of acidity or alkalinity of microorganisms' activity in the human faeces and in the composting lab-scales.
- Weighing scale and autoclave*:* used in the laboratory to weigh reagents and incubate solutions needed for analysis.
- Electric oven*:* used to determine the moisture content of a sample dried at 105^{o}C until constant weight in the laboratory.

3.3.2 Material

For the purpose of this study, three lab-scales composting experiments were built and installed at the Cape Peninsula University of Technology in order to allow a specific control, and to ensure normal working conditions. The three lab-scales were designed based on existing design features presented below in the section dealing with design and description.

3.3.2.1 Selection of the three composting methods

The three composting methods were selected with regard to desiccated human faeces produced by the MobiSan facility. The composting technology may be considered as being for the settlement for the following reasons:

- ✓ Simple methods;
- ✓ Low O&M costs;
- ✓ Use of locally available materials;
- ✓ No energy needed to treat human faeces; and
- ✓ Safety of the land and water from 'leachate' during rainy season.

In this context, it was hypothesised that the application of the three composting methods could provide the local community with work opportunities and improved soil fertility for subsistence farmers unable to purchase chemical fertilisers. Based on the above criteria, the choice of the three composting technologies was considered adequate for dealing with desiccated human faeces produced by the MobiSan facility, using pilot lab-scales composting.

3.3.2.2 Description and design of lab-scales composting

The composting method is the controlled aerobic degradation of organic material using more than one material (faecal matter and organic solid waste). Faecal matter has a high moisture and nitrogen content, while biodegradable solid waste is high in organic carbon and has good bulking properties. Therefore, the following materials for the lab-scale were used:

a) Co-composting method

- **Materials**:

A 30-litre bucket was used with10kg of desiccated human faeces from the MobiSan facility. 15kg of food waste and 3kg of sawdust were mixed within the bucket while sprinkling water. The plastic bucket was covered with a lid to protect the pile from intrusion by animals or rainwater. Aeration was provided within the bucket trough by perforated holes of 10mm around the bucket and a perforated pipe was inserted at the bottom to release leachate from the pile.

Moisture content of the pile was measured through the insertion of the blue pipe placed vertically on top of the plastic bucket, as shown in the figure below.

Figure 3.1: View of Co-composting design

b) Skyloo composting

- **Materials**

Twenty litres of human faeces in a plastic bucket was added to raw vegetable and fruit wastes. After filling the material in, the bucket was buried part way into the ground. The plastic bucket was designed with perforated holes of 10 mm at the bottom of the bucket for microorganisms to pass through from organic soil into the composter. A layer of two litres of garden soil was added on top of the materials in order to control odours. This was covered with a lid to make it virtually impossible for any pest to gain access to the composter.

Figure 3.2: View of Skyloo-composting design

c) Bio- process composting

- **Materials**:

The bio-process composting lab-scale was designed with a plastic bucket with a top diameter of 44cm, a bottom diameter of 34cm and a height of 60cm.

The plastic bucket had a capacity of 30 litres and was used for the composting treatment of organic waste consisting of vegetables like cabbage, flower, potato, tomato, fruits like pineapple and, lastly, desiccated human faeces. The materials used for the composting were mixed in the plastic bucket using a turning device placed in the pile. Aeration was provided with a pipe placed on both sides of the container and holes at the longitudinal side of the drum at the bottom.

Figure 3.3: View of Bio-process composting design

3.3.3 Layout of the lab-scales composting methods

For the purpose of this study it was decided to design the lab-scales of the three composting treatments (co-composting, Skyloo-Composting and bio-process composting) based on suggestions made by their designers. The lab-scales for the three composting treatments investigated consisted of the following:

a) Co-composting (Aerobic composting)

- **Plastic container:** a 30 litre container was provided with holes for aeration.

- **Sampling point:** horizontal pipes inserted to the middle of container for measuring the temperature and vertical pipe inserted on the top of composter for the collection of moisture content.
- **Thermometer probe:** measured through probes inserted into the pile.
- **Drainage pipe**: a perforated pipe, 20mm diameter and 3cm long, inserted at the bottom as the drainage is then ensured the correct moisture level.
- **Lid**: provided to protect the pile from excessive rainfall and direct sunlight to prevent drying out of material.

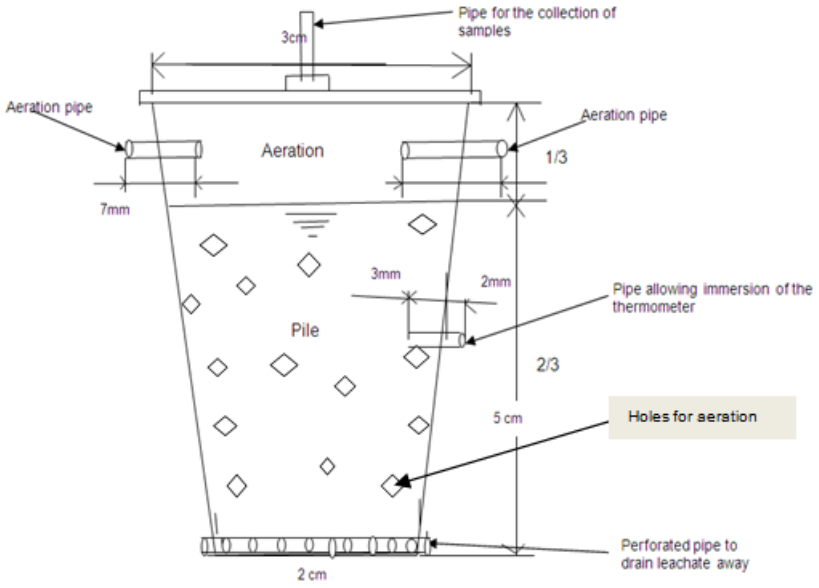

Figure 3-4: Schematic representation of Co-composting

b) Skyloo- Composting (Anaerobic composting)

- **Plastic container:** a 30 litre container was half-buried in the organic soil with perforated holes at the bottom allowing the penetration of microorganisms from the soil into the pile.
- **Thermometer probe**: a pipe, 20mm in diameter and 5mm long, inserted at one side of the bucket in the middle of the pile, allowing for the immersion of the thermometer.
- **Sampling point**: horizontal pipes inserted inthe middle of the container for measuring the temperature and a vertical pipe inserted on the top of the composter for the collection of moisture content readings.
- **Garden soil**: added on top of the pile.
- **Lid**: provided to protect the pile from excessive rainfall and direct sunlight.

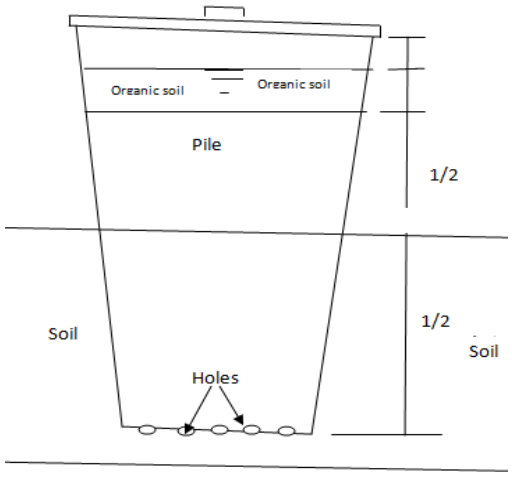

Figure 3-5: Schematic representation of Skyloo-composting

c) Bio-process composting (Aerobic composting)

- **Plastic container:** a 30 litre container was provided as a drum, with holes at the bottom to release the leachate from the pile. The container was manually turned for the mixing of organic matter.
- **Aeration pipe**: two pieces of pipe, 20mm diameter and 7mm long, each used at the top level of the plastic bucket for aeration in the pile.
- **Thermometer probe:** a pipe, 20mm diameter and 5mm long, inserted at one side of the bucket in the middle of the pile, allowing the immersion of the thermometer.
- **Sampling point:** horizontal pipes inserted in the middle of the container for measuring the temperature and a vertical pipe inserted on the top of composter for the collection of moisture content readings.
- **Turning device:** is a manually-operated device allowing the mixture of materials.

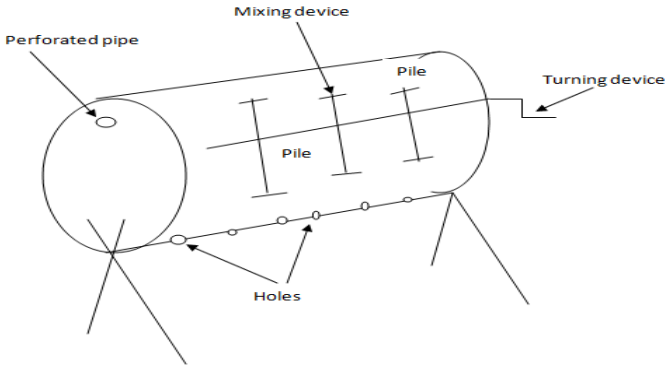

Figure 3-6: Schematic representation of Bio-process-composting

3.4 Research methodology

The research methodology defined the type of data needed to achieve the aim of the study and methods that were used to collect data. This section further describes how analytical procedures were conducted, how data were analysed and how results were presented in order to extract the required meaning.

3.4.1 Data required

In order to meet the study objectives, quality parameters were selected, namely: pH, temperature, moisture content, oxygen, carbon, nitrogen, phosphorus, potassium, E. coli and faecal coliform. These parameters were selected based on their fertilising values and health impact in soil and include the following:

- Temperature, pH, and moisture content were measured as they are considered factors that influence survival and die-off of microorganisms in human faeces.
- Oxygen and carbon were measured as they are considered a source of energy to microorganisms in composting.
- Nitrogen (N), phosphorus (P), and potassium (K) were measured, as they are known essential organic nutrients in human faeces; and
- Faecal coliform and E. coli were measured, as they are considered indicators of pollution in human faeces.

3.4.2 Data collection methods

Data needed for the purpose of the study was collected in the following ways:

3.4.2.1 Collection of desiccated human faeces

Desiccated human faeces were collected in plastic bags from the MobiSan facility using spades. Desiccated faeces were taken while the workers of the City of Cape Town were emptying the MobiSan chamber when full. Desiccated human faeces samples were collected twice over a period of three weeks before starting the actual tests involved in the study, in order to identify the trends. Sterilised bottles were used to collect samples and were analysed on site and in the laboratory the same day they were collected, in order to establish the characteristics of human faeces. Samples were analysed for parameters such as pH, temperature, moisture content, oxygen, carbon, nitrogen, phosphorus, potassium, E. coli and faecal coliform.

Figure 3.7: Collection of desiccated human faeces from MobiSan facility

3.4.2.2 Feeding regime of the lab-scales

80kg of desiccated human faeces was collected and fed into the plastic container using spades in order to conduct the lab-scales of the three composting methods. Desiccated human faeces were mixed with organic solid wastes for each lab-scale composting used. Liang et al., (2004) confirmed that the carbon ratio (C/N) of materials mixed should be known when composting. A C:N carbon ratio between 25:1 and 30:1 is required for raw materials to decompose faster. If this ratio is exceeded, the raw material will take longer to decompose. Therefore; the rate of (C/N) for the materials added was required to be known. The rate was calculated from values of nitrogen and carbon concentration in Table 2.10 as follows:

a) Co-composting

The carbon ratio of co-composting was calculated using the formula in chapter 2, equation (2.1).

Feeding 1: 20 kg of human faeces

Literature gives the range of N and Carbon between:

N= 5.0 – 7.0

C= 50 - 100

Feeding 2: 3kg of kitchen waste

Literature gives the range of N and Carbon between:

N= 6.5 – 10

C= 40 - 100

Feeding 3: 3kg of Sawdust

Literature gives the range of N and Carbon between:

N = 5

C = 200– 500

C:N Ratio, Calculation using the formulae:

$$C:N = \frac{(20 \times 95) + (3 \times 95) + (3 \times 485)}{(20 \times 5) + (3 \times 6.5) + (3 \times 5)}$$

= 3640: 135 = 27:1

The C:N obtained was found in the range and conclude that the materials used can achieve the composting biodegradation.

b) Skyloo-composting

The carbon ratio of Skyloo composting was calculated using the formula in chapter 2, equation (2.1).

Feeding 1: 20 kg of human faeces

Literature gives the range of N and Carbon between:

N= 5.0 – 7.0

C= 50 – 100

Feeding 2: 3kg of raw vegetable

Literature gives the range of N and Carbon between:

N=2.5 - 4

C= 11 – 12

Feeding 3: 3kg of garden soil

Soils contain variable amounts of nutrient elements available for plant use. Literature gives the range of N and Carbon between:

N=10

C= 500 – 750

C:N Ratio

$$C:N = \frac{(20 \times 95) + (3 \times 11) + (3 \times 700)}{(20 \times 5) + (3 \times 3) + (3 \times 10)}$$

= 4033: 139= 29:1

The C:N obtained was found in the range and conclude that the materials can achieve the composting biodegradation.

c) Bio-process-composting

The carbon ratio of Bio-process composting was calculated using the same formula in chapter 2, equation (2.1) as follows:

Feeding 1: 20 kg of human faeces, literature gives the range of N and Carbon between:
N= 5.0 – 7.0
C= 50 - 100

Feeding 2: 3 kg of organic waste, literature gives the range of N and Carbon between:
N= 1.5
C= 35

Feeding 3: 3kg of Sawdust, literature gives the range of N and Carbon between:
N = 5
C = 200– 500

C:N Ratio

$$C:N = \frac{(20 \times 95) + (3 \times 35) + (3 \times 480)}{(20 \times 5) + (3 \times 1.5) + (3 \times 5)}$$
$$= 3445 : 120 = 29:1$$

The C:N obtained was found in the range and conclude that the materials used can achieve perfectly the composting biodegradation.

3.4.2.3 Favourable conditions of composting

Favourable conditions that are required for the composting process are controlled with physical factors, namely moisture content, aeration and temperature. Composting may begin as soon as desiccated faeces are mixed with organic solid waste under controlled conditions. During the initial stages of the process, the decomposition of organic materials in the composter needs to be accelerated with the presence of oxygen to allow microbiological life in the system. Oxygen in the composter is rapidly consumed by the microorganisms for their production.

Microbial activity in the composting process can be achieved by the release of energy in the form of heat. Temperature variation in the composting may speed up the process with the growth of microorganisms if the range is between 20-40^{o}C, allowing different species to survive and decompose the organic materials. Moisture content is one of the critical factors for the production of microorganism species. Thus, moisture is required to be in the range of 40% to 60%. Microorganisms are killed in the composter if the temperature exceeds the level of 65^{o}C and conditions become unfavourable for microorganisms when the moisture decreases to levels lower than 15%.

3.4.2.4 Collection of data during composting treatment

Samples of treated human faeces were collected twice per week over a period of 42 days (as per Table 3:1). For the three composting lab-scales, appropriate testing instrument were used from the beginning to the end of the experiment. Samples were analysed for parameters such as temperature, pH, oxygen, moisture content, carbon, nitrogen, phosphorus, potassium, E. coli and faecal coliform.

Plastic bottles were used for microbiological parameters and glass bottles for other parameters. Collected samples were labelled with a code indicating the day of the week, sampling number and parameters to be analysed. The temperature, oxygen and pH were measured immediately on site and the remainder of samples were taken to the laboratory and analysed for the same parameters selected. The following Table 3.2 presents sampling procedures as recommended by Mane et al. (2009), where samples should be collected once a week over a period of 42 days.

Table 3.2: Sampling and testing schedule of composting

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Days:	1-7th	8-14th	15-21st	22-28th	29-35th	36-42nd
Samples	S1	S2	S3	S4	S5	S6

3.4.2.5 Monitoring of the lab-scales

Monitoring of the lab-scales composting was very important to ensure optimal conditions of the composting process. This was achieved by measuring control parameters such as temperature, oxygen and moisture content daily in the morning. Therefore, these parameters were monitored daily using appropriate instruments as indicated in Table 3.4 from the beginning until the end of experimental work. These three parameters were always recorded after measurement and the pile was turned regularly. Periodic turning of the pile was undertaken if the temperature of the pile was recorded as being high.

A sufficient amount of water was added to the composter if moisture content was found to be reduced. Regular turning of the pile allowed for the reduction of temperature and freeing up of oxygen in the composter. The pile was occasionally turned when the pile temperature started to drop. The following table presents how the parameters were recorded (x) three times per week during the duration of the experiment.

Table 3.3: Monitoring of the lab-scales (adapted from Mane *et al*., 2009)

	Week 1			Week 2			Week 3			Week 4			Week 5			Week 6		
Days:	1-7th			8-14th			15-21st			22-28th			29-35th			36-42nd		
Period:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Temperature (°C)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Oxygen (%) or (aeration)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Moisture content (%)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

3.5 Analytical procedures

The selected parameters were analysed using relevant methods, as recommended by the South African National Standard regulations. Relevant methods such as the membrane filter method were used for microbial analysis and methods such as Inductively Coupled Plasma and the micro-Kjeldahl method were used for chemical analysis, as presented in Table 3.4.

Samples collected were analysed for the parameters indicated previously. If the remainder of the samples could not be analysed immediately, the samples were stored at 4°C until further analysis of other parameters could be conducted. Details of analytical procedures for each parameter analysed are described in Appendix A.

Table 3.4: Measurement method and analytical procedures

Parameters	**Measurement method**	**Analytical procedures**
Temperature	standard thermometer	Use of digital thermometer
Oxygen	Oxygen meter	Use of digital Oxygen meter
pH	pH meter	Use of pH meter Hanna HI 98102.
Moisture content	Gravimetric method	Use of an electric oven at 105°C
Carbon	Loss-On-Ignition (LOI)	Use of Loss-On-Ignition (LOI) method
Nitrogen	Colorimetric	Use of Ultraviolet colorimetric screening method
Phosphorus	Colorimetric	Use of Inductively Coupled Plasma- AES
Potassium	Colorimetric	Use of Inductively Coupled Plasma- AES
E. coli	Test paper	Membrane filter method SANS 5221: 2007
Faecal Coliform	Test paper	Membrane filter method SANS 5221: 2007

3.6 Methodology

In order to meet the study's objectives, the methodology was consistent with the following steps:

3.6.1 Determination of characteristics of human faeces

The characteristics of desiccated human faeces produced by the MobiSan facility were determined to assess the fertilising value and understand its proper application in agriculture.
Samples of desiccated human faeces were collected on a biweekly basis and taken to the laboratory for analysis over a period of six months. The characteristics of desiccated human faeces collected from the MobiSan facility were determined by sampling and testing relevant parameters namely: pH, temperature, oxygen, moisture content, carbon (C), nitrogen (N), phosphorus (P), potassium, (K) faecal coliform and E. coli.

Following this, pH, temperature, oxygen, moisture content and carbon (C), were analysed, as they are parameters contributing to the decomposition of human faeces. Nitrogen (N), phosphorus (P), and potassium (K) were also analysed, as they are considered as essential organic nutrients for plant production. Faecal coliform and E. coli levels were analysed, as they are indicators of human contamination. These parameters were determined as per the analytical procedure presented in Table 3.4

3.6.2 Comparison of characteristics of human faeces to agricultural standards

The characteristics of desiccated human faeces produced by the MobiSan facility were compared to agricultural standards in order to assess compliance for safe use. The characteristics of desiccated human faeces obtained from analysis were compared to agricultural standards, which are the results obtained from previous research focusing mainly in the fertilising value of the relevant parameters of Nitrogen (N), Phosphorus (P), and Potassium (K).

3.6.3 Investigating the three composting methods

Knowing that the characteristics of desiccated human faeces from MobiSan had a very low fertilising value when compared to the agricultural standards, the study was further investigating three composting method namely Co-composting, Skyloo-composting and Bio-process composting in order to determine their ability to enhance the fertilising value of human faeces. In order to achieve this, three pilot-scale composting vessels were designed based on existing design features.

The process of each method was monitored in accordance with recommendations made in the available literature. Samples of composted human faeces were collected from the three composting vessels and were analysed for the same parameters named above.

3.6.4 Comparison of the three composting methods

Results obtained from the three composting vessels were compared in terms of their efficacy in treating desiccated human faeces from a mobile sanitation facility (MobiSan). This allowed the researcher to determine the most suitable treatment method that fit to the MobiSan context and comply with standards for use in agriculture. Based on the results obtained from the comparison, one of the three composting treatment method was selected to provide an indication in enhancing the fertilising value of the desiccated human faeces from MobiSan facility, and improve also the reduction of pathogens in composting process that could make the compost safe for agricultural application.

3.7 Manning of lab-scales and Operating process

For the purpose of the study, the operation of the lab-scales composting presented in Figure 3.6 consisted of collecting human faeces samples from MobiSan facility into the plastic buckets. Desiccated faeces was fed into each composter of 30 litre, when filled with 20 kg approximately 2/3 volume with faeces. After feeding of desiccated human faeces in the container, the composting was to be operated according to the literature developed for the three methods, Co-composting, Skyloo-composting and Bio-process composting. The key operations of these methods consisted of the following:

a) Co-composting

- **Sprinkling of water**

Once human faeces were brought from MobiSan facility, it was filled into the plastic buckets to approximately 2/3 full. Thereafter, kitchen food and sawdust was added to human faeces for balancing the nitrogen and carbon of human faeces in order to make it blend. Then, 1000 ml of water was sprinkled over the faecal matter using garden sprayer. This was manually stirred to uniform consistency for 15 to 20 minutes to provide homogeneous mixing in the composter.

- **Turning frequency**

The frequency of turning was crucial as it was providing aeration into the pile and supplying oxygen to aerobic organisms. This turning of material in the process was on daily basis for

microorganisms to breakdown the material. The turning of the material was performed regularly when the pile temperature reaches the high level above 40^{o}C during its first week.

- **Ventilation**

The ventilation process was provided on daily basis through aeration pipes, and the periodical turning of the pile adjusted fresh air from the bottom to the top of the pile. The lab-scales composting were also provided with a perforated drainage pipe at the bottom to release heat from the system.

- **Monitoring**

Parameters of control such as temperature, oxygen and moisture content of the lab-scales were monitored and recorded three days a week with interval to allow the microbiological life and decomposition of organic matter. Thereafter, the pile was turned to allow the aeration into the system. It is important for the compost pile to reach about 60^{o}C to kill any unwanted pathogens and weed seeds and to breakdown all material properly. This was not supposed to get hotter than 70^{o}C as it can then reduce the nutrients and kill beneficial decomposer organisms.

The moisture content of the compost was maintained between 40% and 60%, and when getting dry, an adequate quantity of water (500ml to 1000ml) was sufficiently sprinkled in the compost pile to make it pliable for the microorganisms.

b) Skyloo-composting

The key operations of the method consisted of collecting human faeces and mixing it with raw vegetables. Food waste, which has high moisture content, was also mixed to desiccated faeces to make the process blend and odour prevention.

After filling the organic material in the plastic container at ¾ full, this was covered with five cm layer of garden soil and closed for 60 days to give the most recent additions a chance to decompose. There was no need of turning the pile as this was an anaerobic composting and the composter was half buried in the ground soil. The system was checked regularly (three times a week) for temperature and moisture level, to make sure that everything was going as intended.

c) Bio-process-composting

The system was operating as the same as with the co-composting method using frequency turning and controlled parameters. The organic waste mixed to desiccated faeces from MobiSan facility consisted of vegetables like cabbage, flower, potato, tomato, fruits like pineapple. The materials used for the composting were properly mixed in the plastic bucket and were aerated with pipe for a faster decomposition of organic materials, with holes as well at the bottom of the composter to release the heat.

3.8 Assessment on the performance of the three composting methods

The performance of the treatment plants was based on its capability to produce a fertiliser product from human faeces that could be used safely for plant production without any negative impact in the environment. In this study, the performance of composting treatment plant was assessed based on the following criteria:

- The feeding ratio C:N
- The treatment efficiency
- Favourable conditions
- Fertilising value
- Final results obtained

3.9 Presentation of results

3.9.1 Desiccated human faeces experimental test

Results for the first objective were collected on a spreadsheet serving as the record sheet used during the experiment of desiccated human faeces is presented in Table 3.5. The spreadsheet was prepared in order to record the necessary data from desiccated human faeces. All the necessary details of desiccated human faeces samples were first written down, as mentioned above, with parameters that needed to be determined (x) from samples shown in the first column, with the second to sixth column showing different samples collected during the experimental work.

The average of the samples is presented in the table, as the samples were collected at different times from MobiSan facility.

Table 3.5: Desiccated human faeces experimental test

Desiccated human faeces							
Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
Temperature (°C)	x	x	x	x	x	x	x
pH	x	x	x	x	x	x	x
Moisture content (%)	x	x	x	x	x	x	x
Carbon (%)	x	x	x	x	x	x	x
Nitrogen as N (%)	x	x	x	x	x	x	x
Phosphorus as P (%)	x	x	x	x	x	x	x
Potassium as K (%)	x	x	x	x	x	x	x
E-Coli (cfu/g)	x	x	x	x	x	x	x
Faecal Coliform (cfu/g)	x	x	x	x	x	x	x

3.9.2 Comparison of desiccated human faeces to agricultural standard

The results for the second objective were presented in the table and graphs below. The table consists of three columns. In the first column, quality parameters of importance in desiccated human faeces were tested and recorded (x). Averages of desiccated human faeces from the MobiSan facility were recorded in the second column and have to be compared to the agricultural standards presented in the third column in order to assess compliance for safe use.

Table 3.6: Desiccated human faeces compared to agricultural standards

Parameter	Average of desiccated human faeces	Agricultural standard
Temperature	x	x
pH	x	x
Moisture content (%)	x	x
Carbon (%)	x	x
Nitrogen (N) (%)	x	x
Phosphorus (P) (%)	x	x
Potassium (K) (%)	x	x
E-Coli (cfu/g)	x	x
FC (cfu/g)	x	x

3.9.3 Composted faeces experimental test

The third spreadsheet in the table below was prepared for recording data needed from the three lab-scales composting methods. Parameters of importance in desiccated human faeces were recorded (x) in the first column of the table. Samples collected twice per week were recorded over a period of 6 weeks and are represented from S1 to S12 in Table 3.7 for easier reading of the results. The same table was used for experimental test week 4 to week 6.

Table 3.7: Composted faeces experimental test week 1 to week 3

Parameters:	Week 1		Week 2		Week 3	
Days:	1-7th		8-14th		15-21st	
Parameters:	S1	S2	S3	S4	S5	S6
Temperature (°C)	x	x	x	x	x	x
pH	x	x	x	x	x	x
Oxygen (%)	x	x	x	x	x	x
Moisture content (%)	x	x	x	x	x	x
Carbon (%)	x	x	x	x	x	x
Nitrogen (%)	x	x	x	x	x	x
Phosphorus (%)	x	x	x	x	x	x
Potassium (%)	x	x	x	x	x	x
E Coli(cfu./g)	x	x	x	x	x	x
FC (cfu/g)	x	x	x	x	x	x

3.9.4 Comparison of the three composting methods

Results for the fourth objective are presented in Table 3.8 below, showing parameters that have to be determined for the three methods in column 1. Three different methods of composting were shown in columns 2 to 4. This table made it easier to compare the quality parameters recorded (x) in each method in order to select the parameter that best fits within the MobiSan context and complies with agricultural standards in terms of efficiency and human faeces capabilities.

Table 3.8: Comparison of the three composting methods

Parameter	*Co-composting*	*Skyloo-composting*	*Bio-process composting*
Temperature (°C)	x	x	x
pH	x	x	x
Oxygen (%)	x	x	x
Moisture cont.(%)	x	x	x
Carbon (%)	x	x	x
Nitrogen (N) (%)	x	x	x
Phosphorus (%)	x	x	x
Potassium (%)	x	x	x
E-Coli (count/g)	x	x	x
FC (count/g)	x	x	x

3.10 Analysis of results

The analysis of results was undertaken in four stages:

- *The first stage* consisted of comparing results of human faeces from MobiSan facility to the available values found in the literature in terms of nutrients NPK, in order to verify if human faeces can be also classified as fertiliser for plant production.

- *The second stage* consisted of comparing results obtained from desiccated human faeces to agricultural standards in order to assess its compliance for safe use.

- *The third stage* consisted of comparing results from different composting methods tested in order to verify the improvement of the fertilising value and compliance with agricultural standards.

- *The fourth stage* consisted of comparing results obtained from composted human faeces to available values of compost quality guidelines set for human faeces in agriculture, in order to select the most suitable method in terms of agriculture, health and environment.

Chapter 4: Results of experimental work

4.1 Introduction

4.1 Introduction

The results of experimental work conducted at the three lab-scales composting vessels are presented in this section of the study. The section presents detailed results in tabular forms for ease and readability. Additional results on the composted faeces, monitoring processes and variation in observed parameters are represented in Appendix B.

4.2 Experimental work

Experimental works was carried out using human faeces that were collected from the MobiSan facility. Results presented in this section detail the characteristics of desiccated human faeces from MobiSan facility, the comparison of desiccated human faeces to required agricultural standards; the characteristics of composted human faeces; and results of the comparison of the three composting methods.

4.2.1 Characteristics of desiccated human faeces

The physical characteristics of desiccated human faeces from the MobiSan facility were used to determine the quality of human faeces produced in order to assess the fertilising value and understand its application in agriculture. The average samples of desiccated human faeces were used in the following table in order to identify any trends, as these samples were collected from the MobiSan facility at different times. The characteristics of desiccated human faeces are summarised as follows:

Table 4.1: Characteristics of desiccated human faeces

Desiccated human faeces							
Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
Temperature (ºC)	15	16	12	15	17	18	16
pH	10.3	9.9	11.2	10.6	9.8	10.2	10.3
Moisture content (%)	15	18	13	12	10	17	14
Carbon as C (%)	52	57	55	58	52	59	56
Nitrogen as N (%)	5.1	4.2	4.5	4.8	5.2	4.5	4.7
Phosphorus as P (%)	4.7	2.6	4.3	3.6	2.1	2.8	3.4
Potassium as K (%)	2.1	1.6	1.4	1.2	1.1	1.8	1.5
E-Coli (cfu/g)	$6.6x10^3$	$5.6x10^3$	$5.8x10^3$	$5.7x10^3$	$5.3x10^3$	$6.2x10^3$	$5.9x10^3$
FC (cfu/g)	$9.8x10^3$	$6.4x10^3$	$8.8x10^3$	$7.4x10^3$	$7.2x10^3$	$7.6x10^3$	$7.8x10^3$

- Temperature

Table 4.1 shows the temperature of six samples of desiccated human faeces collected from MobiSan facility. The temperatures of desiccated human faeces varied between 12 and 18^{o}C, with an average temperature of 16^{o}C. The lowest and the highest temperatures were recorded for Sample 3 and Sample 6.

- pH

Samples of desiccated human faeces collected from the MobiSan facility during the first week of experimental work were characterised by the pH variation between 9.8 and 11.2, with an average pH of 10.3. The lowest pH value was Sample 5 and the highest was recorded from Sample 3.

- Moisture content

Table 4.1 shows the moisture content recorded in six samples of human faeces that were collected from the MobiSan facility. Results obtained showed 10% and 18%, with an average moisture content of 14%. The lowest value was recorded on Sample 5 and the highest was recorded from Sample 2.

- Carbon content

Samples of desiccated human faeces collected from the MobiSan facility during the first week of experimental work were characterised by carbon content ranging between 52 and 59%, with an average of 56%. The lowest carbon content value was Sample 1 and the highest was recorded from Sample 6.

- Nitrogen content

The concentration of nutrient observed in Table 4.1 shows the nitrogen content found in six samples of desiccated human faeces that were collected from the MobiSan facility. For the study experimentation, the concentration of nitrogen found in samples of desiccated human faeces from MobiSan was between 4.2% and 6.2%, with an average nitrogen content of 4.7%. The lowest and highest contents were observed on Samples 2 and 3 respectively.

- Phosphorus content

Table 4.1 shows the phosphorus content observed in the six samples of human faeces that were collected from the MobiSan facility. The results showed that human faeces from the

MobiSan facility have phosphorus content of between 2.1% and 4.7%, with an average phosphorus content of 3.4%. The lowest and highest contents were observed on Samples 5 and 1 respectively.

- Potassium content

The characteristics of sanitised human faeces collected from MobiSan facility show that potassium concentration among the six samples collected was between 1.1% and 2.1%, with an average potassium content of 1.5%. The lowest and highest contents were observed on Samples 5 and 1.

- E. Coli

The following values characterised desiccated human faeces collected from MobiSan facility. Results of the E. Coli population in cfu/g, that were found among the six samples of desiccated human faeces showed the lowest with $5.3x10^3$ and the highest with $6.6x10^3$cfu/g, with an average population of 5.9 $x10^3$cfu/g. The lowest and highest populations, or concentrations, were observed on Samples 5 and 1 respectively.

- Faecal Coliform

Following the analyses on desiccated human faeces characteristics, it was found that the levels of pollutant such as faecal coliform population in cfu/g were observed during the experimentation work. Results showed that the concentrations of the faecal coliform were between 6.4 $x10^3$ and $9.8x10^3$cfu/g, with an average population of $7.0x10^3$cfu/g. The lowest and highest populations were observed on Samples 2 and 1 respectively.

4.2.2 Comparison of desiccated human faeces to agricultural standard

The characteristics of desiccated human faeces obtained from analysis were compared to agricultural standard in order to assess its compliance for safe use. The fertilizing value of desiccated human faeces produced at the MobiSan facility had a very low value when compared to agricultural standards in terms of NPK and high contamination in terms of pollution indicators. Results obtained were compared to agricultural standards in the following table:

Table 4.2: Desiccated human faeces compared to agricultural standard (adapted from WRC, 2006)

Parameter	Average of desiccated human faeces	Agricultural standards	
		Limit required	Relevance
Temperature(^{o}C)	16	>50	Recommended value to eliminate pathogens
pH	10.3	>9	Recommended value to eliminate pathogens
Moisture content (%)	14	0-30%	Organisms survival decrease
		30-80%	Organisms survival increase
Carbon (%)	56	50-60	Recommended value
Nitrogen (N) (%)	4.7	>5.5	Better for crops in South Africa
		>6.0	Better for crops in Kenya
Phosphorus (P) (%)	3.4	>5.0	Better for crops in South Africa
		>4.45	Better for crops in Kenya
Potassium (K) (%)	1.5	>3.5	Better for crops in South Africa
		>2.5	Better for crops in Kenya
E-Coli (cfu/g)	$6.6x10^3$	1000	Maximum recommended value
FC (cfu/g)	$9.8x10^3$	1000	Maximum recommended value

Desiccated human faeces were compared to agricultural standards in table 4.2; and it showed apparently a very low fertilizing value with: Temperature and pH of 16^{o}C and 10.3 were recorded; the content of moisture and carbon were 14 and 56% respectively. The nutrients concentration of Nitrogen; Phosphorus and Potassium content were 4.7; 3.4 and 1.5% respectively; while e.coli and faecal coliform level was found highly pollutant to the maximum recommended value. Thus, there was need for a secondary treatment.

The study was further subjecting desiccated human faeces through various composting methods namely Co-composting, Skyloo-composting and Bio-process composting to assess and increase the fertilizing value of human faeces for agricultural application.

4.2.3 Characteristics of composted human faeces

Desiccated human faeces produced at the MobiSan facility had a very low fertilizing value and should go through composting methods in order to enhance its fertilizing value. Therefore, desiccated human faeces was mixed with organic solid wastes in order to increase the carbon ratio (C/N) trough Composting, (Calculation of carbon ratio is shown in chapter 3.7.1).

Experimental work was carried out using samples from the three lab-scales composting. Results presented in the following section comprise the characteristics of the mixture of desiccated human faeces with organic solid wastes. Results obtained from the three-lab scales for the

same parameters mentioned above were used to select the most suitable that fit to the MobiSan context and complied with the accepted standards. Results of the various methods are presented as follows:

4.2.3.1 Co-composting method

(Desiccated human faeces added to kitchen waste and Sawdust)

Samples were collected twice per week from the lab-scale Co-composting treatment over a period of 6 weeks or 42 days of experimental work. Samples were analysed for parameters: temperature, pH, Oxygen, moisture content, Carbon, nitrogen, phosphorus, potassium, e. coli and faecal coliform. The summary on the characteristics of composted human faeces collected during the first, fourth and sixth week is presented in Table 4.3, and the all results collected during the experimental work are presented in appendix B.

Table 4.3: Characteristics of composted human faeces from Co-composting method

Parameters:	Week 1		Week 4		Week 6	
Days: →	1-7th		22-28th		36-42nd	
Samples: →	S1	S2	S7	S8	S11	S12
Temperature (°C)	13	16	52	61	14	10
pH	5.1	5.5	6.8	6.5	6.4	6.2
Oxygen (%)	2	1	12	11	18	16
Moisture cont. (%)	55	48	32	35	12	08
Carbon (%)	58	54	44	46	44	47
Nitrogen (%)	9.5	11.1	15.8	16.3	19.4	21.5
Phosphorus (%)	14.2	16.1	22.4	22.8	24.1	24.6
Potassium (%)	8.4	8.9	28.3	28.7	29.4	29.8
E Coli(cfu./g)	$3.9x10^2$	$2.6x10^2$	$3.0 x10^2$	$2.8 x10^2$	$2.5 x10^2$	$2.1 x10^2$
FC (cfu/g)	$5.3x10^2$	$3.2x10^2$	$3.1 x10^2$	$3.2 x10^2$	$2.7 x10^2$	$2.6 x10^2$

- Temperature

Various temperatures of samples are illustrated in Table 4.3 for the composting of human faeces during the experimentation. The initial temperature was recorded at 13°C. The highest temperature, 61°C, was observed in Sample 8 and the lowest temperature, 10°C, was recorded on the decomposing of Sample 12 during the last day.

- pH

The pH of the decomposing for samples collected is shown in Table 4.3. The table shows the lowest pH of 5.1 was observed in Sample 1 during the first day. The highest pH of 6.8 was recorded in Sample 7 during the fourth week on the 22th day.

- Oxygen

The content of oxygen of six samples illustrated in Table 4.3 for the composting of desiccated human faeces during the experimentation. The highest oxygen content, 18%, was observed in Sample eleven and the lowest oxygen content of 1% was recorded on the decomposing of Sample 2 during week one.

- Moisture content

The moisture content of composting materials, also recorded in Table 4.3, shows increase of decomposing and decrease towards the maturity of compost. The lowest moisture content, 8%, was recorded in Sample 12 during week six and the highest moisture content, 55%, was recorded in Sample 1 during the first week at first day of experimental work.

- Carbon

The carbon content of the decomposing for the six samples is shown in Table 4.3. The table shows the lowest carbon content of 44% was observed in Sample 7 and 11 during week 4 and 6 respectively. The highest carbon content of 58% was recorded in Sample 1 during the first week.

- Nitrogen content

Table 4.3 shows the results of the nitrogen content observed in the six samples of composted human faeces during the experimental work. The results have shown the decomposing of desiccated human faeces with nitrogen content between 9.5% and 21.5%. The lowest and highest contents were observed during the first week on Samples 1 and 6 respectively.

- Phosphorus content

Table 4.3 shows the phosphorus content in the six samples of human faeces that were collected for the experimentation. The results showed that the decomposing of desiccated human faeces have phosphorus content between 14.2% and 24.6%. The lowest and highest contents were observed during the first week on Samples 1 and during week 6 on Sample 12 respectively.

- Potassium content

Table 4.3 shows the potassium content observed in the six samples of desiccated human faeces that were collected from the experimentation. The results showed that the decomposing of desiccated human faeces have the potassium content between 8.4% and 29.8%. The lowest

content was observed on Sample 1 during the first day of experimental work, and the highest content was observed on the last day on Sample 6.

- E. Coli

Table 4.3 shows the E. coli population in cfu/g, which were observed in the six samples of composting. Results showed that the concentrations of the E.Coli from the composting have been observed between $2.1x10^2$ and $3.9x10^2$cfu/g. The lowest and highest populations, or concentrations, were observed on Samples 1 on the first week and Sample 6 during the last day respectively.

- Faecal Coliform

Table 4.5 shows the results of the faecal coliform population in cfu/g, which were observed in the six samples of composting. Results showed that the concentrations of the faecal coliform from the composting have been observed between 2.6 $x10^2$ and $5.3x10^2$cfu/g. The lowest and highest populations or concentrations were observed on Samples 1 and 6 during week 1 and week 6.

4.2.3.2 Skyloo-composting method

(Desiccated human faeces added to raw vegetable and garden soil)

Composted human faeces samples were collected twice per week from the lab-scale Skyloo-composting method over a period of 60 days or 9weeks. Samples were analysed for parameters: temperature, pH, moisture content, nitrogen, phosphorus, potassium, e. coli and faecal coliform.

Table 4.4: Characteristics of composted human faeces from Skyloo-composting method

Parameters:	Week 1		Week 5		Week 9	
Days: →	1-7th		29-35th		57- 60th	
Samples:→	S1	S2	S9	S10	S17	S18
Temperature (°C)	13	16	24	24	27	27
pH	5.1	5.5	7.8	9.3	6.3	6.0
Oxygen (%)	2	1	1	1	1	1
Moisture cont.(%)	55	48	34	30	26	24
Carbon (%)	58	54	41	40	34	34
Nitrogen (%)	9.5	11.1	14.7	15.2	15.3	15.5
Phosphorus (%)	14.2	16.1	16.8	17.5	18.3	18.1
Potassium (%)	8.4	8.9	11.4	11.8	13.1	13.4
E Coli(cfu./g)	$6.9x10^2$	$2.6x10^2$	$2.5x10^2$	$2.4x10^2$	$1.3x10^2$	$1.1x10^2$
FC (cfu/g)	$5.3x10^2$	$3.2x10^2$	$4.1x10^2$	$4.4x10^2$	$2.1x10^2$	$2.0x10^2$

The summary on the characteristics of composted human faeces is presented in the following Table 4.4 for week 1; 5 and 9. The all results collected for the experimental work are presented in appendix B.

- Temperature

Temperatures of six samples, illustrated in Table 4.4, for the decomposing of desiccated human faeces during 60 days of experimentation have shown the lowest and highest temperature of 13 and 27^{o}C. The lowest temperature was recorded in Sample 1 during the first week on the first day, and in the fifty seventh and sixth day, the highest temperature was recorded in Samples 17 and 18 during the nine week.

- pH

The pH of the composting of human faeces using Skyloo composting method is shown in Table 4.4. The lowest pH of 5.1 was observed in Sample 1 during the first week as an acidic faecal matter in the first day of decomposing and the highest pH of 9.3 was recorded in Sample 10 on the thirty first day during week 5.

- Oxygen

The content of oxygen of six samples is illustrated in Table 4.4 for the composting of human faeces during the experimentation. The highest oxygen content, 2%, was observed in Sample 1 and 5, and the lowest oxygen content, 1%, was recorded on the decomposing of Samples 2; 3 and 4 during week 1 and 2 respectively.

- Moisture content

The percentage of moisture content, shown in Table 4.4, for the composting of desiccated human faeces recorded during the last week was 24% as the lowest and the highest recorded was 55% during the first week on the first day of experimental work. The lowest moisture content was recorded in Sample 9 and the highest moisture content was recorded in Sample 1.

- Carbon

The carbon content of the decomposing for the six samples is shown in Table 4.4. The table shows the lowest carbon content of 34% was observed in Samples 17 and 18 during week 5 and 6 of experimentation. The highest carbon content of 58% was recorded in Sample 1 on the first week of experimentation.

- Nitrogen content

Table 4.4 shows the results of the nitrogen content in the six samples of composted human faeces. Nitrogen content was observed at about 9.5% as the lowest and it was recorded in the first sample of composted human faeces on the first day. The highest nitrogen content was at about 15.5%, was recorded in Sample 18 collected during the last day.

- Phosphorus content

The lowest phosphorus content observed among the six samples of composted human faeces, presented in Table 4.4 was 14.2%, recorded in Sample 1 on the first day of the experimental work. The highest phosphorus content was about of 18.3%, recorded in Sample 17 during week 5.

- Potassium content

Results of potassium content observed among the six samples of composted human faeces have shown that the lowest content of 8.4% was recorded in Sample 1 during the first week in the first. The highest potassium content of 13.4% was recorded in Sample 18 during the week 6 of experimentation.

- E. Coli

Table 4.4 shows the results of the E. Coli population in cfu/g, which were observed in the six samples of composting of human faeces. Results showed that the concentrations of the E. Coli from the composting were between $1.1x10^2$ and $6.9x10^2$cfu/g. The lowest and highest populations, or concentrations, were observed in Samples 1 and 6 respectively in the last week.

- Faecal Coliform

Table 4.4 shows the results of the faecal coliform population in cfu/g, which were observed in the six samples of composting of human faeces. Results showed that the concentrations of the faecal coliform from the composting have been observed between $2.0x10^2$ and $5.3x10^2$cfu/g. The lowest and highest populations or concentrations were observed in Samples 1 and 18 during week 1 and 6 during experimental work.

4.2.3.3 Bio-process composting method

(Desiccated human faeces added to organic waste and sawdust)

Samples were collected twice per week from the lab-scale Bio-process composting method over a period of 42 days. Samples were analysed for parameters: temperature, pH, moisture content, nitrogen, phosphorus, potassium, e. coli and faecal coliform. The summary of the characteristics of composted human faeces during week 1; 4 and 6 is presented below in Table 4.5. The all results collected for the experimental work are presented in appendix A.

Table 4.5: Characteristics of composted human faeces from Bio-process composting method

Parameters:	Week 1		Week 4		Week 6	
Days: →	1-7th		22-28th		36-42nd	
Samples: →	S1	S2	S7	S8	S11	S12
Temperature (°C)	14	15	53	65	18	14
pH	5.1	5.3	7.2	6.4	5.4	5.1
Oxygen (%)	18	18	14	13	16	15
Moisture cont.(%)	51	48	30	30	22	17
Carbon (%)	52	56	44	43	42	41
Nitrogen (%)	15.2	15.6	18.5	16.7	21.2	23.7
Phosphorus (%)	18.5	19.4	24.2	23.9	25.3	25.7
Potassium (%)	26.5	26.1	31.9	32.7	28.2	31.7
E Coli(cfu./g)	$2.5x10^2$	$2.4x10^2$	$1.7x10^2$	$1.5x10^2$	$1.4x10^2$	$1.2 x10^2$
FC (cfu/g)	$6.1x10^2$	$5.3x10^2$	$5.6x10^2$	$5.4x10^2$	$4.8x10^2$	$4.3x10^2$

- Temperature

Results on the characteristics of desiccated human faeces presented in Table 4.5 show the values of the temperature of six samples of composted human faeces collected from the lab-scale. The composted human faeces temperatures vary between 14°C and 65°C. The initial temperature recorded was 14°C. The lowest and the highest temperatures were recorded in Samples 1 and 12. The highest temperature was recorded at sample 8 during week 4 of experimental work.

- pH

The analyses found that composted human faeces, during first to third week of experimentation, have samples that contain the pH variation between 5.1 and 7.2. The lowest pH value was observed in Sample 1 on the first day and the highest was observed in Sample 7 on the twenty second day.

- Oxygen

The content of oxygen of six samples is illustrated in Table 4.5 for the composting of human faeces during the experimentation. The highest oxygen content, 18%, was observed in Samples 1 and 2 during the first week. The lowest oxygen content, 13%, was recorded on the decomposing of Sample 8 during the fourth week.

- Moisture content

Table 4.5 shows the results of the moisture content observed for the six samples of composting of human faeces that were collected from the lab-scale. Results show that the moisture contents of composted human faeces were observed at 17% and 51%. During experimentation, the lowest moisture content was recorded in Sample 12 on the last day and the highest was recorded on Sample 1 on the first day of experimental work.

- Carbon

The carbon content of the decomposing for the six samples is shown in Table 4.5. The table shows the lowest carbon content of 41% was observed in Sample 12 during the last week of experimentation. The highest carbon content of 56% was recorded in Sample 2 during the first week on the seventh day.

- Nitrogen content

The concentration of nutrient observed in Table 4.5 for the results of the nitrogen content show that among the six samples of composted human faeces, the concentration of nitrogen was observed in Sample 1 as lowest with 15.2%, and 23.7% was recorded as the highest nitrogen content on the Sample 12 during the last week of experimental work.

- Phosphorus content

Results of phosphorus contents in the six samples of composted human faeces collected from the case site experimentation showed that composted human faeces have phosphorus content of between 18.5% and 23.7% respectively. The lowest was observed on Sample 1 during the first week and the highest content was observed on Sample 12 during the last day.

- Potassium content

The characteristics of composting of human faeces show that potassium concentration among the six samples of human faeces collected for experimentation were observed at 26.1% and

31.7%. The lowest and highest contents were observed on Samples 2 during the first week. The highest content was recorded on sample 12 during the last day of experimentation.

- E. Coli

The following values characterised composted human faeces collected from case site during experimentation. The results of the E. Coli population in cfu/g, among the six samples of human faeces, showed that the concentrations of the E. Coli found in the composted human faeces have been between $1.2x10^2$ and $2.5x10^2$cfu/g. The lowest populations or concentrations were observed on Sample 12 during the last week and the highest populations or concentrations were observed on Sample 1 during the first day of experimentation.

- Faecal Coliform

The analyses on composted human faeces revealed that the levels of pollutant such as faecal coliform population in cfu/g were observed during the experimentation work with the concentrations of the faecal coliform of about $4.3x10^2$ and $6.1x10^2$ cfu/g. The lowest and highest populations, or concentrations, were observed on Samples 12 and 1 respectively during the last week and first week.

4.2.3.4 Comparison of the three composting methods

The three composting treatment methods results were compared in terms of their efficiency and human faeces enhancement capabilities in order to determine the most suitable treatment that fit to the MobiSan context and complied with the accepted standard. The comparison of the three methods was obtained based on the final results presented in Table 4.6.

Table 4.6: Final results of the three composting methods

Parameter	*Co-composting*	*Skyloo-composting*	*Bio-process composting*
Temperature (°C)	09	25	11
pH	5.8	6.7	5.3
Oxygen (%)	18	1	16
Moisture cont.(%)	08	18	11
Carbon (%)	42	31	47
Nitrogen (N) (%)	22.2	16.2	25.3
Phosphorus (%)	25.4	19.6	28.6
Potassium (%)	31.1	15.2	33.2
E-Coli (count/g)	$1.9 x10^2$	$1.4x10^2$	$1.3 x10^2$
FC (count/g)	$2.3 x10^2$	$2.6x10^2$	$2.1x10^2$

4.3 Computation of the process efficiency

Efficiency results of the three composting methods are obtained from the final results presented in Table 4.6 using the formulae:

$$\text{Efficiency (\%)} = \frac{\text{Sample 1} - \text{Sample 2}}{\text{Sample 1}} \times 100 \quad (4.1)$$

$$\text{Or Efficiency (\%)} = \frac{\text{Final Sample 1} - \text{Desiccated Sample 1}}{\text{Final Sample 1}} \times 100 \quad (4.2)$$

Table 4.7: Comparison of the three methods in terms of effectiveness

Parameter	***Efficiency results of the three composting methods***		
	Co-composting	***Skyloo-composting***	***Bio-process composting***
Temperature (ºC)	-	-	-
pH	-	-	-
Oxygen (%)	-	-	-
Moisture cont.(%)	-	-	-
Carbon (%)	-	-	-
Nitrogen (N) (%)	79	71	83
Phosphorus (P)(%)	87	83	88
Potassium (K) (%)	95	90	95
Pathogen destruction for E-Coli (%)	68	76	80
Pathogen destruction for FC (%)	64	67	75

Results suggest the computation of the process efficiency ranging between 71 and 83% for Nitrogen content, where the highest nitrogen content was achieved at the Bio-process composting method and the lowest content was achieved at Co-composting method.

The computation process efficiency ranging from 83 to 88% was recorded for phosphorus content, while the highest content of phosphorus was achieved at the Bio-process composting method and the lowest content was achieved at the Skyloo-composting method.

The content of potassium recorded from the three composting methods showed the content was ranging between 90 and 95%. The lowest was achieved at the Skyloo-composting method and the highest content of potassium was achieved at both Co-composting and Bio-process composting method with E. coli 80%, Faecal coliform 75% in terms of pathogen destruction.

4.4 Behaviour and operational requirements of the processes

4.4.1 Co- composting

During the operation of the co-composting treatment process, decomposition of organic matter after feeding the plant was observed. This, combined with the fact that the mixture contained kitchen waste such as meat, fats and oils, caused the compost to attract pests. The slow decomposition of organic matter resulted in high temperatures and was omitted from the treatment process. After regular mixing and turning of material, breakdown occurred slowly at the lower temperatures, which could enhance the treatment process.

4.4.2 Skyloo-composting

The treatment process of Skyloo-composting occurred with addition of garden soil for burial of organic matter, resulting in low moisture content which impeded the treatment process because the desired microbes needed water. Low moisture content in the process was not necessary to make the compost piles more susceptible to spontaneous combustion and could also allow for the regulation of temperature gained from sunlight.

4.4.3 Bio-process composting

The process of bio-process composting requires forced aeration. The minimum oxygen content was maintained at 10%, while microbial activity could increase in the compost pile. It was observed that if oxygen had not been supplied into the system by turning the compost pile, the composting would have shifted to anaerobic decomposition, which often produces a characteristic foul odour.

4.5 Summary

This section of the study presents the results of experimental works conducted to determine the characteristics of desiccated human faeces produced by the MobiSan facility in order to assess the fertilising value and understand its application in agriculture. Analysis of uncomposted desiccated human faeces from MobiSan showed a very low fertilising value when compared to agricultural standards. Analysis of composted human faeces showed variability in values caused by environmental factors such as aeration, temperature and moisture content. These factors were identified as those playing the most important roles during the composting process.

Following the composting treatment of human faeces, results showed that the most advantageous approach to pathogen destruction and nutrient enhancement in composting was caused always by the selected parameters.

Chapter 5: Analysis and discussion of results

5.1 Introduction

This section of the study discusses results and findings obtained through different experimental methods, as presented in the previous chapter. Detailed discussion of results and the comparison of desiccated human faeces composting methods were undertaken in order to select the most suitable approach to enhance the fertilising value and make the compost safe for agricultural application. Results obtained during experimental analysis as presented in Chapter 4 are interpreted, evaluated and discussed with reference to the literature reviewed.

This chapter is divided into the following sections, namely: characteristics of desiccated human faeces, comparison of desiccated human faeces to agricultural standards, characteristics of composted human faeces, and efficiency comparison of the three composting methods.

5.2 Characteristics of desiccated human faeces

In view of results presented in the previous chapter, the composition of desiccated human faeces shows a wide range of variability. Table 5.1 presents a summary of parameters such as temperature, pH, moisture content, carbon, nitrogen, phosphorus, potassium, E. coli and faecal coliform. The highlighted parameters demonstrate the fertilising value and pathogen indicators of desiccated human faeces from the MobiSan facility. These parameters needed to be analysed in order to achieve the abovementioned objectives, and results obtained were compared to the literature reviewed.

Table 5.1: Characteristics of desiccated human faeces

Desiccated human faeces							
Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
Temperature (ºC)	15	16	12	15	17	18	16
pH	10.3	9.9	11.2	10.6	9.8	10.2	10.3
Moisture content (%)	15	18	13	12	10	17	14
Carbon as C (%)	52	57	55	58	52	59	56
Nitrogen as N (%)	5.1	4.2	6.2	4.8	5.3	4.5	4.7
Phosphorus as P (%)	4.7	2.6	4.3	3.6	2.1	2.8	3.4
Potassium as K (%)	2.1	1.6	1.4	1.2	1.1	1.8	1.5
E. coli (cfu/g)	$6.6x10^3$	$5.6x10^3$	$5.8x10^3$	$5.7x10^3$	$5.3x10^3$	$6.2x10^3$	$5.9x10^3$
FC (cfu/g)	$9.8x10^3$	$6.4x10^3$	$8.8x10^3$	$7.4x10^3$	$7.2x10^3$	$7.6x10^3$	$7.8x10^3$

- Temperature

Desiccated human faeces from the MobiSan facility demonstrated variability of temperatures, with an average of 16.0^{o}C. This was attributed to the storage of faeces that had been mixed with sawdust for a certain period. Temperature is one of the most important factors affecting microbial growth and biological reactions (Feachem *et al.*, 1983). The variation might be caused by a number of factors, such as ventilation in the system. Literature confirmed that different species of pathogens can survive at temperatures lower than 15^{o}C, 30^{o}C for anaerobic and aerobic composting. Microorganisms were found in desiccated human faeces and most of them exhibit a relatively narrow temperature range over which they can be active.

- pH

Desiccated faeces had an average alkaline pH of 10.3. The variation value from samples was attributed to the mixing of faeces with sawdust and its storage in the system. Kale *et al*.; (1986) confirmed that the change in pH is affected by the sawdust, which is used as an alkaline additive to increase the pH value of the faeces (a pH of 10-11). The higher pH can transform the equilibrium in favour of ammonia loss (NH_3). Thus, the higher levels of pH developed during the mixing of sawdust and desiccated human faeces might enhance ammonia volatilisation. This additive seems to be achieving the intended end, as evidenced by the results in Table 5.1.

- Moisture content

Moisture content shown in Table 5.1 was found to be reduced to an average value of 14%. This is credited to the addition of the sawdust additive or bulking agent, which absorbs moisture, and also the ventilators, which dry up the faecal matter. Moisture content is one of the factors that should be maintained carefully to ensure proper composting and facilitate the proliferation of microorganisms. Moisture levels less than 20% cause the microorganisms to slow their activities and become dormant or die (Feachem*et al*., 1983).

- Nitrogen

The average nitrogen content of 4.7% in the desiccated faeces is relatively low, when compared with the literature reviewed. Nitrogen content might have been lost through evaporation caused by the ventilation process in the chamber of the MobiSan facility, and further reduced through volatilization in the form of ammonia (NH_3) and other nitrogenous gases. Girovich (1983) stated

that excessive aeration and turning enhances emission of ammonia, which escapes more easily when the composting material is exposed to the atmosphere. Hence, an optimum frequency of turning must be found, which balances the need of the pile in the system to be subjected to high temperatures for pathogen inactivation, with the need to limit nitrogen loss.

- Phosphorus

Phosphorus content of desiccated faeces is lower than that recorded in the literature. The desiccated human faeces collected had an average content of 3.4%, lower than the content of phosphorus discussed in the literature. The reduction in phosphorus content was found to occur after the storage period of six months in the MobiSan facility. This reduction may be attributed to factors like ventilation and limiting elements for microbial organisms to survive, such as the carbon and nitrogen ratio (C:N). The carbon-nitrogen ratio of faecal material was found to be lower than the required levels, and this was caused by the addition of sawdust to faecal matter.

Ekelund and Nystrom (2007) confirm that the most important parameter affecting the composting process is the carbon-nitrogen(C-N) ratio. This provides a useful indication of the rate of decomposition of organic matter. The ideal ratio of C to N is between 20-30:1. When there is too little nitrogen, the microbial population will not grow to its optimum size, and composting will slow down, as nitrogen becomes a limiting factor to the growth of microorganisms. Phosphorous levels can also be limiting.

- Potassium

The potassium loss content of the desiccated human faeces stored in the MobiSan facility for a period of six months was recorded lower to that of previous standards obtained. Potassium content reduction was attributed to bulking agent material such sawdust added at high amount to avoid odours in the MobiSan facility. However, the amount of sawdust added also raised the carbon ratio (C:N) and limited the decomposition of faecal matter, which results in limiting of microorganism growth as a result of low levels of nitrogen or potassium. The literature reviewed indicated that when the carbon/nitrogen ratio is lower, the decomposition of organic material is slowed down and nitrogen is rapidly lost by volatilization as molecular ammonia. Low levels of potassium also limit microbial growth.

- E. coli

Following the results presented in Table 5.1, desiccated human faeces from the MobiSan facility had a high concentration of E. coli, with about 6.6 $x10^3$cfu/g. If contact is made with these faeces, infection from bacteria may result. The high concentration of E. coli may be attributed to conditions in the MobiSan facility causing temperatures lower than those required to destroy bacteria. This was also attributed to the presence fresh human faeces from night soil disposal and from children's toilet vaults, where proper mixing with sawdust did not occur.

The WHO (2006) recommends that for excreta to be safe for use it should have a maximum of 1000 cfu/g, but this may be relaxed to a maximum of 1000 cfu/g for high-growing leaf crops. In this regard, the MobiSan system was not able to produce faecal matter that complies with the guidelines presented.

Mason and Mike (2005) stated that mesophilic and thermophilic stages are necessary for the composting process, where the first stage involves temperature lower than 35°C and the second stage involves temperatures above 50°C. The complete destruction of pathogens is achieved at the highest possible temperature range, between 60°C and 80°C.

- Faecal coliform

The average faecal coliform population was found to be high, with $9.8x10^3$cfu/g; The high concentration of faecal coliform indicate the presence of microorganisms in desiccated faeces that may consist of pathogenic organisms, which could cause intestinal infections, dysentery, hepatitis, typhoid fever, cholera and other illnesses. There are different species of pathogens in human faeces. Feachem *et al*. (1983) suggested that at temperatures less than 10°C, each microbial species may survive well, but that they are rapidly killed at temperatures above 45°C. Thus, temperatures around 55-65°C are required to destroy different species of pathogens (except bacterial spores) in the composting processes.

Results obtained in the current study indicate the high levels of faecal coliform was once again attributed to different species of pathogens from fresh human faeces and night soil disposal in the MobiSan facility. With the recorded temperatures lower than those recommended by Feachem *et al*. (1983), the system could not facilitate pathogen elimination.

5.3 Comparison of desiccated human faeces to agricultural standards

The characteristics of desiccated human faeces from the MobiSan facility were compared to the recommended guidelines in terms of the fertilising value. Dessicated human faeces had a very low fertilising value when compared to the standards. Reasons for the low fertilising values were enumerated in Section 5.2. The comparison of desiccated faeces and the standards are presented as follows:

- **Nitrogen**

When comparing the nitrogen content of desiccated faeces with the recommended values, the six samples of desiccated faeces were found to have lower values, lower with an average content of 4.7% and would need to be treated in order to increase the nitrogen content. The nitrogen content was compared to the recommended value presented for crops in South Africa which is 5.5% as shown in the figure below.

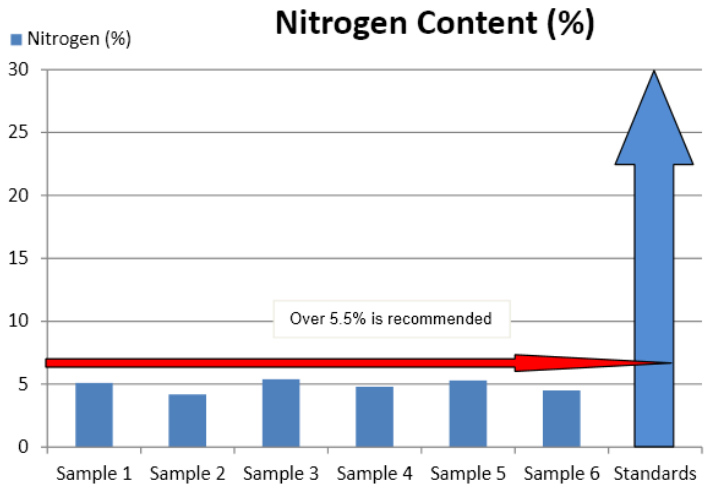

Figure 5.1: Comparison of desiccated faeces nitrogen content with standards

- **Phosphorus**

Figure 5.2 presents the phosphorus content of desiccated faeces, which was found to be lower than that recommended in agriculture. All six samples of desiccated human faeces were found to have lower phosphorus contents than the recommended 5%. This was presented as follows:

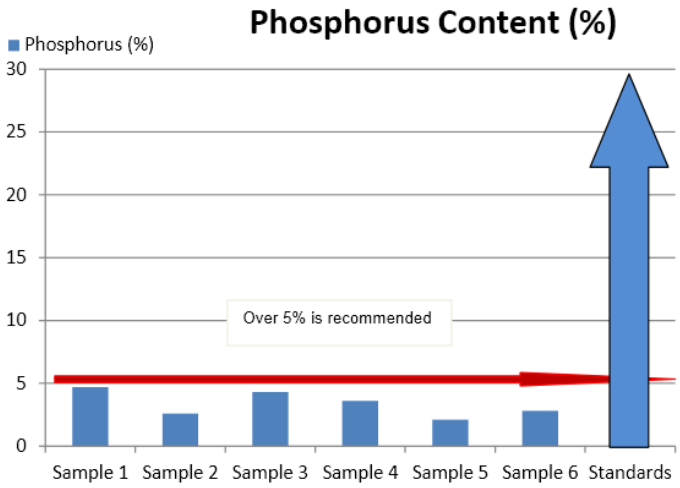

Figure 5.2: Comparison of desiccated faeces phosphorus content with standards

- **Potassium**

The potassium content of six samples of desiccated human faeces from the MobiSanfacilitywasfound to be low when compared to the recommended standards, which are over 3.5%. This was presented as follows:

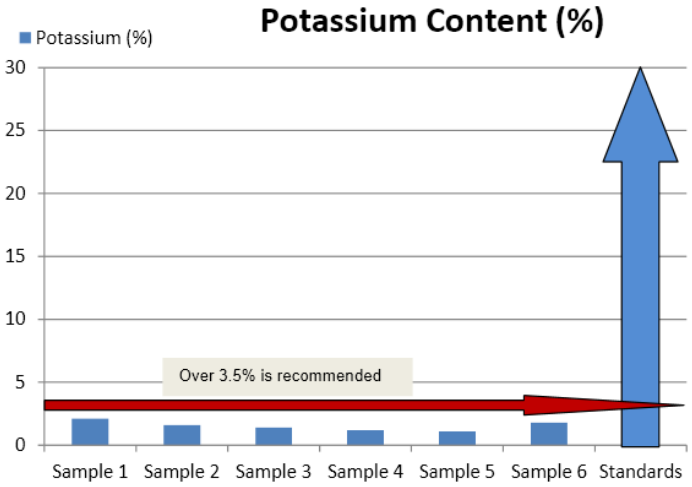

Figure 5.3: Comparison of desiccated faeces potassium content with standards

- **Faecal coliform**

The MobiSan facility produced desiccated faeces with faecal coliform concentrations that were much higher than the recommended guidelines. The six samples of desiccated faeces

confirmed the presence of microorganisms living in faeces, as explained above in Section 5.2. The microbial colonies were compared to the standards as follows:

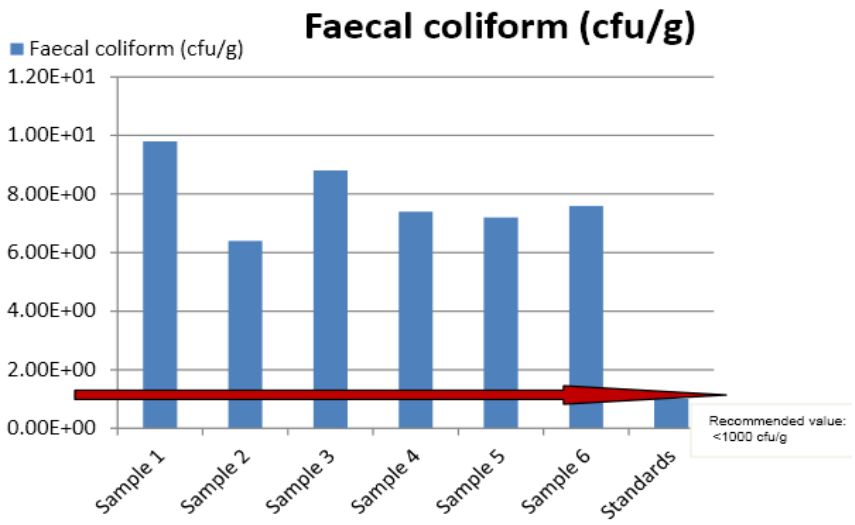

Figure 5.4: Comparison of desiccated faecal coliform content with standard

- **E. coli**

The figure 5.5 shows results of E. coli levels in desiccated human faeces as being high when compared to the recommended standards. The contamination level was presented as follows:

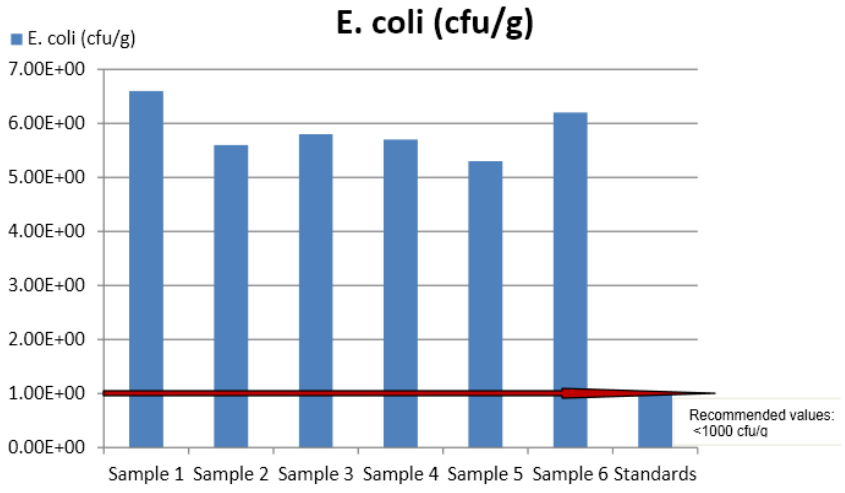

Figure 5.5: Comparison of desiccated faeces e. coli content with standards

5.4 Characteristics of composted human faeces

Results obtained in the previous chapter show that the quality of the compost was variable, due to the activities of microorganisms and environmental parameters. Variations of these parameters are presented graphically and described as follows:

- Temperature

Based on the literature review, active composting takes place between 20ºCand 60ºC in aerobic composting. The recorded temperatures of desiccated human faeces in Figure 5.6 for both co-composting and bio-process composting falls between the recommended ambient temperature range, which is favourable for bacterial activities and chemical reactions. In both systems, It was observed that temperatures fell gradually but at different rates and to different extents.

The highest temperature values were recorded in both aerobic composting methods as occurring during the third week, as a result of better aeration. In the same processes, the temperature started at lower levels, from 13º and 14ºC in week one to the peak recorded value of 61º and 65ºC during week two, and then started falling gradually till week six to the lower temperatures of 10º and 14ºC. Rashad *et al*. (2010) state that in all composting systems, the temperature of the pile drops off gradually towards maturation. Turning frequency also had a significant impact on the heating curve of each composter.

In anaerobic composting, the highest temperature is about 30-35ºC, and the recorded Skyloo composting temperatures were within this range. As with the other composting processes, the starting temperature was recorded at levels lower than 20ºC, rose up to 28ºC during week 4 and dropped to 24ºC during week 6. Studies conducted by Strauss and Blumenthal (1994) reveal that anaerobic composting has a limited capability of killing pathogens. Faecal coliform's average survival time in the composting process at 20-30ºC was reduced over six weeks.

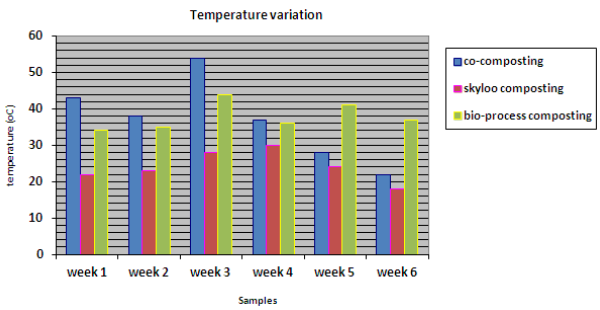

Figure 5.6: Variation of temperature between different composter units

- pH

The stabilisation efficiency decreases at lower or higher pH. This parameter gives an idea about the survival rates of the types of microorganisms that might be dominating the compost pile. The pH values in both co-composting and bio-process composting ranged from 4.4-8.1 and 5.4-7.5 during week one. The figure below shows the rise of pH during the process. The pH values recorded in both processes varied significantly from week one to week six, though the values recorded in co-composting were slightly lower than those recorded in bio-process composting. The particular trend taken by the pH values recorded in both systems may be due to the reduction of organic acids to mineral acids, caused by a decrease in acidity occurring as a result of mixing the faecal matter with sawdust.

As presented in Figure 5.7, results have shown a starting pH of 4.4 and 5.4, which was slightly acidic, and a later shift towards an alkaline range within the sixth week of composting, with values of 7.8 and 7.2.The pH values recorded in co-composting, Skyloo and bio-process composting fell within the basic range at the end of the process. Sundberg (2005) states that during successful and fully-developed composting, pH levels often rise to a range between6.5-9. Also, Cofie *et al*. (2009) observed that, at the end of maturation, pH values of 7.7 and 8.5were obtained respectively in two compost heaps. These results also fall within the range.

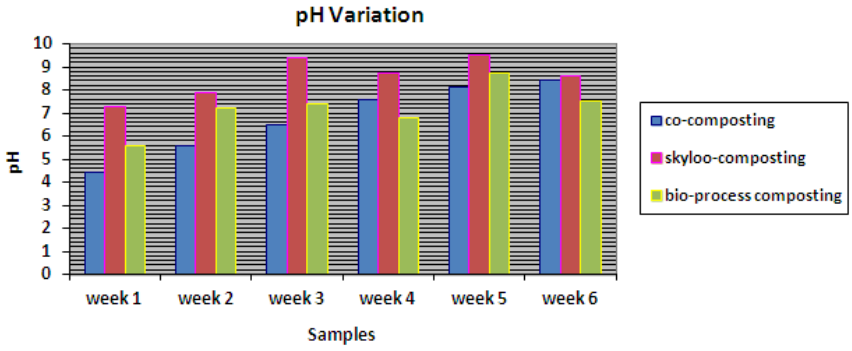

Figure 5.7: Variation of pH between different composter units

- Moisture content

The rise and fall in the moisture content of both co-composting and bio-composting units was due to the variation in temperature and aeration, causing different rates of evaporation of moisture in the systems. Results observed for both were 52% and 54% in week one, which

gradually 8% and 14%. The reduction of the moisture content was attributed to the air flow system used in the bio-process composting during the active compost period.

In general, the moisture content of the three composting methods recorded was consistent with the literature finding for efficient composting, identified to be at 42-60%byCofie *et al*. (2009).

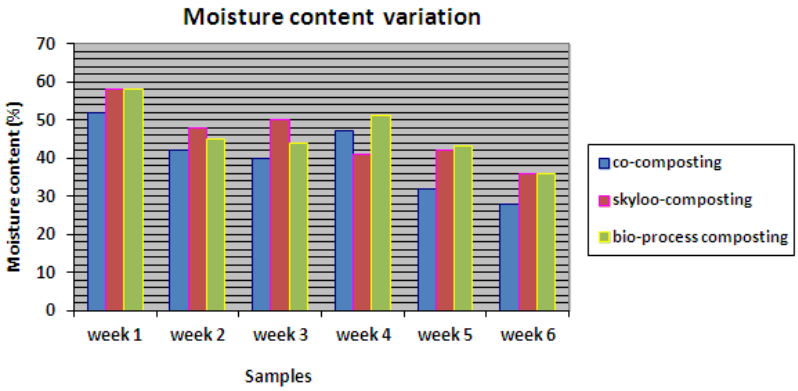

Figure 5.8: Variation of moisture content between different composter units

- Nitrogen

The major nutrient factor in the composting process is the carbon-to-nitrogen ratio (C: N). Based on the relative demands for carbon and nitrogen in cellular processes, the theoretical ratio is 25:1. Nitrogen has only one major use as a nutrient. Consequently, much more carbon than nitrogen is required. The ratios encountered in waste management vary widely.

Results on the composting of desiccated faeces, as shown in the figure below, show an increased amount of nitrogen in all three methods. Results recorded during the initial process were found at lower levels than those required, in all composting processes. Variability of nutrients was also observed from each week and at the end of composting, with high levels of nitrogen concentration. The high level of nitrogen concentration was attributed to the breakdown of proteins from the addition of kitchen wastes and organic wastes in the systems by microorganisms. A study undertaken by Ekelund and Nystrom (2007) confirms that composting is normally taken to be complete when the active decomposition stage is blended with organic material such faeces to produce good quality of carbon/nitrogen (C/N) ratio over around 20.

The high nitrogen content can also be attributed to the rise pH of the pile especially in bio-process composting; and it was observed that the pH range in all the three composting methods

is favourable for the uptake of nutrients. As reported by Govindan (1998) de-nitrification of nitrates and nitrites occurs during the rise of pH.

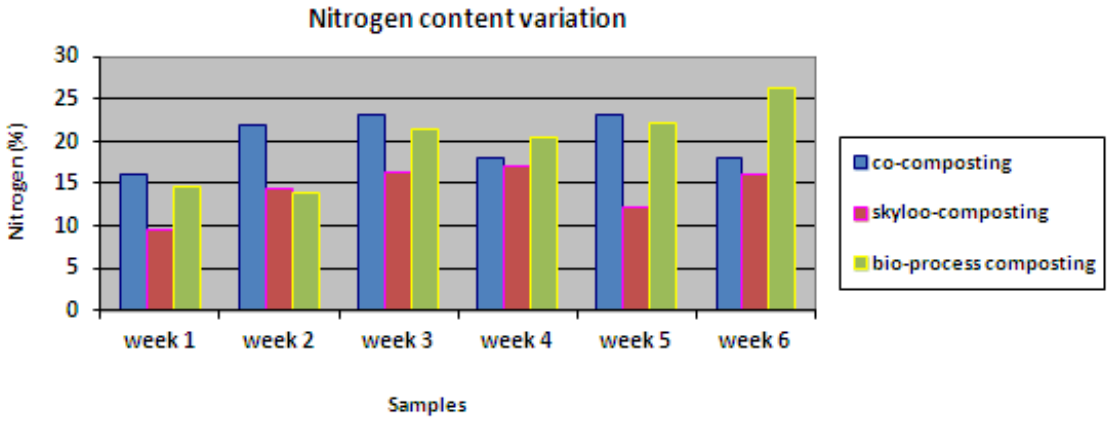

Figure 5.9: Variation of Nitrogen content between different composter units

- Phosphorus

Phosphorus was found to have a great importance in microbial nutrition; during the composting treatment, it may have increased the biological activity, resulting in increased temperature (Stanier *et al*., 1986). Results presented in the following figure show that the lowest phosphorus content was found in Skyloo-composting and the highest in Bio-process composting. Cotton (2001) reports that the rate of decomposition during phosphorus-rich composting is mainly due to the activity of microorganisms.

It is clear from the figure below that composting is ideal for enhancing phosphorus content. Phosphorus is not lost by volatilization during the composting process, but phosphorus concentration may increase as composting proceeds (Warman&Termeer, 1996). The higher rate of decomposition leads to higher mass loss of organic waste and increase of nutrient content. In the light of these observations, the increased rate of decomposition, coupled with mass loss of organic matter, resulted in increased nutrient content in the final phosphorus-rich compost.

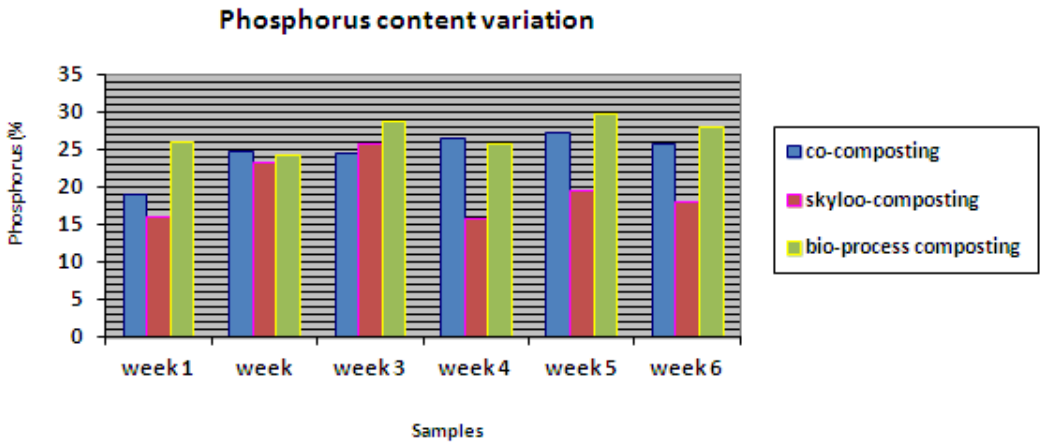

Figure 5.10: Variation of Phosphorus content between different composter units

- Potassium

The concentration of potassium content presented in the following figure shows that all the samples were in the range reported in the literature. However, the concentration was at substantially higher levels in the bio-process composting than in the co-composting treatment method. This may be attributed to the feeding rate of organic materials, coupled with aerobic conditions prompting a rapid and complete degradation by microorganisms.

The high concentration of potassium was also attributed to the aerobic conditions maintained in the system to effect a rapid and complete breakdown of readily-decomposable organic compounds. Kale *et al*. (1986) reported that the addition of dry leaves may also be responsible for increasing the level of potassium-fixer populations in composting, as it increases porosity, allowing sufficient oxygen penetration to restore aerobic conditions and thereby reduce the odour level.

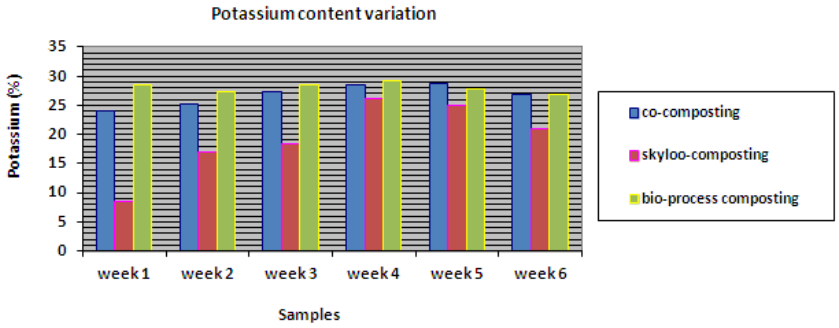

Figure 5.11: Variation of Potassium content between different composter units

5.5 Comparison of the three methods

5.5.1` Findings vs literature reviews

A comparison of the three methods was obtained based on the final results in terms of NPK. Results obtained are compared to the previous literatures and are presented as follows:

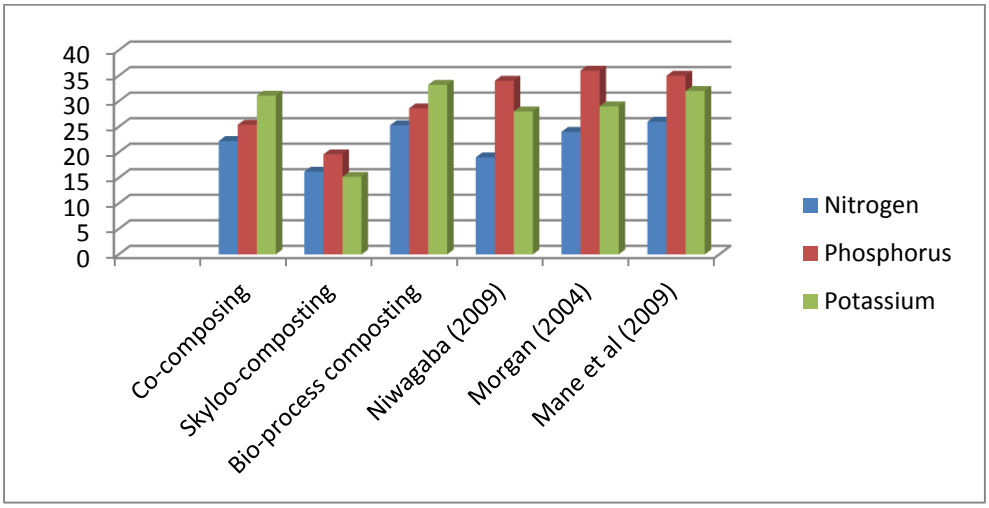

Figure 5.14: Nutrient value NPK of the three processes vs literature reviews

Results presented in figure 5.14 show that the three composting methods were suitable for treating desiccated human faeces from the MobiSan facility. Results obtained show that the level of enhancement in bio-process composting was higher when compared to other methods used for this study. The higher enhancement was attributed to factors such as temperature, moisture content and aeration in the composting processes. The highest levels of nutrients may also be attributed to good mixing of solid organic waste to desiccated human faeces, which resulted in acceptable Carbon-Nitrogen(C:N) ratio, ranged between 20:1 to 30:1. This also allowed microorganism reproduction by creating a favourable environment for their survival.

Results obtained in bio-process composting in terms of NPK: (25.3; 28.6; and 33.2%) were almost similar to those obtained by Niwagaba (2009), Morgan (2004) and Mane *et al.* (2009). The bio-composting treatment method confirmed its treatment efficiency for desiccated faeces and showed enhancement capabilities of 95%, while co-composting and Skyloo-composting were recorded at 70% and 85% respectively. Variations of parameters in the three composting methods are presented graphically in Appendix C.

5.6 Selection of the composting

The selection of the composting methods was undertaken with the following criteria:

- Favourable conditions
- Fertilising value enhancement
- Treatment efficiency
- Carbon ratio C:N
- Microorganism destruction

The bio-composting method was selected as the most suitable for the MobiSan context, due to its human faeces' value enhancement when compared to the other methods used. Results obtained in Table 4-7 for the bio-composting method showed good efficiency with 83%, 88%, and 95% in terms of NPK, when compared to other processes. The microorganism destruction was found to be good, with rates of 80% and 75% for E. coli and faecal coliform.

Chapter 6: Conclusions and recommendations

This chapter of the study summarises the findings and discussions detailed in previous chapters. It highlights the importance of the study by addressing answers to the research problem and objectives. This section also outlines the outcomes of the research and provides recommendations for further study.

6.1 Conclusions

Human faeces contain nutrients that can be used as fertiliser in agriculture. To exploit this waste product as a potential soil-conditioning resource in agriculture, composting is suggested as a means to improve the fertilising value of faeces and to reduce the associated health risks.

Based on the results obtained, the study confirmed after analysis that the characteristics of desiccated human faeces from the MobiSan facility had a low fertilising value, with an average of N: 4.7%; P: 3.4% and K: 1.5%, when compared to previous literature. Results obtained also indicate high concentrations of E. Coli, with an average of: $5.9x10^3$cfu/g, and faecal coliform: $7.8x10^3$cfu/g. The study concluded that desiccated human faeces produced by the MobiSan facility was not compliant with the standard acceptable for agricultural use, as it has lower fertilising value and higher concentrations of pollutants. The study recommends a secondary treatment through composting methods by mixing with organic solid wastes for agricultural applications.

The study further used three composting vessels: co-composting, Skyloo-composting and bio-process composting, to compare their enhancement in treating desiccated human faeces from the MobiSan facility. Results indicate high enhancement of fertilising value. Results on the composted faeces were found for: co-composting method: Nitrogen: 22.2%, Phosphorus: 25.4%, Potassium: 31.1%. Skyloo composting method: Nitrogen: 16.2%, Phosphorus: 19.6%, Potassium: 15.2%. Bio-process composting method: Nitrogen: 25.3%, Phosphorus: 28.6%, Potassium: 33.2%.

The results of the study showed that the three composting methods were suitable for treating human faeces from the MobiSan facility. Results indicate that the enhanced fertilising value and the reduction of pathogens in the composting processes could make the compost safe for agricultural application. Generally, findings from this study concluded that the mixing of

desiccated human faeces from MobiSan facility with organic solid wastes can enhance the fertilising value and make it suitable for agricultural application.

6.2 Recommendations

A better overall understanding of the composting process has been developed with the current research, which has produced the following recommendations:

- To achieve the maximum efficiency on the fertilising value and destruction of microorganisms, the optimal nature and composition of organic materials that can be used to add nutrients should be determined.

- The mixture of human faeces and livestock manure and poultry litter to provide blended carbon nitrogen ratio (C:N) in composting should be investigated in order to provide a better understanding of the fertilising value.

- The aeration of composting material also needs more attention with regard to wind direction. Therefore, when installing an aerobic composting design, wind orientation must be taken into account in order to provide an ambient temperature suitable for microorganism survival in the system.

- The composting design of Skyloo should be revised with perforated holes at the bottom and sides of the container to allow for the passage of species of microorganisms through the system, in order to produce faster decomposition of the pile.

- During the high active phase of composting, optimal performance of the pilot plant requires careful ongoing monitoring of the process, and parameters of control should be maintained in line with agricultural standards. Mixing of the material two to three times per week is needed to ensure that the material is exposed to high temperatures.

- More attention should be given to the moisture content during the composting process. The moisture content should not exceed 60% when composting organic materials that include vegetable waste, flower garden refuse, or fruit and vegetable scraps from the kitchen. The composting process turns anaerobic when the moisture content exceeds a level of 60%, and thermal sanitising temperatures are not reached.

6.3 Future research recommendations

The following subjects should be given attention for the future research work:

- Proper handling of desiccated human faeces
- Composting procedure for the mixture of human faeces and vegetable waste
- Assessment of temperature in the barrel composting of human faeces
- Assessment of heavy metals and nutrients in human faeces composting
- Investigating the vermicomposting of desiccated human faeces from Mob iSan.

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Appendices

Appendix A: Analytical procedures

a) Temperature and pH

The pH and the temperature of these samples were measured using a pH meter and thermometer respectively. Both the pH meter and thermometer were calibrated over the appropriate range, following manufacturer's instructions.

At each sample of desiccated human faeces, the pH was determined using a standard pH meter by adding 10g of human faeces to 250ml distilled water. The suspension was stirred for five minutes and then allowed to settle for one hour. The pH meter was used to determine the pH value of the tinted solution of water.

The pH of the composting material at the lab-scale was determined using a standard pH meter equipped with an electronic reading device. The pH test strip was introduced into the collected sample and it was held in for thirty seconds. After submersion, the pH strip was removed and the strip's colour swatches were allowed to brighten for five to ten seconds. Then the value indicated could be noted.

The temperature at the lab-scale composting was measured daily with a digital thermometer. There was a pipe situated at the composter that can be opened any time, and the probe could be inserted to the centre of the compost pile through the pipe. Once the reading had stabilised, the probe was slowly removed from the pile and the cover of the pipe was closed after the reader device was stable. Temperatures were recorded in the composter daily.

b) Oxygen content

The oxygen content in the composter was measured on site using an oxygen meter equipped with an electronic reading device. The probe of the reading device was also inserted when the cover of the pipe was opened and the electrode was dipped into the composter. The vacuum pump was used to bring air sucked from the composter through the tube that led to the reading device. The vacuum pump was calibrated in air to the equilibrium concentration. The read of oxygen content was undertaken once the reading has stabilised after a gentle flow was kept moving in the tube. Once the reading was recorded, the cover of the inserted pipe was closed

Measurement of oxygen content at the lab-scale

c) Moisture content

The moisture content of human faeces and composting samples was determined by the gravimetric method that consists of drying the sample in an electric oven at 105°C to a constant weight for 24 hours. The moisture content was determined by weighing $\pm$ 50g into an evaporating dish, noting the mass of the dish before and after addition of the sample. This was dried at 105°C $\pm$ 24 for an hour. The percentage of moisture content was determined by the loss of mass after heating at 105°C using the following formula:

$MC = (m_{weit} - m_{dried}) / m_{total}$

Where: MC = moisture content

m_{water} = mass of water

m_{dried} = mass dried

m_{total} = total mass of sample

d) Carbon

Carbon content was determined in the laboratory using the Loss-On-Ignition method, while the weight of different materials or organic matter (OM) was measured. The difference of original organic matter weight to that of the dry sample burned at a high temperature (105^{o}C) should be multiplied to 0.58, as in Formula 4 below. The following formula was used for the determination of carbon content in the composter:

Carbon (C) = OM (Organic matter) x 0.58

e) Nitrogen (N)

The ultraviolet colorimetric screening method was used to analyse the Nitrogen content and the procedure used was firstly performed by sterilising the sample bottles in an autoclave at 121^{o}C for 15 minutes. After the sterilisation, an autoclave tape was used to tape the sample bottle to indicate that autoclaving had been completed. Once the sample bottles had been sterilised, the mixed reagent was prepared by mixing 1 ml of HCl acid solution to 10 g of collected sample of human faeces that had been mixed thoroughly, and then weighed out 1.000g of sludge into a digestion tube.

The solution was placed on a block at 360^{0}C and covered with glass “pears”. This was again digested for two hours or until the solution was clear.

Before this solution dried, it was removed from the block and cooled slightly, and 5 ml of de-ionised water was added to cool it completely. Once cooled, it was rinsed into a 100ml volumetric flask, and the spectrometric measurement was achieved by reading absorbance against redistilled water that was set at zero.

f) Phosphorus and Potassium

The P and K were determined by ICP-AES (Inductively Coupled Plasma – Atomic Emission Spectroscopy). Where necessary, some of the values were confirmed as follows:

- A sock solution of 1000 ppm of phosphate or potassium ions was prepared by weighing 1 g of KH_2PO_4 dissolved in distilled water and made up in a 1l volumetric flask.
- The faecal matter was weighed out at 1g into a digestion tube, and mixed with 2 g of the digestion mixture.
- A 100 ppm solution was prepared by diluting the stock solution and a series of standard solutions of 0.5 ppm, 1 ppm, 1.5 ppm and 2.00 ppm were made from the 100 ppm standard solution in 100 ml volumetric flasks.
- Samples were diluted 250 times because of the high concentration of phosphate ions in faecal matter and the P1 sample was diluted 25 times, leading to high absorbance readings.

- 20 ml of each of the samples was added in clean, dry beakers and 3 ml of the combined reagent was also added in the beaker; similar standards were treated the same and the mixtures were allowed to stand for 10 minutes and run within 30 minutes.
- The standards were run first to obtain the calibration curve.
- The standards and samples' absorbencies were measured at a single wavelength of 822nm.

g) E. coli

The membrane filter was used to determine the microbiological parameters of desiccated human faeces from MobiSan facility. The procedure performed was to sterilise the sample bottle and filter membrane holder. This was performed as explained in section (e) nitrogen content measurement. Once the sample bottles and filter were sterilised, the following steps were taken:

- The 10g sample of human faeces was mixed with distilled water that was shacked for 30 seconds and filtered through a filter membrane.
- Forceps were used to transfer the filter membrane to a plate of m-Endo agar LES.
- It was ensured that no air was trapped between the surface of the agar and the membrane and that the membrane was wetted with the agar by placing the filter membrane correctly.
- The filter membrane was then inverted and incubated in the m-Endo plates at 37^{o}C for 24 hours.
- The of colonies that lacked sheen were considered to be non-coliform and so were not counted.

h) Faecal coliform

The method used was a membrane filter that consisted of incubating the sample on m-Endo for 2h at 37^{o}C and then at 44^{o}C for 22h. The faecal coliform count was completed after incubation and was followed immediately when the bacteria colonies are formed and counted as bacterial count indicator value.

The following apparatus was used: microscope counter, filter plates, weighing scale and autoclave.

The following presents the method used for the colony forming count:

Part 1: Growth medium preparation

- Nutrient Agar: 31g weighted
- 1litre of Scott bottle is used to pour it
- Demineralised water is added
- Shaking of bottle to dissolve Nutrient Agar
- Using autoclave at 121^{o}C for 0.25h
- Cooling of Agar to 45-50^{o}C

Part 2: Spreading, incubating and count

- After serial dilutions (10^{-1} – 10^{-5}) of sample suspensions, the total heterotrophic were done in triplicate on Nutrient agar plates.
- Incubation of plates for 3-4 days at 37 ^{o}C
- Counting and recording of visible cells [colony forming units, (CFU)]

Appendix B: Results of experimental work

This section of the study presents results of the experimental work conducted at the laboratory and monitoring process of the three composting treatment methods.

B.1 Characteristics of composted human faeces

Table 1: Composted human faeces from Co-composting method (from week 1-3)

Parameters:	Week 1		Week 2		Week 3	
Days:	1-7th		8-14th		15-21st	
Parameters:	S1	S2	S3	S4	S5	S6
Temperature (°C)	16	18	28	36	43	48
pH	4.4	5.6	6.5	7.6	8.1	7.5
Oxygen (%)	14	15	12	16	12	14
Moisture cont.(%)	48	42	40	40	38	35
Carbon (%)	44	46	46	48	46	45
Nitrogen (%)	13.6	13.8	14.1	14.4	15.3	15.7
Phosphorus (%)	17.6	17.8	18.5	19.4	19.7	21.7
Potassium (%)	24.1	25.3	26.3	26.4	26.7	27.2
E Coli(cou./100 ml)	3.3×10^3	3.6×10^3	3.7×10^3	3.8×10^3	3.5×10^3	3.1×10^3
FC (count/100 ml)	5.6×10^3	5.4×10^3	4.3×10^2	3.5×10^3	3.7×10^3	3.3×10^3

Table 2: Composted human faeces from Co-composting method (from week 4-6)

Parameters:	Week 4		Week 5		Week 6	
Days:	22-28th		29-35th		36-42nd	
Parameters:	S7	S8	S9	S10	S11	S12
Temperature (°C)	52	61	46	25	14	10
pH	6.8	6.5	7.1	6.8	6.4	6.2
Oxygen (%)	12	11	13	16	18	16
Moisture cont.(%)	32	35	26	18	12	08
Carbon (%)	44	46	47	46	44	47
Nitrogen (%)	15.8	16.3	17.7	18.2	19.4	21.5
Phosphorus (%)	22.4	22.8	22.9	23.7	24.1	24.6
Potassium (%)	28.3	28.7	28.5	28.9	29.4	29.8
E Coli(cou./100 ml)	3.0×10^3	2.8×10^3	2.7×10^3	2.4×10^3	2.5×10^3	2.1×10^3
FC (count/100 ml)	3.1×10^3	3.2×10^3	3.3×10^2	2.9×10^3	2.7×10^3	2.6×10^3

Table 3: Composted human faeces from Skyloo-composting method (from week 1-3)

Parameters:	Week 1		Week 2		Week 3	
Days:	1-7th		8-14th		15-21st	
Parameters:	S1	S2	S3	S4	S5	S6
Temperature (°C)	13	16	20	23	24	26
pH	5.1	5.5	6.3	6.2	6.5	6.9
Oxygen (%)	2	1	1	1	2	1
Moisture cont.(%)	55	48	43	45	44	37
Carbon (%)	58	54	53	50	48	48
Nitrogen (%)	9.5	11.1	11.2	11.0	12.7	12.9
Phosphorus (%)	14.2	16.1	16.3	16.0	16.8	15.7
Potassium (%)	8.4	8.9	9.5	9.3	9.1	9.4
E Coli(cou./100 ml)	$0.9x10^3$	$2.6x10^3$	$3.5x10^3$	$5.4x10^3$	$3.2x10^3$	$2.8x10^3$
FC (count/100 ml)	$5.3x10^3$	$3.2x10^3$	$5.1x10^3$	$8.4x10^3$	$6.3x10^3$	$7.7x10^3$

Table 4: Composted human faeces from Skyloo-composting method (from week 4-6)

Parameters:	Week 4		Week 5		Week 6	
Days:	22-28th		29-35th		36-42nd	
Parameters:	S7	S8	S9	S10	S11	S12
Temperature (°C)	24	28	24	24	22	17
pH	8.6	8.4	7.8	9.3	9.5	7.7
Oxygen (%)	2	1	1	1	2	1
Moisture cont.(%)	35	34	34	30	28	27
Carbon (%)	47	45	41	40	40	39
Nitrogen (%)	12.8	14.4	14.7	15.2	15.3	15.1
Phosphorus (%)	17.2	17.5	16.8	17.5	17.8	17.9
Potassium (%)	9.7	11.2	11.4	11.8	13.2	11.8
E Coli(cou./100 ml)	$2.7x10^3$	$2.6x10^3$	$2.5x10^3$	$2.4x10^3$	$2.2x10^3$	$2.2x10^3$
FC (count/100 ml)	$6.4x10^3$	$6.2x10^3$	$4.1x10^3$	$4.4x10^3$	$3.3x10^3$	$3.1x10^3$

Table 5: Composted human faeces from Skyloo-composting method (from week 7-9)

Parameters:	Week 7		Week 8		Week 9	
Days:	43-49th		50-56th		57- 60th	
Parameters:	S13	S14	S15	S16	S17	S18
Temperature (°C)	26	26	24	26	27	27
pH	7.1	6.6	6.5	6.4	6.3	6.0
Oxygen (%)	1	1	2	1	1	1
Moisture cont.(%)	26	26	25	24	26	24
Carbon (%)	38	37	36	35	34	34
Nitrogen (%)	15.8	15.7	16.2	16.3	15.3	15.5
Phosphorus (%)	18.1	19.2	18.8	18.6	18.3	18.1
Potassium (%)	12.6	12.8	12.8	12.9	13.1	13.4
E Coli(cou./100 ml)	$2.1x10^3$	$1.8x10^3$	$1.4x10^3$	$1.4x10^3$	$1.3x10^3$	$1.1x10^3$
FC (count/100 ml)	$2.9x10^3$	$2.5x10^3$	$2.4x10^3$	$2.3x10^3$	$2.1x10^3$	$2.0x10^3$

Table 6: Composted human faeces from Bio-process composting method (from week 1-3)

Parameters:	Week 1		Week 2		Week 3	
Days:	1-7th		8-14th		15-21st	
Parameters:	S1	S2	S3	S4	S5	S6
Temperature (°C)	14	15	31	33	46	48
pH	5.1	5.3	5.8	7.4	7.6	8.5
Oxygen (%)	18	18	16	12	14	12
Moisture cont.(%)	51	48	44	39	37	31
Carbon (%)	52	56	53	49	46	46
Nitrogen (%)	15.2	15.6	15.2	16.3	17.4	17.2
Phosphorus (%)	18.5	19.4	17.4	18.6	19.4	23.5
Potassium (%)	26.5	26.1	26.2	28.7	28.5	31.2
E Coli(cou./100 ml)	$2.5x10^3$	$2.4x10^3$	$1.9x10^3$	$1.7x10^3$	$1.6x10^3$	$1.8x10^3$
FC (count/100 ml)	$6.1x10^3$	$5.3x10^3$	$5.2x10^3$	$4.8x10^3$	$4.6x10^3$	$4.1x10^3$

Table 7: Composted human faeces from Bio-process composting method (from week 4-6)

Parameters:	Week 4		Week 5		Week 6	
Days:	22-28th		29-35th		36-42nd	
Parameters:	S7	S8	S9	S10	S11	S12
Temperature (°C)	53	65	54	27	18	14
pH	7.2	6.4	6.2	6.1	5.4	5.1
Oxygen (%)	14	13	17	14	16	15
Moisture cont.(%)	30	30	28	25	22	17
Carbon (%)	44	43	41	40	42	41
Nitrogen (%)	18.5	16.7	18.7	19.3	21.2	23.7
Phosphorus (%)	24.2	23.9	23.9	24.1	25.3	25.7
Potassium (%)	31.9	32.7	32.5	28.6	28.2	31.7
E Coli(cou./100 ml)	$1.7x10^3$	$1.5x10^3$	$1.5x10^3$	$1.2x10^3$	$1.4x10^3$	$1.2 x10^3$
FC (count/100 ml)	$5.6x10^3$	$5.4x10^3$	$5.1x10^3$	$5.1x10^3$	$4.8x10^3$	$3.8x10^3$

B.2 Monitoring and control parameters at the lab-scales

B.2.1 Co-composting

Table 5:Co-composting method (From week 1-3)

Parameters:	Week 1			Week 2			Week 3		
Days:	1-7th			8-14th			15-21st		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	14	16	18	25	28	36	40	43	48
Oxygen (%) or (aeration)	13	14	15	10	12	16	12	12	14
Moisture content (%)	46	48	42	39	40	40	39	38	35

Table 6: Co-composting method (From week 4-6)

Parameters:	Week 4			Week 5			Week 6		
Days:	22-28th			29-35th			36-42nd		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	51	52	61	49	46	25	13	14	10
Oxygen (%) or (aeration)	12	12	11	12	13	16	15	18	16
Moisture content (%)	33	32	35	25	26	16	18	18	16

B.2.2 Skyloo-composting

Table 7:Skyloo-composting method (From week 1-3)

Parameters:	Week 1			Week 2			Week 3		
Days:	1-7th			8-14th			15-21st		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	11	13	16	18	20	23	23	24	26
Oxygen (%) or (aeration)	2	1	1	1	1	1	1	2	1
Moisture content (%)	58	55	48	45	43	45	41	44	37

Table 8:Skyloo-composting method (From week 4-6)

Parameters: Days:	Week 4			Week 5			Week 6		
	22-28th			29-35th			36-42nd		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	25	24	28	25	24	24	23	22	17
Oxygen (%) or (aeration)	1	1	1	1	1	1	1	1	1
Moisture content (%)	35	35	34	35	34	30	29	28	27

Table 9: Skyloo-composting method (From week 7-9)

Parameters: Days;	Week 7			Week 8			Week 9		
	43-49th			50-56th			57- 60th		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	28	26	26	25	24	26	28	27	27
Oxygen (%) or (aeration)	1	1	1	1	2	1	1	1	1
Moisture content (%)	23	26	26	25	25	24	25	26	24

B.2.3 Bio-process composting

Table 10: Bio-process composting method (From week 1-3)

Parameters: Days:	Week 1			Week 2			Week 3		
	1-7th			8-14th			15-21st		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	25	14	15	22	31	33	40	46	48
Oxygen (%) or (aeration)	16	18	18	14	12	14	13	14	12
Moisture content (%)	54	51	48	45	44	39	38	37	31

Table 11: Bio-process composting method (From week 4-6)

Parameters: Days:	Week 4			Week 5			Week 6		
	22-28th			29-35th			36-42nd		
	1	2	3	1	2	3	1	2	3
Temperature (°C)	55	53	65	60	54	27	25	18	14
Oxygen (%) or (aeration)	16	14	13	15	17	14	15	16	15
Moisture content (%)	26	30	30	27	28	25	22	22	17

Appendix C: Variation of parameters in the three composting methods

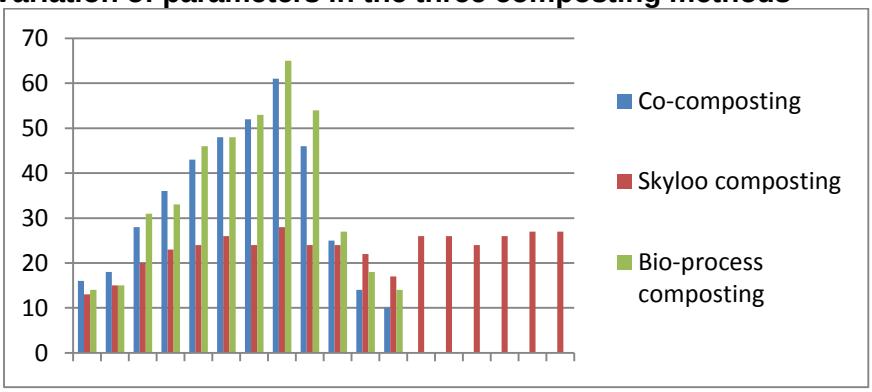


Figure 1: Change level of temperature

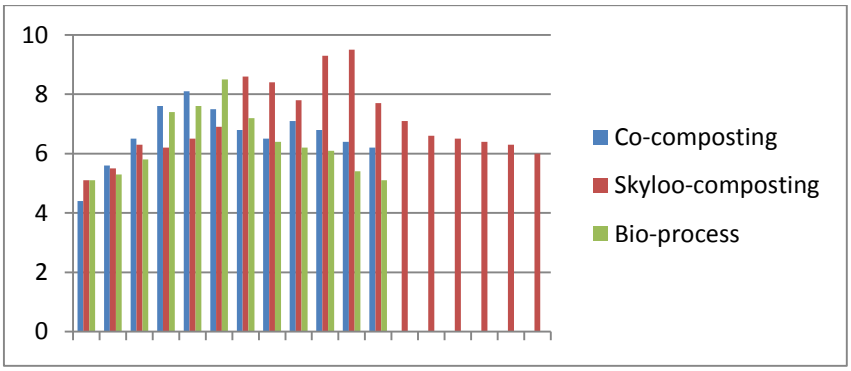


Figure 2: Change level of pH

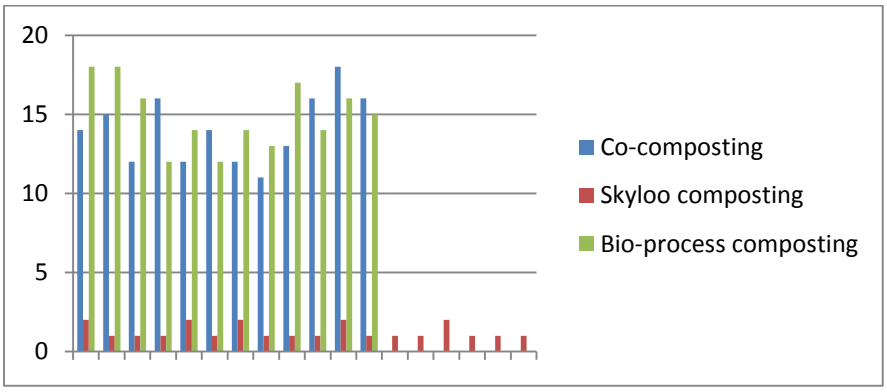


Figure 3: Change level of oxygen

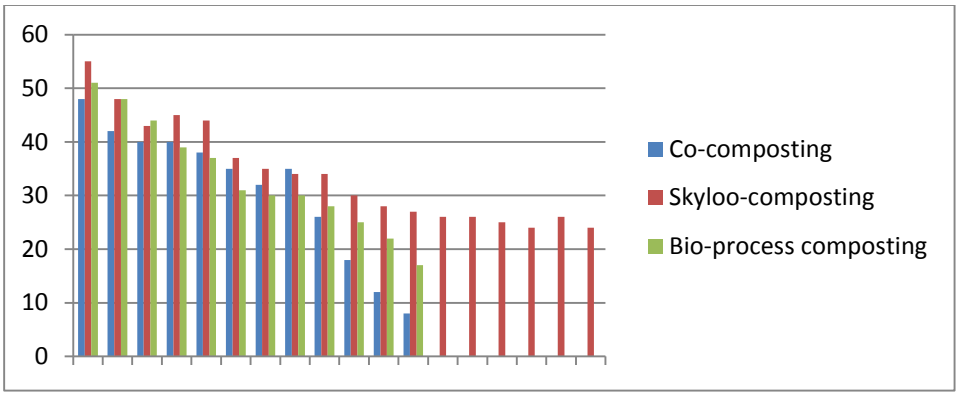


Figure 4: Change level of moisture content

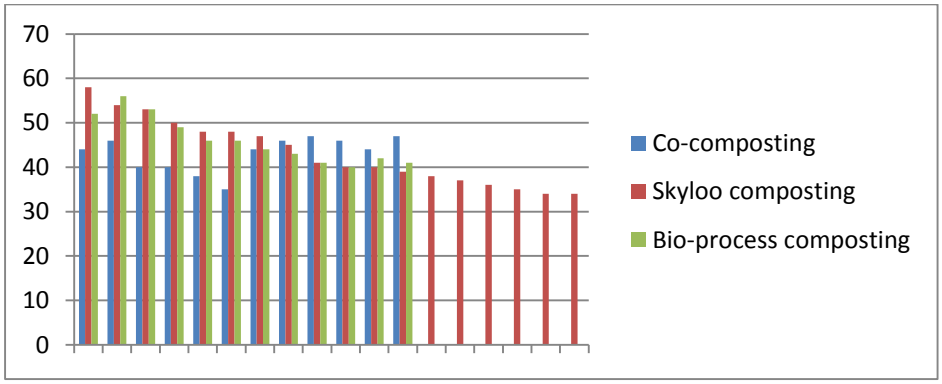


Figure 5: Change level of carbon content

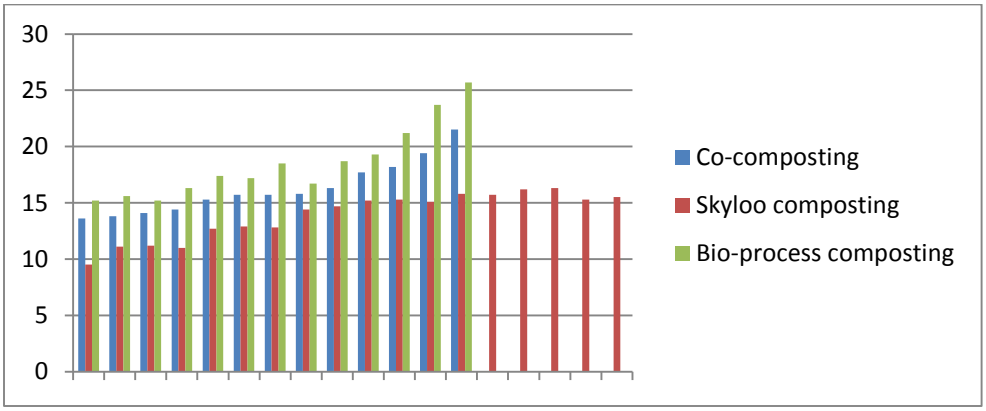


Figure 6: Change level of nitrogen content

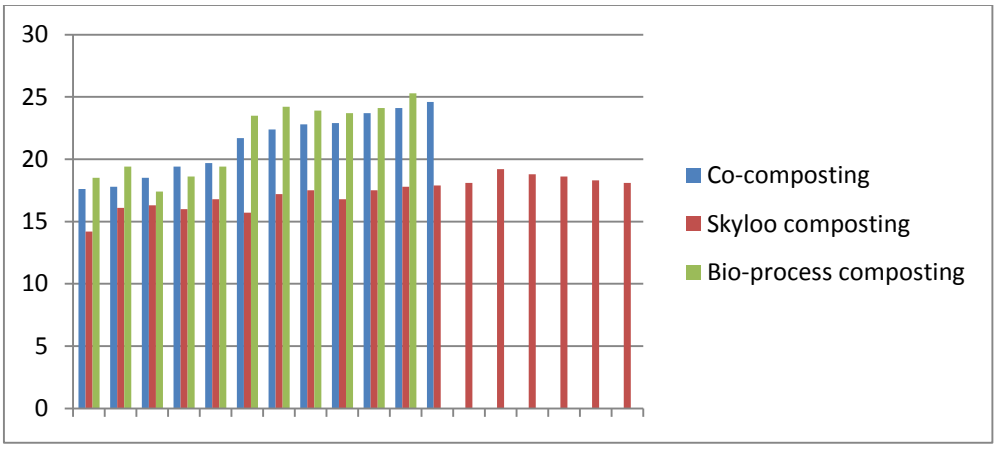


Figure 6: Change level of phosphorus content

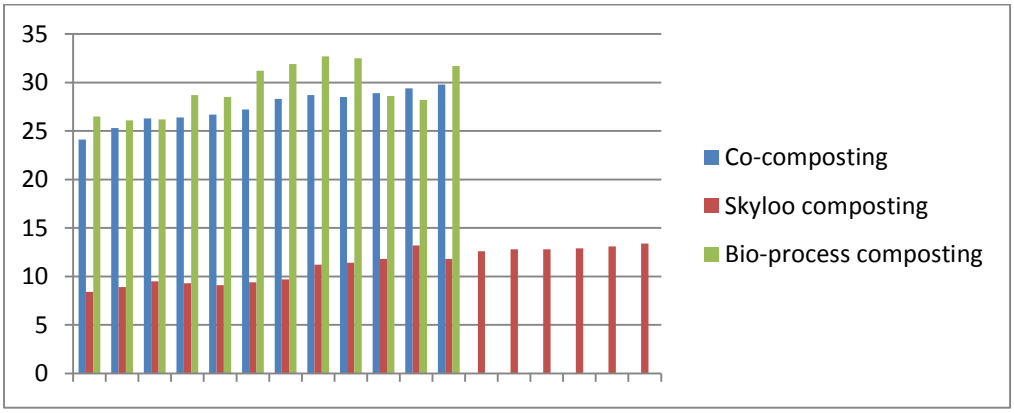


Figure 7: Change level of potassium content

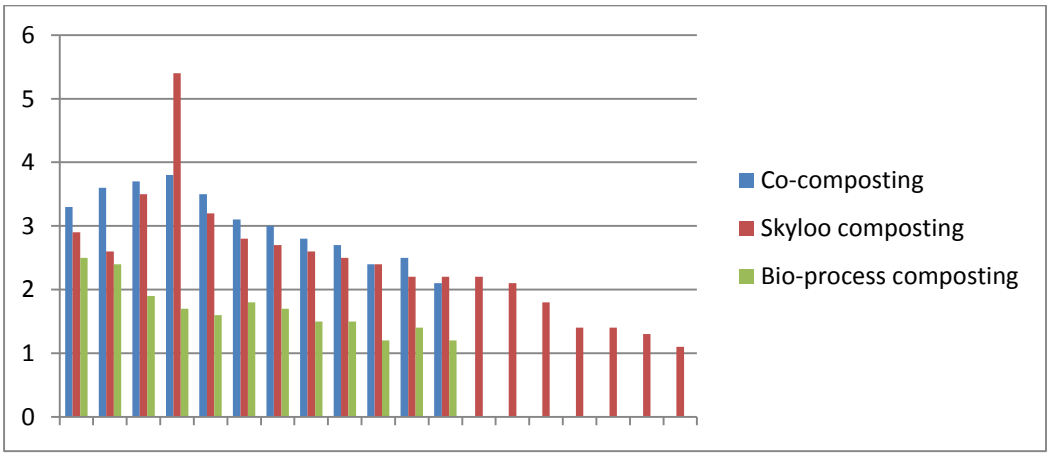


Figure 8: Change level of E.coli

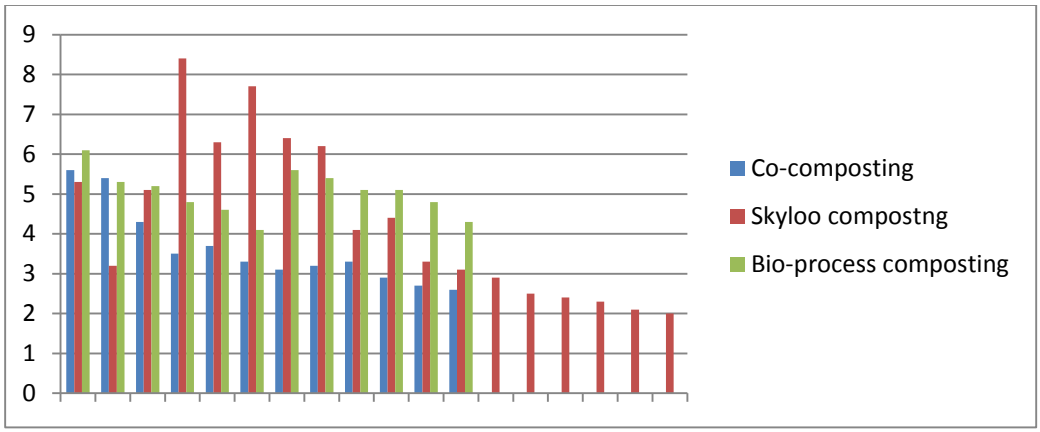


Figure 9: Change level of Faecal coliform

Appendix D: Pictures of experimental work on site and at the laboratory

D1: MobiSan facility installed at Pooke se Bos Informal settlement (Cape Town)

D2: Mixing devices 1 and 2 situated at one side of the MobiSan

D3: Desiccated HF in the male toilet vault

D4: Desiccated HF in the female toilet vaults

D5: Desiccated HF from night soil disposal

D6: Desiccated HF in the children toilet vaults

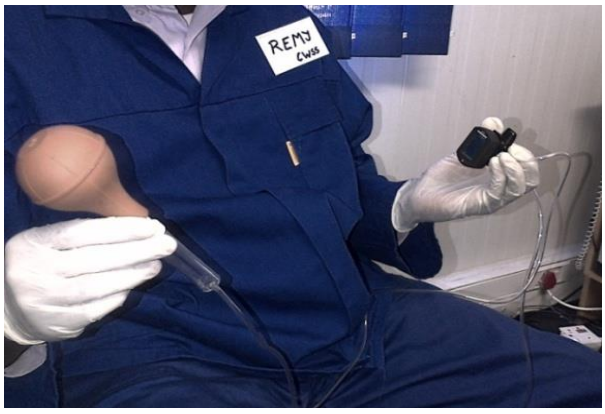
D7: Collection of Desiccated HF from night soil disposal

D8: Desiccated human faeces is collected in the plastic bags for its transportation to the lab scales.

D9: Desiccated human faeces is transferred in the first composter for the composting process.

D10:Temperature measurement on the Co-composting process

D11: Oxygen meter is used for the measurement of oxygen in the composter



D12: Reading of oxygen content from the lab-scale during the operation.

D13: Collection of moisture content

D 14: Three samples of composted faeces are collected from three different lab-scales to measure the moisture content.

D15: Composted human faeces is taken out from Skyloo composting lab-scale.

D16: Final quality or matured compost from two lab-scales Co-composting and Bio-process composting

D17: Sample of composted faeces have to be weighed to determine the carbon content.

D18: Mixing indicator for the measurement of nutrients

D19: Addition of some chemical to the reagent

D20: Mixing of distilled water with reagent for the determination of Nitrogen content

D21: Bottle of distilled water is used for pH testing

D22: The measurement of pH at the Lab using pH meter device

D23: Mixing of distilled water and sample of composted human faeces

D24: Determination of colony forming count using the nutrient Agar