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Optimizing Vermitechnology for the Treatment of Blackwater: A Case of the Biofil Toilet Technology

By

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DECLARATION

I hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of any university, except where due acknowledgement has been made in the text.

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ABSTRACT

Human excreta management in urban settings is becoming a serious public health burden. This thesis used a vermi-based treatment system; "Biofil Toilet Technology (BTT)" for the treatment of faecal matter. The BTT has an average household size of 0.65 cum; a granite porous filter composite for solid-liquid separation; coconut fibre as a bulking material and worms "*Eudrilus eugeniae*" as waste digesters. The effluent after bio-filtration is discharged into the subsurface soil via a drain field. Laboratory scale models of the BTT were setup to assess the effect of different filtering composites [palm kernel shell (PKS), granite aggregates (GR), polyethylene terephthalate (PET)] on contaminant removal; effect of continuous solid loading at different rates (light - 10 users, moderate - 15 users, heavy - 25 users); and toxicity effect of household chemical reagents (chloroxylenol in dettol, hydrogen chloride in harpic, sodium hypochlorite in bleach) on the BTT. Soil columns (red laterite soil, sandy soil, loamy soil) were used to assess the treatment efficacy of subsurface infiltration using the BTT effluent. The BTT was effective in the removal of BOD_5, COD, helminth and microbial loads in blackwater. There was no significant removal of dissolved solids and nutrients in the effluent through the porous filter composites. However, there was a significant reduction of microbial loads in the effluent through the PET. Red laterite soil was the most effective in the reduction of dissolved solids, nutrients and microbial loads from the BTT effluent up to 80 % within the first 0.3 m and an overall effective removal up to 90 % at depth 1.5 m. The toxicity test revealed a 100 % survival rate of the spiked earthworms under normal application of the chemical reagents. In the solid loading test, organic matter was degraded by 32.2 % to 52.5 %. Volatile solid reduction in the low loading (8.3 %) within a week conformed to prevailing studies. Light loading exhibited rapid loss of N (with an overall 40.7 % N loss). This thesis recommends the BTT as a robust technology for blackwater treatment.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ASAD	Average Solid Area of Digester
BIOFILCOM	Biological Filters and Composters Ltd
BOD_5	Biochemical Oxygen Demand
BTT	Biofil Toilet Technology
C	Carbon
Cu	Coefficient of Uniformity
CED	Civil Engineering Department
CFU	Colony Forming Unit
COD	Chemical Oxygen Demand
CS	Clayey Soil
EcoSan	Ecological Sanitation
ECL	Elevated Compost Latrine
FMR	Faecal Mass Remaining
FS	Faecal Sludge
Ghana EPA	Ghana Environmental Protection Agency
GR	Granite
GSGDA	Ghana Shared Growth and Development Agenda
HCL	Hydrogen Chloride
KNUST	Kwame Nkrumah University of Science and Technology
KVIP	Kumasi Ventilated Improved Pit latrine
LS	Loamy Soil
LSD	Least Significant Difference

N	Nitrogen
OSS	Onsite Sanitation Systems
PCF	Pervious Concrete Filter
PKS	Palm Kernel Shell
PL	Pit Latrine
PVC	Polyvinyl Chloride
RLS	Red Laterite Soil
PET	Shredded polyethylene terephthalate
SS	Sandy Soil
TDS	Total Dissolved Solids
TFMA	Total Faecal Mass Added
TN	Total Nitrogen
TP	Total Phosphorous
TS	Total Solids
TSAD	Total Surface Area of Digester
TSAED	Total Surface Area of Experimental Digester
TSS	Total Suspended Solids
VIP	Ventilated Improved Pit
VS	Volatile Solids
WC	Water Closet
WHO	World Health Organization

DEFINITION OF TERMS

Aerobic degradation: In the presence of oxygen and appropriate aerobic micro-organisms, biodegradable material will be converted to CO_2, water and more cell mass for the participating micro-organisms

Biochemical Oxygen Demand (BOD): This represents the organic material that can be degraded biologically.

Biodegradable: a substance that can be broken down into basic molecules (e.g. carbon dioxide, water) by organic processes carried out by bacteria, fungi, and other microorganisms.

BIOFILCOM: is a private firm under which the inventor of the Biofil Toilet Technology (Mr. Kweku Anno) markets the technology

Biological treatment: the use of living organisms (e.g. bacteria) to treat waste; this is in contrast to chemical treatment which relies on chemicals to transform or remove contaminants from waste.

Biomass: refers to the quantity of living organisms. It is often used to describe the 'active' part of the sludge that is responsible for degrading the organic matter.

Biosolids: faecal sludge accumulated on the top of porous filters and has been digested/stabilized. It is a term also given to the residue when sludge is dewatered.

Blackwater: the mixture of urine, faeces and flushwater along with anal cleansing water (if anal cleansing is practiced) and/or dry cleansing material (e.g. toilet paper).

Bulking material: dry and fibrous materials such as sawdust, leaf moulds, finely chopped straw, peat moss, rice hulls or grass clippings, mixed in the Biofil digester in order to prevent odour, absorb urine, and eliminate any fly nuisance.

Chemical Oxygen Demand (COD): measures the equivalent amount of oxygen required to chemically oxidize organic compounds

C/N ratio: carbon to nitrogen ratio. This ratio describes the relative amounts of dry available carbon to dry available nitrogen. The ideal value for microbes is around 30:1 (usually expressed as just 30).

Desludging: the process of removing sludge from a tank, pit, or other storage unit.

Digestion: similar to decomposition, but usually applied to the decomposition of organic materials (including bacteria) by bacteria, in sludge.

Ecological Sanitation: is a term applied to waste treatment technologies when they not only limit the spread of disease, but protect the environment and return nutrients to the soil in a beneficial way.

Effluent: is the general term for liquid that has undergone some level of treatment and/or separation from solids.

Environmental sanitation: refers to solid waste as well as industrial and household waste (e.g. liquid waste and grey water).

Excreta: consists of urine and faeces that is not mixed with any flushing water. Excreta are small in volume, but concentrated in nutrients and pathogens. Depending on the quality of the faeces it is solid, soft or runny.

Faecal sludge: sludge of variable consistency (partially digested slurry or solid) that result from the storage of blackwater or excreta and collected from on-site sanitation systems such as latrines, non-sewered public toilets, septic tanks, and aqua privies.

Faeces: refers to (semi-solid) excrement without urine or water.

Filtrate: the liquid that has passed through a filter.

Flush water: is the water that is used to transport excreta from the User Interface to the next technology. Freshwater, rainwater, recycled greywater, or any combination of the three can be used as a flush water source,

Full-flush system: a Biofil toilet that uses as much as 9 - 12 litres of water per flush

Helminth: A parasitic worm, i.e. one that lives in or on its host, causing it damage. Examples include especially parasitic worms of the human digestive system, such as roundworm (e.g. *Ascaris*) or hookworm.

Improved sanitation: connection to a public sewer, connection to a septic system, pour-flush latrines, simple pit latrines and ventilated improved pit latrines, whilst not improved facilities are defined as public or shared latrines, open pit latrines and bucket latrines.

Leachate: the liquid fraction of a mixed waste that, through gravity or filtration, is separated from the solid component.

Micro flush system: a Biofil toilet that uses up to 1 litre of water per flush

Onsite Sanitation: On-site sanitation refers to the range of actions related to the treatment and reuse/disposal of domestic waste water that cannot be transported by off-site systems

Organics: refers here to biodegradable material that could also be called biomass or green organic waste.

Pathogen: infectious biological agent (bacteria, protozoa, fungi, helminth, viruses) that inflicts disease or illness on its host.

Percolation: the movement of liquid through soil with the force of gravity.

Porosity: the fraction of volume of void space area to total volume of medium (Nield and Bejan 1992)

Porous filter composite: It is pervious gravel packing bonded by a correct mix cement and water that is used for solid-liquid separation of blackwater in the biofil digester.

Sanitation: in this thesis sanitation is defined as the safe management of human excreta.

Septage: sludge from septic tanks

Sewage: general name given to the mixture of water and excreta (urine and faeces), although in the Compendium it referred to as blackwater.

Shared sanitation facilities: These are sanitation facilities of an otherwise acceptable type that are shared between two or more households, including public toilets.

Sludge: the thick, viscous layer of materials that settles to the bottom of septic tanks, ponds, and other sewage systems. Sludge is comprised mostly of organics, but also sand, grit, metals, and various chemical compounds.

Solid loading rate: total solid weight of faecal sludge applied to the BTT system per unit surface area and time.

Stabilization: the extent of conversion of degradation of biodegradable organic material to biomass and gases

Stabilized: the term used to describe the state of organic material that has been completely oxidized and sterilized.

Sustainable sanitation system: economically viable, socially acceptable, technically and institutionally appropriate, and protect the environment and natural resources (SuSanA, 2008).

Treated sludge: is the general term for partially digested or fully stabilized faecal sludge.

Volatile solids: are those solids in water or other liquids that are lost on ignition of dry solids at 1020°F (550°C).

Waste digester: these are invertebrates (e.g. earthworms and Black Soldier Fly) that feed voraciously on organic waste including faecal matter.

DEDICATION

I dedicate this work to the Almighty God.

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CHAPTER ONE

1.0 INTRODUCTION

Ghana is one of the most urbanised countries in Africa (WSUP, 2017) with a population of 27.4 million (WSUP, 2015). An estimated 53 % of the population lived in cities in 2014 (WSUP, 2017), with an estimated 37.9 % of urban dwellers (population of 14 million) living in slums (WSUP, 2017). This rapid urbanization is putting a lot of pressure on its social interventions. Urban sanitation infrastructure has not kept pace with the growing urbanization; this has led to Ghana failing its Millennium Development Goal (MDG) for sanitation with only 15 % sanitation coverage (WHO, 2015) as against the anticipated 54 %.

Shared toilets facilities are mainly used by households in Ghana (60 % of the population), with about 73 % of urban dwellers relying on such facilities (WSUP, 2017). The shared toilets are in two main types: (1) “Compound toilet”, a facility shared by more than ten households living in a single compound or residence; and (2) Public toilet, a facility located within a large community where people pay to use daily.

The provision of sanitation infrastructure in Ghana can be captured under two scenarios:

(1) There are situations where sewerage systems are the means of sanitation, but these serve a small proportion of the urban population (national percentage of 3.4 %: GSS, 2013). Sewerage services are present in parts of Accra, Tema, Akosombo and Kumasi. Most of the treatment facilities are mostly non-functional (WSUP, 2017). A study carried out in 2012 reported on 75 wastewater treatment systems in Ghana. Out of these only 24 % were functional and 69 % were either not functioning or partially functioning. The status of the remaining 7 % could not be ascertained (Waterbiotech report, 2012). Consequently, generated wastewater is disposed untreated into most water bodies;

(2) Most of the toilet facilities (including household toilets) are on-site technologies. In Ghana, many on-site sanitation (OSS) technologies are being used in urban communities to serve households. The following urban sanitation technologies can be identified: Pit latrines (PL), Ventilated Improved Pits (VIP), Kumasi Ventilated Improved Pit (KVIP), Elevated Compost Latrine (ECL), Water Closet and/or Pour flush connected to septic tanks and the Biofil toilet technology. Septic tanks have been heavily relied on in areas where there are no central sewerage systems. Septage has to be desludged and sent for further treatment at central treatment systems. Since these are limited, septage ends up mostly in drains, bushes and open water bodies. In the case of dry on-site toilets, high-strength faecal sludges are generated and have to be sent for further treatment but these also end up being indiscriminately disposed into drains and bushes. The Biofil toilet technology is a vermi-based treatment technology which does not require deep excavation for construction of tanks/pits and emptying of its contents for further treatment, but has yet to scale-up for household application (WSUP, 2017).

The sanitation situation and the complexities of urban cities call for more innovative sanitation approaches that close material cycles, protect human and environmental health to be researched and developed (Buzie-Fru, 2010).

1.1 Background

The lack of access to improved sanitation potentially contributes to environmental pollution. In situations where toilet facilities are lacking, human excreta may be found around homes, in nearby drains and garbage dumps, leading to environmental pollution (Kulabako *et al.,* 2007). Rapid urbanization and population growth is making human excreta management in urban poor communities very challenging. These new sites lack standard municipal infrastructure including access roads, sewerage and adequate water supply. Without these basic services, effective excreta management becomes expensive; but it is essential in order to prevent environmental contamination and disease transmission (Hill and Baldwin, 2012). To solve these sanitation challenges, several novel techniques have been introduced in recent years. Recovery of nutrients and energy from solid/liquid wastes with low-inputs is now recognized potentially in several aspect of waste management (Suthar, 2010).

Given the need to seek alternative solutions to conventional systems, priority has been given to those technologies which have minimum energy cost, simple operational and maintenance procedures and high treatment efficiency (Li *et al.*, 2012). In recent times, most scientific literature has been conducted on the technical aspects of innovative technologies based on bench-scale research under controlled conditions. Vermicomposting is one such technology employing the use of earthworms to decompose organic waste. For instance, substrate such as human faeces has been investigated into their decomposability using different species of earthworms (Gajalakshmi and Abbasi, 2008). An appropriate process design and optimisation for vermicomposting of human faeces at the household is still unaddressed (Abbasi *et al.*, 2008).

The Biofil Toilet Technology (BTT) is an innovation of Mr. Kweku Akuam Anno of the Biological Filters and Composters Ltd (BIOFILCOM). It employs solid-liquid separation and vermicomposting for the treatment of blackwater. The technology has a porous filter made from granite aggregates and cement to separate solids from the liquid fraction in blackwater. It is also stuffed with coconut fibre with a net lining on top of the porous filter (Figure 2-2). The technology was officially launched with the Ghana Institute of Engineers in 2008.

There have been little in-depth studies conducted on the BTT regarding its treatment mechanism and the process conditions for optimal performance. This study seeks to assess and optimise the performance of the BTT for the treatment of blackwater.

1.1.1 History of the development of the Biofil toilet technology

The development of the Biofil toilet technology started with the desire to correct a failed septic tank used by Mr. Kweku Anno and his family while growing up. The tank frequently spilled due to groundwater infiltration into the tank. It had to be frequently desludged. This was usually associated with odour. His area of residence (Dzorwulu) was situated in a low-lying area of Accra with a very high water table. In the bid to remedy the situation, he began to circulate the effluent in the septic tank by pumping. Initially this helped reduce the odour but not the amount of wastewater. In addition, it became very expensive with the continuous pumping.

He further went on to develop a box with a porous filter made from coarse aggregate to separate the solid from the liquid as he likened the odour generation in the septic tank to having soaked clothes overnight in water as against wet clothes which were squeezed and also left overnight. This box after separating the solids from the effluent from the septic tank demonstrated a reduction in the odour. With time, earthworms began growing on the solids by crawling from the neighbouring soil into the box, thereby reducing the volumes of solids within a short time. A continuous study of this box revealed a steady state where there was considerable reduction of odour upon addition of fresh faecal matter. He further realized the earthworms needed something more to remain in the box, thus, he started introducing humus and other kitchen waste. In addition, anytime the box was submerged, the earthworms would disappear. To resolve this, he created an upper haven with straw where they could migrate. The outcome of this design made him install the same setup on their residential building at Dworwulu by cutting off the pipe connecting the septic tank. He attached the box to the building at the point where the pipe connecting the toilet seat exited the building; to prevent turbulent mixing of the faeces and flushwater before entering the box. He further went on to install a number for family and friends to use, and in a farmhouse of a colleague. Positive feedback from all these initial users, gave him the idea to try to commercialize the product.

In the initial years, it was very difficult getting people to use the product. New users were apparently begged to have the installation at no cost to them. The performance of the invention got many people interested through recommendation by users. There were interests from other international partners. In a bid to protect the product, Mr. Kweku Anno launched the BTT with the Ghana Institute of Engineers (GHIE) in 2008. At the launch, the AngloGold Ashanti Iduaprim Mines had similar problems with their staff quarters septic tanks and invited him for a feasibility assessment. A contract for installation of the products for some 120 staff quarters got the team busy for almost two years. In this period, the product was perfected to its current design to meet commercialization standards. The aftermath of this project was marketing of the products through exhibitions and recommendations by word of mouth from users.

In between this time in 2009, Stephen Mecca found Mr. Kweku Anno and used the Biofil Toilets on one of his initiated projects in Pokuase in Ghana under the auspices of the Global Aid Sanitation Project (GSAP). He later got the Bill and Melinda Gates Foundation (BMGF) to visit BIOFILCOM out of which the BMGF started engaging directly with BIOFILCOM and Mr. Kweku Anno leading to a grant award with the BMGF to help the company scale-up to other markets.

The main competitor of the BTT globally which is the “Tiger” toilet was initiated through a Bill and Melinda Gates Foundation (BMGF) funded project with the London School of Hygiene. Before their study, Walter Gibson (Founder & Director) of the “Tiger” toilet met with Mr. Kweku Anno in Seattle in 2012 by which time the BMGF had contacted BIOFILCOM and Kweku Anno.

1.2 Problem Statement

Generally, there have been a number of studies on vermicomposting using municipal organic waste and sludge but there is little literature on its application on blackwater. Since the development of the Biofil toilet technology for the treatment of blackwater at the household, there has been little data/literature on its treatment mechanisms and performance amongst other things. The technology has been said to rapidly degrade faecal matter without the need to be desludged; it eliminates odour compared to the other traditional technologies like the pit latrines; these have not been documented. It is also not documented how the various system components such at the porous filter composite for solid-liquid separation and bulking material contribute to treatment of blackwater. The existing porous composite made from granite aggregates is thought to be heavy to carry and transport. There have been a number of questions around its treatment mechanism; and the rate of fill and/or the rate of decomposition when heavily used. Particularly for the Biofil toilet technology, there is a perception that household chemicals and disinfectants can destroy the bacteria and earthworm population of the system, thus rendering them dysfunctional after the use of such chemicals. There is limited data regarding the toxic effects of such household cleaning chemicals on invertebrates, such as earthworms and notably the BTT. The extent to which effluent discharge from the biofil toilet technology through the sub-surface soil can cause groundwater pollution is also unknown.

1.3 Research Questions

Key questions on the Biofil toilet technology need to be addressed and gaps bridged and the system optimized for sustainability and effective contribution to the WASH sector. As a result of the limited studies conducted on the BTT, the following questions remain to be addressed. They include:

- What is the quality of effluent generated from the BTT and after percolation through soil; is it a potential source of groundwater contamination?
- What are the levels of microbial and nutrient load reduction effected by the different porous filter composites in the BTT?
- What operational conditions will adversely affect or enhance the performance of the vermin in the BTT?
- What operational practices or maintenance activities will affect the performance of the BTT?

Answers to the above questions will serve as the basis for the optimization of the BTT for effective solids-liquid separation and solid reduction without contamination of the surrounding environment.

1.3.1 Hypotheses

The underlying hypotheses of the research include:

1. Porous filters composites only play a solid-liquid separation role in the BTT;
2. Coconut fibre will increase the rate of decomposition of faecal matter irrespective of the role of the earthworms in the BTT;
3. Subsurface infiltration can effectively treat effluent from the BTT;
4. Heavy solid loading of the BTT will cause it to fill quickly; different hydraulic loading affect faecal matter decomposition; and
5. Household cleaning chemicals kill 100 % population of earthworms in the BTT and stops faecal matter degradation.

1.4 Research aim and objectives

1.4.1 Goal of Research

The main aim of the study was to assess and improve the performance of the BTT for blackwater treatment.

1.4.2 Specific Objectives

The specific objectives of the research are:

(SO1) To assess the effect of different porous filter composites and coconut fibre on contaminant removal from the blackwater

(SO2) To assess the treatment efficiency of subsurface infiltration using pre-treated effluent from the BTT

(SO3) To assess the effect of the solid loading rate on the treatment performance for optimization of the BTT

(SO4) To assess the toxicity effect and recovery rates of the vermin in the BTT to household chemicals reagents normally applied in cleaning or disinfecting the toilet bowls.

1.5 Justification

The patronage of the BTT as a novel worm-based blackwater treatment facility is gaining much momentum within and beyond the boundaries of Ghana. The uniqueness of the facility in handling blackwater at the household level is overwhelming due to the relatively smaller size of the facility (0.65 sqm) compared with the other traditional toilet technologies such as the pit latrines, compost toilets and septic tanks.

According to Hill and Baldwin (2012) in their study of source-separating vermicomposting toilets, there was little literature documented for comparison of their results on such treatment systems of human waste, thus the need for this study. Other works by Buzie-Fru (2010) suggested that although the potential of vermicomposting source-human excreta has somewhat been demonstrated, there needs to be more work on the technology design, operation and engineering. The solid loading rate applied during start-up is among the important parameters that influence the design parameter of a reactor and subsequently, the effective treatment of the waste sludge. A further call by Yadav (2011) suggested the need for a lot more studies to establish accurate design criteria of efficient and economical vermicomposting systems. Since the BTT has been identified as one of the commercialised vermi-based facility; to the best knowledge of the author, it was very crucial to attempt to study the technology, answer a number of pertinent questions around its operations and recommend some optimization mechanisms for the effectiveness of the technology.

1.6 Scope of Study

The scope of the study have been summarised in Figure 1-1. It focused on testing the currently used granite filter composite and two other composite materials (Polyethylene terephthalate and palm kernel shells) to assess the potential for contaminant reduction in blackwater. The potential for effluent treatment using the sub-surface soil was also investigated. Different solid loading rates of faecal matter on the performance of the Biofil toilet technology have also been studied. The effect of three commonly used household cleaning chemical reagents on the system was also studied.

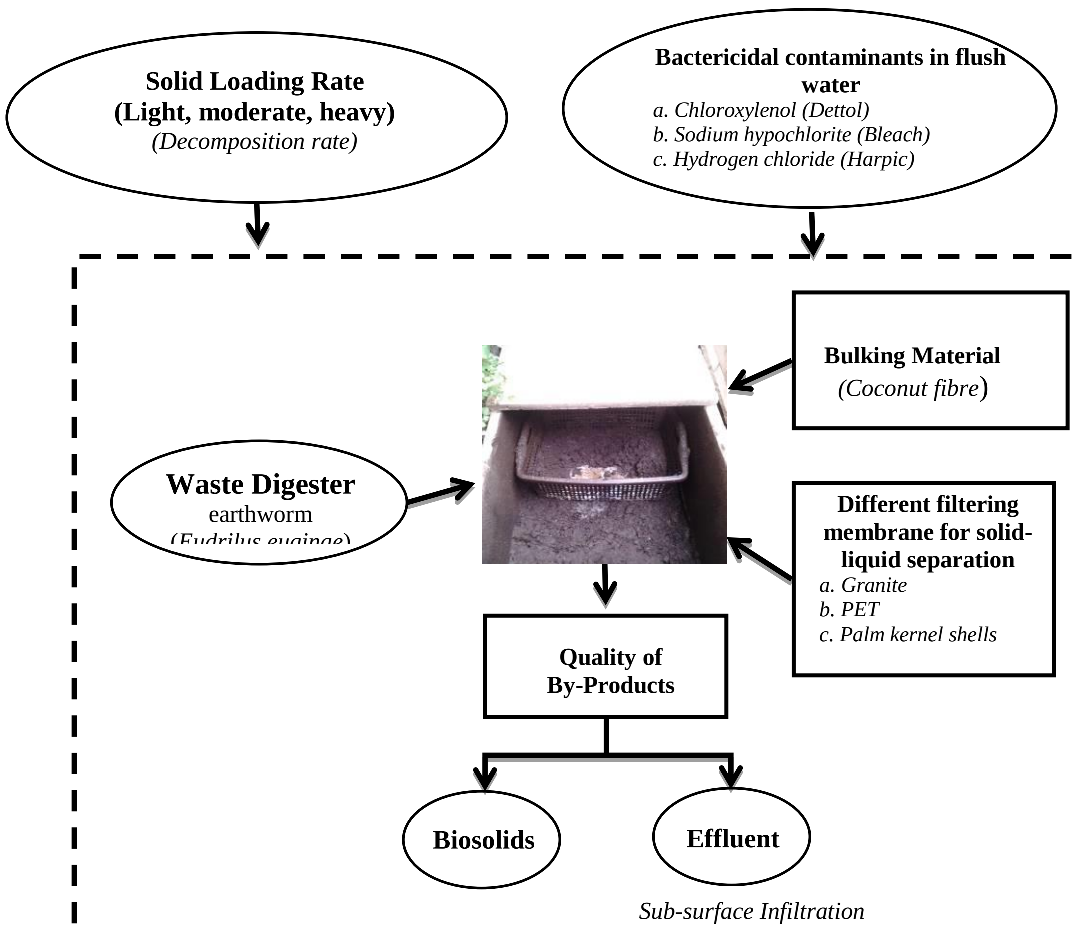

Figure 1-1: Conceptual framework for scope of study

1.7 Structure of the Thesis

The thesis is written in five chapters. The first chapter introduces the thesis and provides a background to the problem statement. Research questions, objectives, significance and scope of the study are all discussed in this chapter.

Chapter two presents review of pertinent literature related to the topic. Experimental procedures, protocols and methods for analysing data are discussed in Chapter three.

Chapter four presents the results of the study and a thorough discussion and evaluation of the findings. Chapter five concludes the thesis and presents recommendations based on the findings of the study.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Definition of Sanitation

Sanitation is defined as the protection of a community from diseases associated with poor waste management practices and improvement in the overall environmental quality (Awuah, 2014). Sanitation is a term primarily used to characterize the safe and sound handling (and disposal) of human excreta (Avvannavar and Mani, 2008). The Ghana National Sanitation policy defines sanitation as developing and maintaining a clean, safe and pleasant physical environment for all human settlements, to promote the social, economic and physical well-being of all sections of the population.

2.2 Global sanitation

Globally, an estimated 32 % of people live (global population stands at 7.3 billion) without improved sanitation (WHO, 2015), with majority resorting to use of buckets/plastic bags to dispose of faeces (BMGF, 2011). Conventional sanitation; a flush toilet connected to a centralized sewer system is only possible for a small fraction of people in developing nations, thus the poor are left with on-site systems of faeces disposal such as pits or bucket latrines (BMGF, 2011; Wittington *et al.,* 1993; Arku *et al.,* 2008).

It is estimated that one third of the world's population rely on on-site sanitation installations such as pit latrines, aqua privies and septic tanks (WHO, 2015).

2.2.1 New trends in sanitation

There is a focus on sustainable sanitation with the numerous sanitation challenges that need to be solved. The primary focus is to rely on locally adapted solutions to sanitation problems.

Biological toilets work on the basis of collecting faeces, urine and/or flush water and anal cleansing material in a container and then composted by an aerobic degradation process with the objective of getting rid of so much flush water such that the remaining solids become sufficiently porous. Draining of the excess water in the blackwater can be achieved by the following methods though the last two can be technically challenging: a) by draining the liquid off— though this may cause a pollution problem; b) by absorbing the liquid — thereby increasing the necessary compost volume; c) by evaporating the liquid. Notwithstanding this, the first and simplest option has the potential of causing pollution problems when not tackled well (Dag Guttormsen, 1983).

2.3 History of sanitation in Ghana

Before colonial rule, residents in Ghanaian towns used pit-latrines located at the outskirts of the community to minimize stench and prevent flies, which they considered an environmental hazards (Okechukwu *et al.,* 2012). However, as a result of population growth and its imminent public health hazards, the use of pit latrines outside the communities became obsolete. Consequently, “bucket latrine” system sited the household with “night soil” collection, became dominant (Ayee and Crook, 2003). In line with the development of sanitation policies, the government constructed public toilets in the early 1930s in Accra and Kumasi. This period also set the introduction of the aqua privy toilets or “bomber latrines”. The Aqua Privy toilet has a water tight settling tank with one or two compartments that serve as receptacles for the waste. The waste is flushed through a pipe submerged in a liquid layer and drops directly into the tank positioned immediately under the latrine (WASHTech report, 2012). The number of public toilets increased during the post-colonial period not only because of policies pursued by successive governments but also the practical problem of dealing with rising population (Arku, 2010; Ayee and Crook 2003). In 1939, a legislation was passed in Gold Coast for the provision of sanitary facilities in all domestic dwellings. The use of Aqua Privy then became a common practice in the 1940s throughout Ghana. Various sanitation options have since evolved; more to solve peculiar ground conditions. The Ventilated Improved Pits (VIP) was a modification of the traditional pit latrines with the inclusion of a vent pipe to eliminate odour from the privies. A further modification on the VIP called the Kumasi Ventilated Improved Pit (KVIP) incorporated a double chamber with vent pipes to eliminate sinking pits (i.e. traditional latrines and VIPs) around locations when they were full. The former has its chambers used alternatively. The Enviro-loo is a more sophisticated waterless technology with a gas extraction unit introduced into the country from South Africa and mainly intended for public use. This technology was introduced and piloted in the country in the 1990s. The Water Closet (WC) with septic tanks was more used by the affluent and quite recently in the urban poor communities largely due to the stench of pit latrines but due to limited space and frequent desludging and lack of routes for desludging, the system is becoming unpopular in poor communities. Beyond this, a number of Ecosan facilities with urine diversion have evolved. Between 2002 – 2005, German Ministry of Research and Education and the Valley view University piloted a urine-diversion compost toilet in Ghana called the Elevated Compost Latrine (ECL). In 2008, the toilet was re-launched with the Ghana Institute of Engineers (GHIE) and piloted under the WASH-UP with Global Communities (Formerly CHF International) in a high water table zone area in Accra. However, the technology required additional treatment facilities for effective treatment which led to the construction of a compost plant to receive waste from the toilets. The latest technology is the BTT. This technology has been designed and tested by the K. Anno Engineering Limited in 2002, launched with the GHIE in 2008 and currently marketed by BIOFILCOM. Over 6000 installations have been done across the country mainly in households and schools. They are typically used in areas where septic tanks and other pit latrines are not feasible due to high water table and areas with limited space. The technology does not require desludging by cesspit emptier and most recently used by new developers.

2.3.1 Current situation of human excreta management

In Ghana, approximately 80 % of the population rely on on-site sanitation (OSS) facilities with only 3.4 % of the population served by sewerage systems (GSS, 2013). Sewerage services are generally lacking and serve a small fraction of the population. In Accra, less than 20 % of the land area is sewered (WSUP, 2017) and the remaining areas are served by OSS facilities in the form of septic tank, improved pit latrines and other innovative toilets such the biofil toilet (ADF, 2005). Accra Metropolitan Assembly (AMA) reports about 1,100 connections to the sewerage network in the central business district and surrounding areas including Labone (WSUP, 2017). Tema has the largest proportion of urban residents (23,000 official connection) connected to the sewerage network (WSUP, 2017). In Akosombo, the entire community is 100 % sewered.

Due to the large number of dysfunctional sewerage systems, huge quantities of faecal sludge are desludged and discharged indiscriminately into the environment (Cofie *et al.,* 2009). In Kumasi, about 500 m^3 of faecal sludge is generated daily (Keraita *et al.*, 2002) and treated by pond systems. The most common system used for treating faecal sludge in Ghana is the waste stabilisation ponds (Awuah *et al.*, 2001). Municipalities, together with private operators, increasingly offer emptying services of most traditional toilet facilities like the septic tanks and pit latrines. According to a Shit Flow Diagram prepared for Greater Accra in 2010, an estimated 82 % of faecal sludge produced is being emptied. Another for Kumasi indicated that 75 % of the population use emptying services. However, only 8 % and 57 % of sludge collected in Accra and Kumasi are safety treated respectively (WSUP, 2017). Ghana's sewer treatment plants are not fully functional (WSUP, 2017).

2.3.2 On-site Sanitation facilities in Ghana

There are different OSS facilities available in Ghana. Generally, the application of OSS is dependent on peculiar conditions such as: (1) Availability of space; (2) Accessibility; (3) Affordability; (4) Availability/scarcity of water; (5) Geographical conditions and (6) Applicability (i.e. number of users).

In Ghana, the predominantly used on-site toilets are pit latrines. These are predominant in low income areas. The usual application in most homes has been the use of single pits requiring relocation when pits are full. A recent improvement in the pit latrines has been in the use of the double alternating pits but these require large foot prints making their use in densely populated urban areas difficult. Pit latrines are generally associated with deep excavations making their use in areas with high groundwater table difficult to construct. Pit latrines constructed in high water table areas have the potential to cause groundwater contamination. Furthermore, issues such as bad odour, fly/mosquito breeding and pit collapse are also associated with pit latrines. Additionally, in most cases, the solid by-products cannot be used for recycling of nutrients in human excreta (Buzie-Fru, 2010). In the affluent urban communities, septic tanks are mostly used.

In Ghana, the proportion of households using public toilet facility has increased from 31.4 percent in 2000 to 34.6 percent in 2010 (GSS, 2013) suggesting a challenge in the ownership of household toilets which is a prerequisite of improved sanitation as defined by the Joint Monitoring Programme (WHO, 2015). On the other hand, the proportion of households that use pit latrines reduced from 22.0 percent in 2000 to 19.0 percent in 2010 with more dwellers resorting to water-based facilities due to the stench of the former (Ditto). Beyond the use of septic tanks, it is indicative that there are really no sanitation alternatives known to many dwellers in Ghana. The proportion of households using septic tanks increased from 8.5 percent in 2000 to 15.4 percent in 2010.

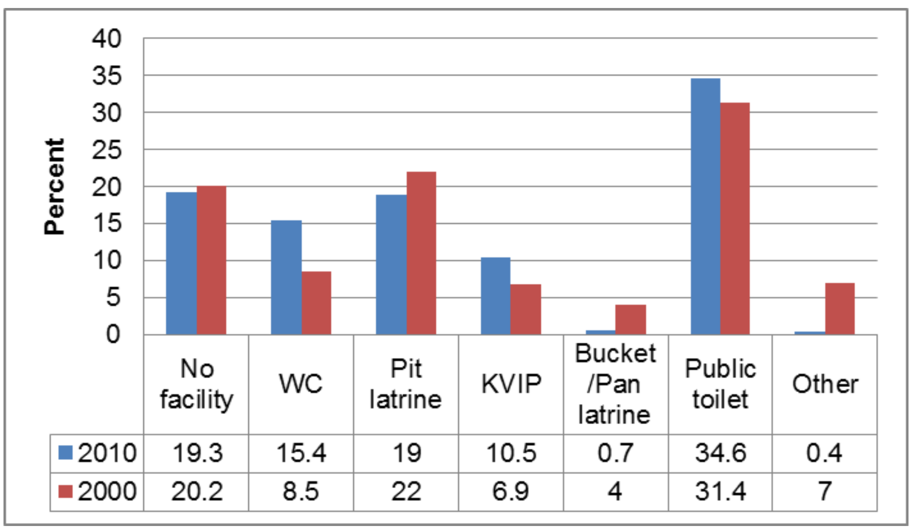

Figure 2-1: Percentage distribution of toilet facilities by type

Source: Ghana Statistical Service (2013)

2.3.3 Sanitation trends in Ghana

The recent census study (2010) shows most households reside in single rooms in compound houses (51.5 %) and separate houses (28.7 %) suggesting the high dependence on shared toilet facilities (60 %) as reported by the WHO report (2015). The 2010 census also revealed that nationally 47.2 % of dwelling units are occupied by their owners, 31.1 % are rented out and 20.8 percent are occupied rent-free. There is largely no motivation for the bottom two to own their own household toilets with the latter normally resorting to open defecation. 19.3 % of dwellings occupied by their owners do not also have toilet facilities as toilet spaces are converted into renting rooms.

Ghana's overall sanitation coverage as reported by the WHO report (2015) stands at 15 %, with a deficit of 39 % compared to the MDG target of 54 %. Ghana had a national population of 60 % using shared toilets (WHO, 2015) which includes public toilets (a major sanitation option for many cities in Ghana). City Authorities are gradually phasing this option out due to its own challenges and this is bound to worsen the sanitation situation in the country as many households do not have the spaces for their own facilities.

2.4 Generation rate of faeces

The amount of faeces produced by a person depends on the composition of the food consumed. Foods low in fibres, such as meat, result in smaller amounts (mass and volume) of faeces than foods high in fibre (Guyton, 1992). Faecal excretion rate in the developing countries is on average 350 g/p,d in rural areas and 250 g/p,d in urban areas (Feachem *et al*., 1983). In China, Gao *et al*. (2002) measured 315 g/p,d while Pieper (1987) measured 520 g/p,d in Kenya. Schouw *et al*. (2002) measured faecal generation of 15 individuals in three different areas in Southern Thailand and obtained wet faecal generation rates of 120-400 g/p,d. Faecal excretion rate is on average one stool per person per day, but it may vary from one stool per week up to five stools per day (Lentner *et al*., 1981; Feachem *et al*., 1983). Rose *et al.*, (2015) reports a range of 75 – 520 g/cap/day wet weight of faeces generated by humans in low income populations with a mean value of 243 g/cap/day and a median value of 250 g/cap/day. In addition, it has also been reported that frequency of defecation mostly is one time/person/day (Triastuti *et al.*, 2009). For the purpose of this study, 300 g/person/day was used.

2.4.1 Nutrients in faeces

The nutrient content of faeces originates from the food consumed. It is estimated that the food nutrient content is distributed to the faecal fraction in the proportions: 10-20 % nitrogen (N), 20-50 % phosphorus (P) and 10 - 20 % potassium (K) (Lentner *et al*., 1981; Vinnerås *et al*., 2006). About 20 % of faecal nitrogen is ammonia, biochemically degraded from proteins, peptides and amino acids, some 17 % is found in living bacteria and the remainder is organic nitrogen combined in molecules such as uric acid and enzymes (Lentner *et al*., 1981). Urine contains the largest proportion of nutrients found in the household waste and wastewater fractions.

2.4.2 Description of the Biofil Toilet Technology

The BTT is primarily designed to treat blackwater at the household level. The technology operates based on aerobic processes based on the principle of vermicomposting. It has a porous filter made from granite aggregate (GR) for rapid solid-liquid separation of blackwater. Effluent from the BTT is typically discharged into the sub-surface soil. Coconut fibre is used as bulking material and the main decomposition facilitated by the interaction between microbes and earthworms (*Eudrilus eugeniae*).

The BTT comprises of a compact concrete panel box with a standard size of 0.65 cum. The BTT has the following features as presented in figure 2-2:

a. A filtration system rapidly separates solids from the liquids,
b. Trapped solids are rapidly “eaten” by a diverse group of micro and macro organisms,
c. The dark, humid, aerobic environment enables macro-organisms to flourish and procreate while being protected from natural predators,
d. The rapid separation and aerobic decomposition achieved by organisms deliberately introduced into the Biofil digester means that no odour emits from the digester,
e. Small footprint, only 1.65 m^2 required for installation of a standard digester.
f. No desludging and haulage services.

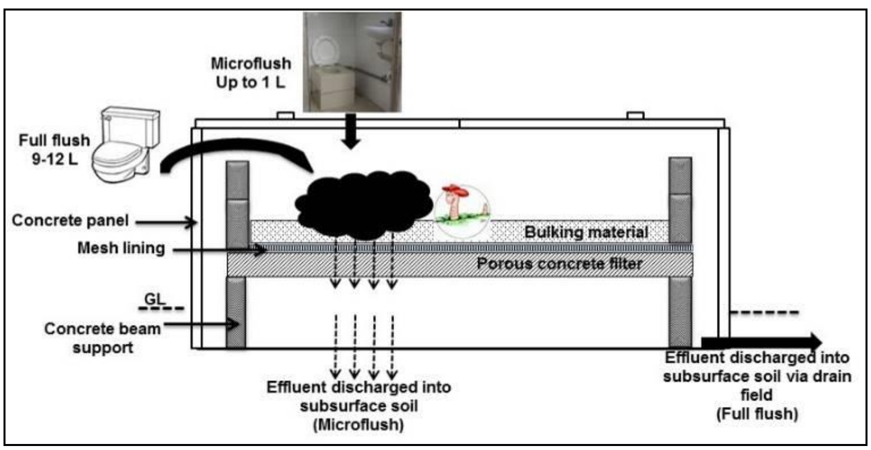

Figure 2-2: Schematic of the Biofil Toilet Technology

Table 2-1 show an external evaluation of effluent characteristics conducted by the International Water Management Institute (IWMI) in 2014. They were assigned by the BMGF as external evaluators on the BIOFILCOM grant.

Table 2-1: Characterization of the BTT before sub-surface infiltration

Parameter	Influent	Effluent	Ave. Removal eff	GH EPA guideline for discharge into water bodies
	Mean ± SD	Mean ± SD	%	
pH	7.7 ± 0.1	8.1 ± 0.0	-	6.0 to 9.0
BOD_5 (mg/L)	1,692.0 ± 140.0	271.0 ± 26.0	84	50
COD (mg/L)	5,599.0 ± 344.0	775.0 ± 70.0	86.1	250
TSS (mg/L)	2,847.0 ± 689.0	500.0 ± 55.0	82.4	50
TDS (mg/L)	3,449.0 ± 255.0	1,648.0 ± 73.0	52.2	1000.0
NH_3-N (mg/L)	139.8 ± 11.8	132.8 ± 8.0	5	-
NO_3-N (mg/L)	10.1 ± 1.3	8.1 ± 1.8	19.8	50
PO_4-P (mg/L)	11.6 ± 1.1	8.9 ± 0.8	23.3	-
E. coli (CFU/100 ml)	$4.6 \times 10^7 \pm 4.6 \times 10^7$	1.7×10^7	63	10
Total coliform (CFU/100 ml)	$1.6 \times 10^9 \pm 1.4 \times 10^8$	7.0×10^7	95.6	400
Helminths	0.2 ± 0.1	0	100	-

Source: External evaluation report by IWMI (2014)

2.4.2.1 Applicability

The BTT since its launch has been installed across the length and breadth of the country with over 6000 units installed in Ghana. These installations comprise approximately 24 % allocation to the low-income groups, 58 % allocation to the middle to high income groups and

18 % allocation to schools. Most of the installation in the low-income groups and schools has been by way of projects through Non-Governmental Organisations while the middle to high-income group installation has been through walk-ins.

In 2012, BIOFILCOM won a grant with funding from the Bill and Melinda Gates Foundation to improve the quality of the effluent with the intention of discharge into water bodies. In 2013, the company again won a project through the Ghana Wash Window funded through the Dutch Government to install some 2000 units in selected communities in Ghana.

2.4.2.2 Technical details of the BTT

There are various forms of the digester for specific features and sizes ranging from the standard to the special which is usually customised to suit the particular facility. The Table 2-2 details the various forms of the BTT uses and their use categories.

Table 2-2: Variations of the BTT

no.	Products	Features	# of users	use categories
1.	Standard flush digester	Connected to a flush toilet bowls and installed with a drainfield. Measures 0.6m x 1.8m x 0.6m	10	Residential, Recreational
2.	Large digester	Connected to a flush toilet bowls and installed with a drainfield. Measures 0.9m x 1.8m x 0.6m	15	High density households, Multi storey apartments
3.	Special digester	Connected to a flush toilet bowls and installed with a drainfield. Customised to suit building styles for large users	25-50	Schools, clinics, multi-storey apartment
4.	Microflush standalone	Privy installed on digester with a customised microflush toilet bowl; waste line from hand wash basin is connected to the microflush seat	10	Slum/Peri-urban areas, security posts

Source: BIOFILCOM

Materials for the BTT are locally sourced and pre-fabricated for sale to its customers unlike other technologies which are manufactured on site. The concrete panels forming the box of the BTT are made from ferrocement. Ferrocement is a thin reinforced concrete construction in which large amounts of small-diameter wire meshes are used uniformly throughout the cross section instead of discretely placed reinforcing bars and in which Portland cement mortar is used instead of concrete (Shah, 1981).

The cost details of the various BTT products have been presented in Appendix E.

2.5 Composting of faecal sludge

Composting is an accelerated biooxidation of organic matter typically within temperature rages of 45^{o}C to 65 ^{o}C (thermophilic stage) where microorganisms (mainly bacteria, fungi and actinomycetes) interact to release heat, carbon dioxide and water as by-products. Heterogeneous organic material is transformed into a homogeneous and stabilized humus like product through turning or aeration (Dominguez *et al*., 1997).

2.5.1 Chemical reactions during composting of faecal sludge

Blackwater consists of a mixture of urine, faeces and flush water along with anal cleansing water and/or dry cleansing material (e.g. toilet paper). All the components undergo biodegradation. The nitrogen content of faecal matter (urine and faeces) is very high. The biggest contributor to the total nitrogen excreted is the urine fraction, contributing 93 % to the total nitrogen concentration (Geigy, 1962). In this fraction 84 % consists of urea-nitrogen, which is readily converted to ammonia (Geigy, 1962).

It is known that urea will be hydrolysed rapidly by the enzyme urease to form ammonium ions according to the following reaction equation (Orhon and Artan, 1994):

$$(NH_2)_2CO + 2H_2O \Rightarrow 2NH_4^+ + CO_3^{2-}$$

According to Benefield *et al.* (1982), urea in the presence of water are hydrolysed to produce ammonium ions (NH_4^+) and kept in equilibrium with ammonia (NH_3) (Benefield *et al.*, 1982):

$$NH_3 + H_2O \Rightarrow NH_4^+ + OH^-$$

Any increase in pH causes equilibrium of the reaction to shift to the left to convert ammonium ions to ammonia gas. Ammonia gas is very insoluble in water and escapes to the atmosphere.

The amount of ammonia produced is a function of pH and temperature (Medcalf and Eddy, 2003).

When oxygen gets in contact with the ammonium ions, the following chemical reaction occurs during the nitrification (Metcalf and Eddy, 2003).

$NH_4^+ + 2O_2 \Rightarrow NO_3^- + 2H^+ + H_2O$ (Nitrifying bacteria)

Because of the production of hydrogen ions, alkalinity decreases and the pH declines (WRC, 1984) resulting in the production of nitrate and nitrite ions in the effluent.

In addition, denitrification is a major removal process in biological systems. The mechanism is as follows:

$6NO_3^- + 5CH_3OH \Rightarrow 5CO_2 + 7H_2O + 6OH^- + 3N_2$ (Denitrifying bacteria)

2.5.2 Principal operating variables of composting

Extensive studies have been carried on the operation conditions required for effective composting of organic matter. Several variables such as temperature, moisture content, and pH are selected as control variables together with other physical, chemical and biochemical properties such as respiratory indices (Barrena *et al.*, 2005).

2.5.2.1 Temperature

Studies by Richard *et al.*, (2002) suggest temperature ranges between 45 and 59 ^oC for effective composting of organic matter. High temperatures inhibit microbial growth, slowing the biodegradation of organic matter. To have a high rate of biodegradation and a maximum microbial diversity, the temperature must range between 30 and 45^{o}C (de Bertoldi *et al.,* 1983; Finstein *et al.,* 1983). Temperatures below 20^{o}C inhibit the activity of micro-organisms and reduce their decomposition capacity (Strom, 1985, Finstein *et al.,* 1986). Only few species of thermophilic bacteria show metabolic activity above 70^{o}C.

2.5.2.2 Hydrogen Ion Level (pH)

Generally, organic matter with a wide range of pH (from 3 to 11) can be composted (de Bertoldi *et al.,* 1985). However, the optimum range is between 5.5 and 8.0. High pH values above the upper limits in the starting material in association with high temperatures can cause a loss of nitrogen through the volatilization of ammonia which is toxic to micro-organisms.

In practice, the pH level in a composting mass cannot be changed easily. Generally, the pH begins to drop at the beginning of the process (i.e., down to 5.0) as a consequence of the activity of acid-forming bacteria that break down complex carbonaceous material to organic acids as intermediate products. When this acidification phase is over and the intermediate metabolites are completely mineralized, the pH tends to increase and at the end of the process is around 8.0–8.5 (Diaz *et al*., 2007).

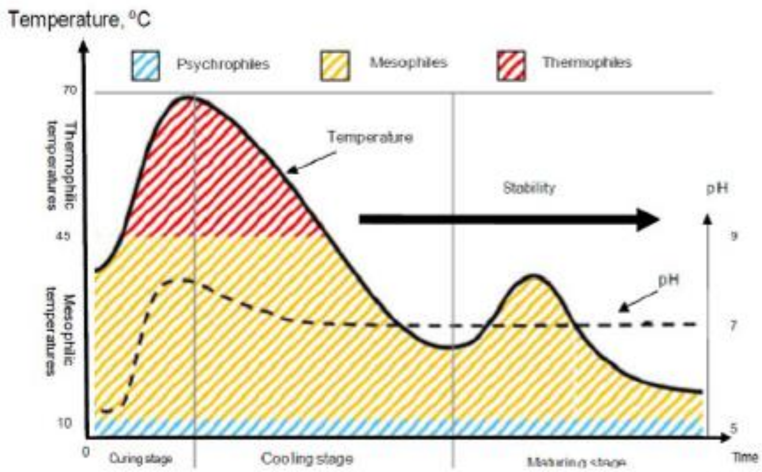

Figure 2-3: Typical Temperature and pH profiles through the composting process

Source: Sergio (2010); PhD Thesis

2.5.2.3 Moisture Content

Micro-organisms require moisture to absorb nutrients, metabolize and produce new cells. Under conditions of low moisture content, the rate of decomposition turns to diminish. High moisture content can also reduce or stop oxygen transfer. The recommended range of moisture content for effective composting process was suggested as 40-60 %. Below 20 % moisture content, very few bacteria are active (Haug, 1980).

2.6 Vermitechnology

According to literature, Vermitechnology is the use of worm species (e.g. earthworms) to provide cheaper solutions to several social, economic, environmental and health problems plaguing human society. The notably technologies include: (1) Vermicomposting (worms as waste engineers) for efficient management of waste (municipal and industrial) by biodegradation and stabilization and converting them to useful resources; (2) Vermifiltration (worms as wastewater engineers) for treatment of municipal and industrial wastewater, their purification and disinfection for reuse; (3) Vermiremediation (worms as biochemical engineers) for cleaning up chemically contaminated lands while also improving the total physical, chemical and biological properties of the soil for reuse; (4) Vermi-agroproduction (worms as soil engineers) for restoring and improving soil fertility to produce safe and chemical-free food for the society by the use of vermicomposting and without recourse to the destructive agro-chemicals (Sinha *et al*,. 2010b).

The biofil toilet technology operates under the principle of vermicomposting. Many Authors have sought to define vermicomposting. Dominguez (2004) described vermicomposting, saying that "earthworms act as mechanical blenders, and by comminuting the organic matter, they modify its biological, physical and chemical status, gradually reducing its C/N ratio, increasing the surface area exposed to microorganisms, and making it much more favourable for microbial activity and further decomposition". Suthar (2009) defined it as the decomposition of complex organic waste resources into odour-free humus-like substances through the action of earthworms. A follow-up study defined vermicomposting as the stabilization of organic material through the joint action of earthworms and mesophilic microorganisms and does not involve a thermophilic stage (Yadav *et al.*, 2010). While microbes are responsible for biochemical degradation of organic matter, earthworms are the important drivers of the process, conditioning the substrate and altering the biological activity.

Source separated human waste (Yadav *et al.,* 2010), human biosolids (Eastman *et al.,* 2001), and sewage sludge (Dominguez *et al.,* 2000), all viable feedstocks, have been transformed into vermicompost meeting standards for compost stability and maturity. The majority of research supports the ability of vermicomposting to reliably and greatly reduce pathogens from contaminated feedstock. Yadav *et al.,* (2010) and Brahambhatt (2006) documented total coliform elimination (>8log reduction) in large 60 kg batch tests. Kumar and Shweta (2011) documented complete removal of *Salmonella*, *Shigella*, *Escherichia* and *Flexibacter spp*. in an analysis pre, mid, and post worm gut.

2.6.1 Species for vermicomposting of organic waste

The study of vermiculture indicates a number of earthworm species that could be applied in vermicomposting of sewage sludge though there is still little literature on vermicomposting of faecal sludge. Long-term research into vermiculture has indicated that the Tiger worm (*Eisenia fetida*, a widely occurring species), Red Tiger worm (*Eisenia andrei*), the Indian Blue worm (*Perionyx excavates,* a tropical species from Asia), the African Night Crawler (*Eudrilus eugeniae,* a tropical species from West Africa), and the Red worm (*Lumbricus rubellus*) are detritus feeders and can be used potentially to minimize the anthropogenic wastes from different sources (Suthar, 2006, 2007a, 2007b, 2008b; Gupta and Garg, 2008). According to Suthar (2009), *E. fetida* are and still remain the favoured earthworm species for laboratory trail experiments on vermicomposting due to its wide tolerance of environmental variables (pH, moisture content, temperature, etc.).

2.6.2 Various studies carried out on vermicomposting

Research into the potential use of earthworms to break down and manage sewage sludge began in the late 1970s (Hartenstein, 1978) and the use of earthworms in sludge management has been termed vermicomposting or vermistabilization (Neuhauser *et al.,* 1988).

Vermistabilization is a complex mechanical and biochemical transformation of sludge achieved through the action of earthworms (Sinha *et al.*, 2010). The worms act as an aerator, grinder, crusher, chemical degrader and a biological stimulator (Sinha *et al.,* 2002). Worms decompose the organic fraction in the sewage sludge, mineralize the nutrients, ingest the heavy metals and devour the pathogens (bacteria, fungi, nematodes and protozoa) (Sinha *et al.,* 2010c). It was demonstrated quite early, at a laboratory scale, that aerobic sludge can be ingested by the earthworm *E. fetida* and egested as casts, and that in the process the sludge is decomposed and stabilized (i.e. rendered innocuous) about three times as fast as non-ingested sludge, apparently because of the increases in rates of microbial decomposition in the casts (Dominguez, *et al.*, 2000).

A number of studies have been done using vermicomposting on municipal waste and vermistabilization of sludges such as industrial (paper mill, dairy and textile industry) sludge as well as effluents and sludge from intensively housed livestock (Contreras-Ramos *et al.,* 2005). The study reports of accelerated decomposition of waste, high pathogen removal up to 70 % and odour-free by-products. As worms create aerobic conditions in the waste materials by their burrowing actions, the action of anaerobic microbes which release foul-smelling hydrogen sulphide is inhibited. The quality of vermicompost upon stabilization is significantly better, rich in key minerals and beneficial soil microbes as compared to the conventional composting which is thermophilic (temperature rising up to 55°C) in which many beneficial microbes are killed and nutrient especially nitrogen is lost (due to gassing off of nitrogen).

Other researches have sought to treat human excreta through vermicomposting. The first attempt by Bajsa *et al.,* (2004) demonstrated the feasibility of stabilising faecal solids by vermicomposting. Other researchers (Shalabi 2006, Yadav *et al.,* 2010, Buzie-Fru 2010, Yadav *et al.,* 2011) have also contributed scientific knowledge to the suitability of using vermicomposting technology for managing faecal solids. Shalabi (2006) treated partially degraded faecal matter with earthworms. Puri (2004) also reported the survival of earthworms in human faeces with the addition of bulking material. Source-separated human faeces were also treated under vermicomposting using earthworms, soil and vermicompost as supporting material by Yadav *et al.* (2010); their study revealed a reduction in the pathogen content of the feed substrate. Larger-scale community worm-based systems have been trialled in China for the treatment of sludge (Zhao *et al.,* 2010; Xing *et al.,* 2011) and sewage (Xing *et al.,* 2010; Wang *et al.,* 2011). Commercial on-site systems are currently available, e.g. Biolytix™ (Biolytix, 2008), which is seeded with worms and are attached to flushing systems. They are mostly designed for use in rural locations in developed countries but are cost-prohibitive for households in developing countries. They also have large footprints for installation in an urban context and are designed for waste containing higher liquid content than is typical in developing countries (Furlong *et al.,* 2014). A recent study by Hill and Baldwin (2012) compared the performance of source-separating vermicomposting toilets (SSVCs) with composting toilets. Their study revealed a pathogen reduction mechanism and showed consistently low *E. coli* counts in end-product and minimized faecal contaminated leachate. Nevertheless, their study concluded that disposal of treated waste and wastewater must be conducted according to relevant regulations and indicated that vermicomposting is not (yet) an approved method in most locations, thus the need for further investigation. They also indicated little literature for comparison of their results in the area of Vermitechnology. According to a Buzie-Fru (2010) on continuous vermicomposting of source-separated human excreta, although the potential of vermicomposting human excreta has somewhat been demonstrated, there needs to be more work on the technology design, operation and engineering. A further call by Yadav (2011) suggests that there needs to be a lot more studies to establish accurate design criteria of efficient and economical vermicomposting systems. A recent study by Furlong *et al.* (2014) looked at the use of vermifilters containing *Eisenia fetida* to process human excreta in a continuous wet system.

2.6.3 Role of earthworms in vermicomposting

Earthworms promise to provide cheaper solutions to several social, economic and environmental problems affecting human society (Kumar and Shweta, 2011). Their bodies work as 'bio-filter' and they can 'purify' and also 'disinfect' and 'detoxify' wastes. They are both protective and productive for the environment (ditto). Oligochaetes are divided into two distinct groups; aquatic and small sized worms and terrestrial oligochaetes (earthworms). Vermiculture scientists all over the world knew about the role of earthworms as 'waste managers', as 'soil managers' and 'fertility improvers' for many years past (Sinha *et al.*, 2010). However, some news about their role in removal of pathogen may revolutionize the vermiculture industry (Kumar and Shweta, 2011).

Eastman *et al.* (2001) documented more rapid and more complete pathogen destruction (bacteria, virus, and helminth) using high densities of earthworms than thermophilic composting of the same feedstock. According to a study by Elissen *et al.* (2006), the rate of sludge breakdown by earthworms is significantly higher than the sludge breakdown rate in the absence of worms. The volume of faecal sludge is significantly reduced from 1m^3 of wet sludge (80% moisture) to 0.5m^3 of vermicompost (30% moisture) (Sinha, 2012). In practice, much higher worm densities in sludges results in a higher sludge consumption rate. This is determined by the available sludge and the maximum possible worm density per surface area.

2.6.3.1 Adaptation of earthworms to physical environment

Worms are adapted to survive in harsh environmental and in moderately acidic-to-alkaline conditions with pH values ranging from 4.5 – 9. They are also tolerant to temperature ranges of 5 - 29 ^{o}C. According to Hand (1988), a temperature of 20 - 25 ^{o}C and moisture content of 60 - 75 % is optimum for good worm function. They are tolerant to moderate salt salinity and can also tolerate toxic chemicals including heavy metals.

2.6.3.2 Stocking density and growth of earthworms

Various stocking densities have been suggested by different authors for vermicomposting. Neuhauser *et al.* (1980) reported an ideal *E. fetida* stocking density of 0.8 kg- worms m^{-2} for horse manure and 2.9 kg-worms m^{-2} for activated sludge. They observed that using regression analysis, the earthworm production increased with population density while growth declined. Ndegwa *et al.* (2000) reported a stocking density of 1.60 kg-worms/m^2 and a feeding rate of 1.25 kg-feed/kg-worm/day for highest bioconversion of the substrate into earthworm biomass. Yadav *et al.* (2010) used a stocking density of 4.0 kg/m^2 for the vermicomposting of source-separated human faeces. Singh and Kaur (2013) reported an optimum stocking density of 12.5 g-worms kg^{-1} feed of *E. fetida* for chemical sludge and spent carbon obtained from industrial soft drinks. The ideal earthworm stocking density for waste biodegradation seem to vary with substrate type (Unuofin, 2014). A study by Giraddi (2008) suggests that significant quantities of vermicompost are produced at higher stocking rates of earthworms using soybean crop residue and little millet straw. However in terms of conversion rate, lower stocking densities are most productive. He attributed this to the fact that there is a threshold density beyond which earthworms will compete amongst themselves for space and food. Therefore, at higher stocking rates, the increase in population growth rates was not as per theoretical rates of multiplication. Generally, earthworms grew and matured fast in low than high stocking densities (Ndegwa *et al.*, 2000). The increase in cocoon, and clitellate numbers was marginal when stocking rates were increased from 100 to 250 densities (Giraddi, 2008). Similar observations on effect of crowding on population growth rate have been reported in *Eudrilus eugeniae* worms (Hegde *et al.,* 1997). Studies by Hand (1988) suggested a growth rate of 2 earthworms per day.

2.6.4 Role of bulking material in vermicomposting

Common bulking materials (e.g. coconut fibre, palm fibre etc.) are fibrous carbonaceous materials with low moisture content (Miner *et al.,* 2001). Coconut fibres have high lignin but low cellulose content, as a result of which the fibres are resilient, strong, and highly durable.

Bulking material plays an important role during vermicomposting of organic wastes. Earlier studies have revealed that mixing of bulking material in some noxious wastes minimized the concentration of toxic substances in vermireactors and consequently speeded the decomposition process. The importance of bulking material in vermicomposting of waste is as follows:

(1) It makes the waste more acceptable for earthworms (Dominguez, 2004);

(2) Lowers the concentration of some unfavourable chemicals, e.g., metals, grease and cellulose in feedstock (Suthar, 2007b);

(3) Sets the pH within the acceptable limit for earthworms (Suthar, 2006);

(4) Enhances the quality of ready product, i.e., vermicompost by adding some important nutrients (Suthar, 2008a);

(5) Changes the microclimatic conditions of the decomposing waste by promoting microbial colonization in feedstock, although microbes are important part of earthworm diet (Suthar, 2008b) and;

(6) Plays an additional role of increasing the pore space to allow oxygen into the compost (Schaub and Leonard, 1996).

Garg and Kaushik (2005) studied the vermistabilization of solid textile mill sludge mixed with poultry dropping using *E. fetida*. The experiment resulted in significant reduction in C/N ratio and increase in nitrogen and phosphorus contents. Total potassium, total calcium and heavy metals (Fe, Zn, Pb and Cd) contents were lower in the final product than initial feed mixtures. Suthar (2006) used saw dust and cow dung as bulky agents for vermicomposting trials of guargum industrial wastes. He suggested that 60:20:20 ratio of industrial waste, cow dung and saw dust was an ideal combination to achieve the maximum biopotential of earthworms. Garg *et al.* (2006) suggested that substrate containing 40 % textile mill sludge 60 % biogas plant slurry is a suitable combination for better mineralization and earthworm production during process. Elvira *et al.* (1998) studied the vermicomposting of wastewater sludge from paper mill. They recorded an excellent earthworm growth in vermibed containing paper mill sludge and sewage sludge (3:1). Recently, Singh *et al.* (2009) demonstrated the vermicomposting of sludge from a beverage industry and suggested 50:50 as ideal waste combination of industrial sludge and cow dung in terms of nutrient quality of end material and earthworm growth performances.

2.6.5 Role of solid/liquid separation in vermicomposting

Vermicomposting requires aerobic conditions to enhance growth by the worm and mesophilic microbes to digest the waste. The separation of solids (i.e. faeces, toilet paper) and liquids (i.e.

flushwater, urine) is crucial to prevent anaerobic conditions. The separated solids will in most cases require further composting resulting in biosolids usable as a soil conditioner-cum-fertilizer. The liquid fraction will normally have to undergo polishing treatment to satisfy criteria for discharge into surface waters and/or to avoid groundwater pollution, where effluents are allowed to infiltrate (Kone and Strauss, 2004).

2.6.5.1 Porous filter composites

Porous filter composite (PCF) has properties that enhance infiltration of wastewater; thus can be used for treatment of wastewater (Luck *et al.,* 2006). Porous filter composites consist of Portland cement, uniformly sized coarse aggregate, and water. The addition of fines blocks the void spaces in the composites between the coarse aggregate particles and hinders rapid water flow through the composite (Ghafoori and Dutta, 1995a).

2.6.5.2 Physical properties of porous filter composites

Researchers have conducted laboratory tests to determine the physical properties of porous filter composites (Crouch *et al.,* 2003; Sung-Bum and Mang, 2004). Four properties of porous filter composites that have typically been the focus of most of these laboratory investigations include: density, porosity, permeability, and compressive strength. The density and porosity of porous filter composites can depend on various factors including the properties of the materials, the proportions of those materials in the concrete mix, and the methods used for placement and compaction. Porous filter composite densities typically range between 1,570 and 2,000 kg/m^3 (Ghafoori and Dutta, 1995d; Tennis *et al.,* 2004).

The porosity of porous filter composite is a measure of the void space between the coarse aggregate particles that are available for the infiltration of water. Individual void sizes can be controlled based on the size of the coarse aggregate used in the concrete mix. Mix designs utilizing larger aggregates would result in larger void spaces while smaller aggregates would result in smaller and more numerous void spaces. Crouch (2003) found that using high density paver placement resulted in "lower mean effective air voids" (18.4 % air voids) compared to that of porous filter composites placed by hand (27.8 % air voids). The permeability of porous filter composite is directly related to the porosity of the mixture and is therefore controlled by the materials, proportions, and placement techniques.

The compressive strength of porous filter composites is of particular importance because potential applications can be limited by the strength of the composites. Compressive strengths in the range of 3.45 to 12.76 MPa can be attained which makes them suitable for several different applications. Major factors influencing the strength of a given composite include; the types of materials, the proportions of those materials, and the methods used for placement and compaction (Tennis *et al.,* 2004). Most research has demonstrated that there is an inverse relationship between the porosity of the mixture and the compressive strength (Crouch *et al.*, 2003).

2.6.5.3 Application of porous filter composites

The research and development of porous filter composites has been driven by the need to control stormwater (Luck and Workman, 2007). Composites provide effective separation of solids in liquid which enhances the removal of chemical, nutrients and pathogens in wastewater through the mechanism of straining and adsorption (USDA-NRCS, 1997); but there have been very little studies on the use of porous filter composites in blackwater treatment. Previous studies investigated the growth of micro-organisms within porous filter composite by monitoring the consumption of the dissolved oxygen in the voids (Sung-Bum and Mang, 2004). The study demonstrated the reduction of total nitrogen, total phosphorous and microorganisms from water samples through the composite by attempting to use composites to remove organics in wastewater from an animal husbandry by incorporating the composites in the floors (Swierstra *et. al.,* 2001). Studies to determine the ability of porous filter composites to be used in solid/liquid separation in blackwater treatment are limited to the best knowledge of the author.

2.6.6 Physico-chemical and microbial changes during vermicomposting

Studies have reviewed that earthworm-processed waste mixture i.e. vermicompost are more stabilized, odour-free, dark brown and nutrient rich material (Eastman *et al.,* 2001). During the process of vermicomposting, the physico-chemical properties of waste mixtures change drastically and end material are rich in soil nutrients (Vasanthi *et al.,* 2013). The pH of waste mixtures is lower than their initial values (Parthasarathi, *et al.,* 2014). The shifting in pH could be attributed to the production of CO_2, ammonia, NO_3^- and organic acids by microbial decomposition during vermicomposting process, which lowers the pH of substrate (Elvira *et al.,* 1998). The pH level within acidic or neutral ranges seems beneficial for microbial enhancement of bedding materials, as it accommodates the rapid colonization of major decomposer (bacteria and fungi) in decomposing waste feed stocks. There are also reductions in organic carbon in vermicompost than initial feed mixtures, indicating significant reduction in organic carbon contents (Suthar, 2010).

2.7 Differences between vermicomposting and composting

Many benefits have been associated with vermicomposting of organic waste over composting. Vermicompost after the same period of maturity become more effective for soil fertility improvement than compost (Unuofin, 2014). Details of the differences between traditional composting and vermicomposting have been presented in Table 2-3.

Table 2-3: Comparison between composting and vermicomposting of organic waste

Parameters	Composting	Vermicomposting
Temperature	involves a thermophilic stage (45° to 65°C)	does not involve a thermophilic stage (<45 °C)
Waste digesters	Does not involve the joint action of earthworms and microorganisms	involves the joint action of earthworms and microorganisms
Means of aeration	Mechanical turning or blowers	Earthworms are the agents of turning, fragmentation and aeration.
Humification	Low	Higher and faster: humic substances increased by 40 – 60 %
Germination index	Low	Higher: 65 to 70 percent higher in the treatments with earthworms than in the control (no earthworms).
Pathogen destruction	Low (though thermophilic stage during the composting process is known to eliminate the pathogenic organisms)	Human pathogens may not survive vermicomposting: faecal coliform bacteria in biosolids dropped from 39,000 MPN/g to 0 MPN/g.
Nitrogen mineralization	Slow	Faster
Heavy metals reduction	Low	Greater decrease
C/N ratio	high	Lower

Adapted from Dominguez *et al.,* (1997) and Lazcano *et al.,* (2008)

2.8 Faecal sludge stability

Lasaridi and Stentiford (1998) defined biological stability as a characteristic that determines the extent to which readily biodegradable organic waste has been decomposed. Referring to compost, the stability is a quality parameter related to the microbial decomposition or microbial respiration activity of composted matter (Komilis and Tziouvaras, 2009). According to Polprasert (2007), there are many criteria to judge the maturity or completion of a composting process. In general, a composted product should contain a low organic content that will not undergo further fermentation when discharged on land, and the pathogens inactivated. Some of the approaches to measure the degree of compost stabilization are (Haug 1980): (1) decrease in organic content of the compost as measured by the volatile solid (VS) content; (2) chemical oxygen demand (COD); (3) percent carbon content, and C/N ratio; (4) presence of particular constituents such as nitrate, and the absence of others such as ammonia; (5) lack of attraction of insects or development of insect larvae in the final product; (6) absence of obnoxious odour; a high biological stability implies lower environmental impacts (like odour generation, biogas production, leaching and pathogen's re-growth) during land application of the bio-solids (Muller *et al.,* 1998). Rate of organic matter stabilisation have been determined by volatile solids to total solids (VS/TS) ratio and carbon to nitrogen (C/N) ratio.

2.8.1 Volatile Solids (VS)

Loehr *et al.* (1998) found that *E. foetida* increases the rate of volatile solid destruction when present in aerobic sludge and this reduces the probability of putrefaction occurring in the sludge due to anaerobic conditions. Hartenstein & Hartenstein (1981) reported a 9 % reduction in volatile solids over 4 weeks of sludge vermicomposting by earthworms.

Fredrickson *et al.* (1997) found a reduction in volatile solids of 30 % in compost after 4 months of conventional composting, whereas the reduction was 37 % after only 2 months of vermicomposting.

2.8.2 Volatile Solid to Total Solid ratio

VS/TS ratio indicates the viable microorganisms present in total sludge measured or in other words, reflects percentage of inert matters content in sludge. The greater VS/TS ratio indicates larger percentages of viable sludge (Gangrekar *et al*., 2005). The VS/TS ratio is important because it indicates the amount of viable sludge in total sludge.

2.8.3 Carbon to Nitrogen ratio

C/N ratios are one of the most widely used indexes of organic waste maturity (Ludibeth *et al.,* 2012). The decomposition process of organic waste is effective when the carbon (C) is in excess of the nitrogen (N). Several studies have suggested that a ratio of 30 parts C to 1 part N is optimum. C/N ratio in the range of 25-30:1 is considered suitable for organic waste treatment. Higher values have been suggested to slow the rate of decomposition, and lower ones often result in N loss. Sewage sludge may have low C/N ratio due to higher nitrogen content. This can be improved by mixing in carbon- rich ‘bulking materials’ such as straw and decaying leaves. A C/N ratio less than 20 indicates an advanced degree of maturity in organic waste (Senesi, 1989). The C/N values within the limit of 12 have also been suggested by Bernal *et al.* (1998a).

2.9 Sub-surface infiltration of effluent

Human excreta can be a source of infection from pathogenic bacteria, viruses and eggs of parasitic worms which are spread through the deposition of excreta from infected persons, passing on infection via the soil and groundwater. Percolation through a natural soil profile or separate filters containing natural or engineered porous media, are the most frequently used treatment systems (Stevik *et al.,* 2004). To prevent groundwater contamination, effluent should be discharged into the sub-surface soil with an optimal depth clearance of 200 cm to the groundwater table (UNEP, 2002).

Water quality is improved by a combination of biological, chemical, and physical processes (biodegradation and adsorption being the most important) in the vadose zone and subsequently in the aquifer (Quanrud *et al.,* 1996a). Filtration, sorption and biodegradation processes in the soil can reduce or remove microbial and other contaminants in wastewater (Powelson *et al.,* 1993).

2.9.1 Filtration

Filtration is widely used for removing particles from water and wastewater. It is defined as any process for the removal of solid particles from a suspension by passage of the suspension through a porous medium (Howe *et al.,* 2012). During filtration, various forms of contaminants in this case ranging from physical, pathogenic/biological as well as chemical contaminants; are removed from the liquid phase.

2.9.1.1 Contaminant removal mechanisms during filtration

Several contaminant removal mechanisms associated with filtration have been reported. However, in the context of sanitation, the most relevant mechanisms responsible for removing the bulk of contaminants and the immobilization of pathogens in wastewater are straining and adsorption (Stevik *et al.*, 2004).

2.9.1.1.1 Straining

When particles are larger than the void spaces in the filter, they are removed by straining. When particles are smaller than the voids, they can be removed only if they contact and stick to the grains of the media (Howe *et al.*, 2012). This removal mechanism involves the physical blocking of the movement of contaminants through pores smaller than the contaminant. The straining effect is influenced by the pore size of the porous media, contaminant size and shape, hydraulic load on the media, and level of clogging within the filter (Stevik *et al.*, 2004). Straining causes a cake to form at the surface of the filter bed as well as within the pores, which can improve particle removal but also increases head loss through the filter (Howe *et al.*, 2012). Development of biofilm within the pores of the filter reduces the pore size within the filters. This also enhances the effect of straining to remove the contaminants together with other minor mechanisms such as adhesion and flocculation (Metcalf and Eddy, 2004).

2.9.1.1.2 Adsorption

Stevik *et al.* (2004) also reported that adsorption has been observed as an important mechanism influencing bacterial transport in porous media. Once a particle is brought in contact with surface of the filtering medium or other particles, either physical or chemical adsorption or both will act to hold it there (Metcalf and Eddy, 2004).

2.9.2 Factors influencing the performance of filtration

The performance of a filtration system depends on the quality of the effluent, and process conditions (hydraulic loading rate, pre- and post-treatment, wetting and drying cycle) applied (Fox *et al.*, 2001a).

Aerobic, anoxic and anaerobic conditions promote biodegradation of organic carbon under different electron acceptors in filtration systems. Dissolved oxygen decreases as wastewater percolates through the vadose zone and redox potential decreases, Nitrate becomes the next electron acceptor followed by iron or manganese (Fox *et al.,* 2001b). Bacteria are removed by filtration, predation, adsorption and the occurrence of adverse conditions (Katukiza, 2006).

2.9.2.1 Porosity in filter media

Porosity is defined as the fraction of volume of void space area to total volume of medium (Nield and Bejan 1992). During soil infiltration, adhesion plays a key role in contaminant removal and will be reduced due to decreased contact time and increased distance between bacteria and the media (Otis *et al.,* 1977). Smaller particle sizes expose a larger surface area compared to coarse particles, hence providing more adhesion sites (Fortes *et al.,* 1991). The surface roughness of a medium may increase the adsorption as a result of reduced shear forces thereby lowering desorption rates and increased substratum area (Characklis 1984; Characklis *et al.*, 1990).

The presence of clay particles in any media influences the adhesion of bacteria due to the very small size of the clay particles, their generally platy shapes, large cation exchange capacity and the occurrence of a large surface area per unit volume (Huysman and Vertraete, 1993). Coating of Fe oxides on media surface increases the adsorption by altering the surface charge, thus making it more positive, and the interaction between bacteria and media more favorable (Fontes *et al.*, 1991).

2.9.2.2 Organic matter

Organic matter attached to the media may increase the cation exchange capacity, surface area and number of adsorption sites for bacterial adsorption (Lawrence and Hendry, 1996). Once these can be removed the effective removal of microbial organism in effluent increases.

2.9.2.3 Temperature

Hendricks *et al.* (1979) suggested that adsorption of bacteria was substantially greater at higher temperatures.

2.9.2.4 pH

Increased retention of bacteria has been found to occur when pH was decreased from 9.3 to 3.9 (Goldschmith *et al.*, 1973). In a study of Pseudomonas, Gammack *et al.* (1992) found a higher number of cells in the effluent at pH 7.5 than at pH 4.5.

2.9.2.5 Filtration rate

Previous studies have shown that fine clay result in low filtration rates (Fox *et al.*, 2001a). Soils with high hydraulic conductivities provide high infiltration rates during the beginning of discharge of effluent through the soil and infiltration rates decrease as clogging layers develop (Pescod, 1992).

2.9.2.6 Hydraulic loading

High flow rate increases the average water suction in an unsaturated filter medium. This results in greater transport through larger pores, which decreases the effect of bacterial straining by the porous material. Mostly the intermittent dosing of flushing at homes will not cause the negative effects of higher loading rates (Stevik *et al.*, 2004). Blombat *et al.* (1994) and Ausland *et al.* (2002) observed a higher removal of faecal coliform bacteria in filtration systems using uniform pressure distribution, compared to gravity dosing.

2.9.3 Chemical transformations during filtration

During mineralization, organic nitrogen containing amine groups, are broken down by micro-organisms, into simple amino compounds which are then hydrolysed releasing nitrogen in the form of ammonium (NH_4^+). The reduction in ammonium concentration in the wastewater as it percolates through the unsaturated filtering membrane is accompanied by an increase in nitrate (NO_3-) concentration brought about by the process of nitrification (Equation 1) (Brady and Weil, 2002).

(**Eqn. 1**) $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$

When the nitrified wastewater infiltrates down and encounters an anaerobic pocket, or zone of reduced oxygen concentration, in the presence of appropriate bacteria and a supply of readily available carbon source in the form of organic substrate, it further undergoes denitrification (Equation 2). This reduces the nitrate to other nitrogen forms (NO, NO_2) and ultimately gaseous nitrogen (N_2).

(**Eqn. 2**) $2\ NO_3^- + 5H_2 + 2H^+ \dashrightarrow N_2 + 6\ H_2O$

2.9.4 Challenges with filtration systems and possible remedies

Infiltration system using primary effluent has a limitation of clogging (reducing infiltration rate) (Lance *et al.*, 1980; Rice and Bouwer 1984; Fox *et al.*, 2001a; Crites *et al.*, 2006). Clogging may be due to an improper balance of the intricate micro-organism population within the filter and accumulation of biomass from the growth of the micro-organisms (Anderson *et al.,* 1885). The intermittent discharge of effluent through the sub-surface soil such that periods of wet and dry cycles are achieved have been reported to improve the clogging effect of infiltration systems and nitrification and denitrification in soil layer can be influenced (Sharma *et al.,* 2011). Additionally, pre-treatment of primary effluent by sieving before applying onto the infiltration system is likely to reduce clogging and hence the frequency of scrapping (Sharma *et al.*, 2011).

2.10 Solid loading and sludge decomposition

According to literature, treatment systems may be prone to several potential disruptions consisting of overloading. A system with good stability and fast recovery with respect to the treatment process would be desirable. Potential threats include:

(1) Organic shock load (e.g. sudden increase in kg BOD_5/day from increased population or increased organic concentration (mg/L) from low water use;

(2) Hydraulic shock load (e.g. sudden increase in flow from increased activity); unexpected chemical constituents in the influent (e.g. disinfectants or other strong chemicals);

(3) Unexpected physical constituents in the influent (e.g. large debris, small animals or oil).

The organic loading rate (OLR, expressed as kg COD/m^3 d) and sludge loading rate (SLR, expressed as kg COD/kg VSS d) applied during start-up are among the important parameters that influence the design parameter of a reactor and subsequently, the effective treatment of the waste sludge. For instance, a study by Li *et al.* (2012) revealed a decrease in removal efficiency of nitrogen, total suspended solids, ammonium and COD with increasing solid loading rate partly due to overloading of their system. These two parameters, respectively, define the capacity of the reactor per unit volume, and the capacity of organisms (micro and macro) per unit mass present in the reactor, to convert organic substrate into safe by-product (Ghangrekar *et al.*, 2005).

A study by Furlong *et al.* (2014) have indicated a drop in faecal reduction in their vermifilters after the feed rate was increased at the start of their experiments suggesting the period taken by earthworms to acclimatise to new feed, since in other studies the worms were acclimatised prior to the experiments (Yadav *et al.*, 2011). In the same study, a mean value of 24.2 kg of fresh faeces was added to the vermifilters as at the end of the 360 day test period, implying an average of 0.062 kg (67 g) was fed daily on the vermifilters. Their study suggests a rather low solid loading and/or users per day. Under this study, emphasis will be placed on the faecal solid loading based on the amount in mass of faecal matter per person per day.

2.10.1 Mass reduction of faecal matter

Mass reduction is important when assessing a technology's suitability for on-site sanitation, as it is directly related to the necessary size of the system and emptying frequency (Furlong *et al.*, 2014). A study by Furlong *et al.* (2014) demonstrated a 96 % faecal reduction in the presence of worms, compared to 38 % in control systems for a vermicomposting process of faecal matter. Between 23.7 and 24.7 kg of fresh human faecal matter was vermicomposted over a 360 day period.

2.11 Effect of household cleaning chemicals on the treatment performance of toilet systems

A variety of household cleaning chemical reagents are used in cleaning toilet bowls and eventually flushed down into toilet treatment systems in many homes. Many of household cleaning chemical reagents used comprise of detergents, disinfectants, soaps, bleaches, toilet cleaners etc. These chemicals have different chemical make-ups and contain active ingredients for their cleaning effects. For instance, disinfectants contain antimicrobial ingredients to kill germs on contaminated surfaces (Schwartz *et. al.,* 2004).

Under normal use conditions, the chemicals found in these cleaning products pose a minimal risk to the environment because they are diluted in septic tanks or degraded in the leach field for instance. Some household chemicals, however, contain ingredients that may harm the faecal treatment system (e.g. septic tank) or contaminate groundwater for instance fuels, motor oils, solvent-based lubricants, and lawn or garden chemicals such as pesticides (Schwartz, *et al*., 2004). These should not be disposed into treatment system like the septic tanks and into drains that end up into surface water bodies.

Although household cleansers and disinfectants may perform well in destroying bacteria in home usage of the disinfectants, their toxic effects are not expected to destroy the bacteria in many treatment systems (Gross, 1987).

In the bid to manage water, many households prefer to use wastewater from their laundry to flush and/or clean their toilet bowls. These laundry detergents and other household cleaning products contain surfactants. Surfactants commonly found in laundry detergents include linear alkyl benzene sulfonate and alkyl dimethyl ammonium chloride. These compounds may be removed in septic tanks for instance if they settle to the bottom or naturally degrade. Typically, however, surfactants are absorbed by the soil surrounding the leach field. This reduces their mobility below the leach field, which in turn provides more time for other treatment processes such as biodegradation. As a result, most laundry detergents and surfactant-based cleaning products are considered safe for both septic systems and groundwater (Schwartz *et. al.,* 2004).

Based on a rapid household assessment, the commonly used household chemical cleaning reagents comprised of chloroxylenol, hydrogen chloride and sodium hypochlorite. These are active ingredients found in dettol, harpic and bleach respectively.

Chloroxylenol (C_8H_9ClO) is generally used as a preservative in cosmetics, topical medications and urinary antiseptics (pH = 5.0). In liquid form, they are used for cleaning and disinfecting wounds and abrasions. The creams are used for cuts, scratches, insect bites, burns and similar problems and its powders are used to treat problems of the feet and skin inflammations. It is also found in hair conditioners, toilet and deodorants, soaps and paste (http://www.chemotechnique.se).

Hydrogen chloride (HCL), is a compound of the elements hydrogen and chlorine; a corrosive acid that is commonly used as a laboratory reagent (pH = 2). It is also used in the production of chlorides, fertilizers, and dyes, textile, and rubber industries (https://pubchem.ncbi.nlm.nih.gov/compound/hydrochloric_acid). It is the active ingredient in the harpic product for cleaning toilet.

Sodium hypochlorite for instance is one of the most effective and fast-acting disinfectants available. They are also used in laundry detergents and soaps. Sodium hypochlorite (NaOCl) is a compound that can be effectively used for water purification with a pH of 13. It is typically a bleaching agent and an active ingredient in most bleaches for domestic use and used in swimming pools for disinfection

(http://www.lenntech.com/processes/disinfection/chemical/disinfectants-sodium hypochlorite.htm).

2.11.1 Toxicity effect of chemical reagents in toilet systems

There has been considerable interest in the short-term environmental impacts of certain chemical residues in faecal material, which have been shown to reduce invertebrate populations and decomposition rates (Warren and Paul, 2006). A number of studies have been reported on the toxicity of certain chemicals on the functionality of septic tanks. A report by Cornell University indicates that more than 2 gallons of hypochlorite bleach is required to kill most of the bacteria in a 1,000 gallon capacity septic tank. The ensuing result is 45-60 hours for the bacterial populations to recover from a lethal dose of hypochlorite bleach (Schwartz *et. al*., 2004). Additionally, a number of studies have been conducted on worms in developing herbal medicine for treatment of intestinal worms using plant extracts (Hammond *et al.*, 1997). The main goal of Hammond *et al.* (1997) study was to investigate the potency of some plant extracts and how they affected intestinal worms. This was achieved by using earthworms for the toxicity test. Earthworms are a representative soil invertebrate, and are widely used in soil toxicity testing (Kwak *et al.*, 2014). Their choice to use earthworms in this experiment was due to the ease of their availability, anatomical and physiological resemblance with the intestinal roundworm parasite *Ascaris lumbricoids* of human beings. In agriculture, the effects of pesticides on earthworms have been studied by Edwards and Bohlen (1992); insecticides such as phorate and carbofuran when applied in soils are not harmful to earthworms. In other studies, the effect of single application of pesticides such as diazinon, isazophos, benomyl, carbaryl and bendiocarb in soil caused significant short-term reduction in earthworm numbers (Potter *et al.,* 1990).

As a result of the occurrence of household chemicals in toilet systems, there are potential concerns on the effect of chemical reagents on the rate of decomposition of these worms and their resistance to such harsh concentrations which have the potential to cause total death and dysfunctioning of the toilet systems. Toxicity tests can therefore be used to measure the robustness of a toilet facility. Robustness was described by Furlong *et al*., (2014) in their study of vermicomposted systems as the ability of earthworm population to survive periods when they are not fed and periods of variable feeding. In this study, robustness was defined as the ability of earthworms in the BTT to overcome the negative effect of household chemicals on their movement and the ability of the BTT to still breakdown organic matter when exposed to such household chemicals.

2.11.2 Time of paralyses and Time of death

The Time of paralyses and Time of death are parameters usually used in pharmaceuticals in the evaluation of In-vitro Anthelmintic Property of certain plant extracts at different concentrations on intestinal worms but using earthworms due to their anatomical similarities and physiological resemblance with intestinal worms in human beings. Time for paralysis is noted when no movement of any sort is not observed except when the worms are shaken vigorously. Time for death of worms is recorded after when worms neither moved when shaken vigorously nor when dipped in warm water (50°C) (Sangeetha *et. al.,* 2010). A recent study by Kumar *et al*. (2015) sought to investigate the paralysis and death of methanolic, ethyl acetate and aqueous extracts of aerial parts of *Lasia spinosa* against *Pheretima posthuma* (Indian adult earthworm). Their study suggested that the aqueous extract exhibited paralysis and also caused death of worms especially at higher concentration of 100 mg/ml.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Study Area

The study was conducted at the Department of Civil Engineering laboratory in Kumasi Metropolitan, Ghana. Faecal material was obtained fresh from a toilet facility (Enviro-loo) used by the "Kotei" community in the province. This was located about 1 km from the laboratory. The faecal matter was accessed fresh from the inside of the toilet bowls with the help of the toilet attendant and stored in plastic containers with air-tight lids. The samples were sent to the laboratory of the Department of Civil Engineering where it was thoroughly homogenised and analysed for physicochemical parameters prior to loading of the prototype BTTs.

3.1.1 Location of Study Area

The Kumasi Metropolitan is one of the 30 administrative districts in the Ashanti Region. It is located between Latitude 6.35 ^{o}N and 6.40 ^{o}S and Longitude 1.30 ^{o}W and 1.35 ^{o}E and elevated 250 m to 300 m above sea level. The Metropolis shares boundaries with Kwabre East and Afigya Kwabre Districts to the north, Atwima Kwanwoma and Atwima Nwabiagya Districts to the west, Asokore Mampong and Ejisu-Juaben Municipality to the east and Bosomtwe District to the south. It has a surface area of approximately 214.3 km^2.

3.1.2 Climate of Study Area

The temperature ranges between an average minimum of 21.5 ^{o}C and an average maximum temperature of about 30.7 ^{o}C. The average humidity is around 84.16 % at sunrise and 60 % at sunset. It has a double maxima rainfall regime of 214.3 mm in June and 165.2 mm in September. The Metropolis lies in the transitional forest zone specifically within the moist semi-deciduous South-East Ecological Zone.

3.2 Material Collection and Pre-Processing

Three main input materials were used in this study; earthworms, coconut fibre and human faeces. These are briefly described in the following sections. The prototype models of the Biofil Toilet Technology (BTT) were made from ¾ inch plywood. The base of the prototypes was covered with aluminium sheets to prevent rot and with perforations to drain effluent. The porous filter composite were manufactured from granite, PET and palm kernel shells at the structures laboratory of the Department of Civil Engineering. Other materials used were specific to the particular specific objectives and have been outlined in the following sections.

3.2.1 Earthworms

Earthworms, *Eudrilus eugeniae*, were obtained from existing BTT installations from Accra (It was difficult to get the quantities required for the experiment from installations in Kumasi due to the limited spread of installations) and cultured in the laboratory of the Department of Civil Engineering. The specie was confirmed at the Department of Biology, KNUST.

The earthworms were kept in plastic baskets lined with felt. Felt material is a good absorbent material for water to keep the environment moist. The basket was filled with soil (i.e.

biosolids from existing Biofil toilets) to act as a medium for the earthworms to thrive. Water was intermittently sprinkled on the beds to keep them moist. The top part of the basket was covered to maintain a dark environment to prevent the earthworms from migrating out of the baskets (Appendix B: Plate 11).

3.2.2 Coconut fibre

Coconut fibre were collected from coconut sellers in Accra and taken to the production site of BIOFILCOM for shredding. The shredded material was sieved to remove chaff and the coconut fibre transported to the laboratory of the Department of Civil Engineering where it was air dried before applying into the prototype BTTs.

3.3 Design of prototype BTT

The prototype BTTs were designed as shown in the schematic of the BTT (Figure 2-2). The prototypes were used to investigate specific objectives SO1, SO3 and SO4. Details of the design setup have been described in the sections below. Prototype models of the BTT were setup in the Environmental Quality and Soils Laboratories of the College of Engineering at KNUST, Kumasi.

3.4 Research Activities Related to Specific Objectives

3.4.1 Assessment of the effect of different porous filter composites and coconut fibre on contaminant removal from the blackwater (SO1)

The focus of this experiment was to investigate the contaminant reduction potential in blackwater by the different porous filter composites and coconut fibre used as bulking material in the BTT. The experiment compared the treatment performance of the existing porous filter composite (PCF) used in the BTT, which is made from granite aggregates (GR) with alternative porous filter composites made from shredded polyethylene terephthalate (PET) and palm kernel shell (PKS).

3.4.1.1 Preparation of porous filter composites

The porous filter composites were made from palm kernel shells (PKS), shredded polyethylene terephthalate (PET) bottles and granite aggregates (GR). The effective grain sizes of the PKS, PET and GR used for the fabrication of the porous filter composites were 3.41 mm, 4.8 mm, 4.9 mm respectively. The PKS was crushed and PET shredded with a grinding machine and shredder respectively. Sieve analysis was conducted on the aggregates using the mechanical shaker.

The different porous composite filters were fabricated by mixing their aggregates (granite crushed palm kernel shells and shredded PET) with cement and water in an 18 litre head pan. The porous filter composites after mixing were placed by hand in wooden forms and compacted using a hand trowel to achieve a final compacted height of 0.05 m and surface area of 0.3 sqm. The porous slabs were cured for 14 days as per ASTM C192. A mix ratio of 1: 3 was used with a water-cement (w/c) ratio of 0.35. Ordinary Portland cement of class 32.5R was used in all mixes. All measurement of component ingredients was by volume.

3.4.1.2 Physical characteristics of the porous filter composites

To determine the physical and hydrologic properties of the porous filter composites, six cylindrical porous filter composites (r = 50 mm, h = 110 mm) were fabricated and used for analysis of the density, hydraulic conductivity and compressive strength.

The bulk density (kg/m^3) of each porous filter composite was calculated by dividing their weights by their respective volume. A constant-head permeameter designed in the laboratory was used to measure the permeability as described by Luck *et al.*, (2007). The permeability of each porous filter composite was calculated by dividing the recorded flow rate by their surface area.

3.4.1.3 Experimental setup

The setup was constructed with wood in the form of a tabular frame. Each of the six compartments (three for the PKS, GR and PET; three for the coconut fibre) had an internal area of 300 mm x 300 mm with a depth of 600 mm (Plate 3-1). A plastic receptacle, with a diameter of 400 mm, was placed under the filtering membranes (PKS, GR, PET) and the coconut fibre compartments to collect any filtrate passing through for analysis. A spirit level was used to level the top of all the filtering membrane slabs to ensure that the flow of water is not skewed in one particular direction.

The coconut fibre was placed approximately 50 mm thick over an area of 300 mm x 300 mm (Plate 3-1).

Plate 3-1: Experiment setup for pervious concrete filters

3.4.1.4 Description of experiment

To mimic the flush water that is produced in the BTT, blackwater with composition of 150 g faeces in 3.3 litres of water was prepared and used as feed on the coconut fibre and different porous filter composites. The blackwater was mixed homogenously and poured onto the first compartments of the prototype model of the BTT containing the coconut fibre and net lining (Plate 3-1). The effluent through the initial layer of coconut fibre was collected in the 400 mm diameter receptacle and divided into two parts. 500 mL each of the effluent through the coconut fibre was run through the different porous filter composites (GR, PET and PKS). The remaining effluent through the coconut fibre were analyzed for their physico-chemical and bacteriological characteristics. Effluent through the different porous filter composites were also collected and analyzed for their physico-chemical and bacteriological characteristics.

The experiments were conducted between the hours of 6 – 8 am (due to the activities of microbes) for 25 days continuously.

3.4.1.5 Physico-chemical and bacteriological characteristics

The physico-chemical characteristics of the blackwater and effluent through the coconut fibre and the different porous filter composites were: pH, temperature, ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), Total Nitrogen (TN), Total Phosphorus (TP), *Escherichia coli* and total coliforms. All analyses were performed in accordance with the Standard Methods for the Examination of Water and Wastewater 20th ed. (APHA, 1998).

Membrane filtration and pour plate technique were used in monitoring the microbial populations in the effluent samples.

3.4.2 Assessment of the treatment efficiency of subsurface infiltration using pre-treated effluent from the Biofil Toilet Technology (SO2)

The objective of this experiment was to investigate the removal efficiency of subsurface infiltration using pre-treated effluent from the Biofil Toilet Technology. To mimic the effect of subsurface infiltration of BTT effluent, different soil columns (laterite, sand, clay, and loam) were applied (Figure 3-1). The setup was designed to run under unsaturated conditions to depict typical flushes from the BTT into the sub-surface soil. The soil columns were developed with a depth of 150 cm to represent the clearance between a typical toilet installation and groundwater table.

Effluent sampled from the soil columns were monitored for the reduction of contaminants in the wastewater. Details of the column preparation and sampling have been described in the subsequent sections.

3.4.2.1 Experimental Design

The soil columns were designed with polyvinyl chloride (PVC) tubes of 110 mm internal diameter and 180 cm long (Figure 3-1). A free board of 20 cm depth was used. The PVC pipe were supported at the base with a gravel packing of diameter of 2 cm and depth of 10 cm. The effluent through the soil columns were sampled at ports provided along the columns at 60 cm, 110 cm, and 160 cm below the freeboard.

3.4.2.2 Column Feeding Regime and Periodic Sampling Schedule

BTT effluent was obtained from three households in Kumasi and mixed homogenously. The effluent was collected by diverting into a container installed below the ground level (Appendix B: Plate 9). The BTT effluent was obtained from the full-flush. The full flush gave adequate effluent that could be applied onto the different soil columns for filtration and analyses of the various physico-chemical parameters. The full-flush systems use between to 6 – 9 litres of water for flushing while the microflush systems use up to 1 litre of water for flushing.

Biofil effluent was collected every morning between 6.00 am and 7.00 am for two consecutive months from private homes and transported immediately to the experimental setup. Blackwater was also collected from direct flush into the BTT before solid-liquid separation by the porous filter composite and characterized for its physico-chemical and microbiological constituents as a baseline data. The BTT effluent after solid-liquid separation was also characterized to determine the contaminant removal from the blackwater by the BTT to establish the effluent characteristics being applied onto the different soil columns.

To start the experiment, the effluent was first poured into a collection tank connected to a constant head feed tank. Effluent from the feed tank was evenly distributed via a 10 mm flexible distribution pipe onto the different soil columns (Figure 3-1). Sampling was done at the three different depths along the columns for physico-chemical and microbiological analyses. Samples from the various sampling ports were taken on the second, fifth, and eighth weeks, after the start of the filter runs for laboratory analyses. This was done to get enough filtrates for analyses.

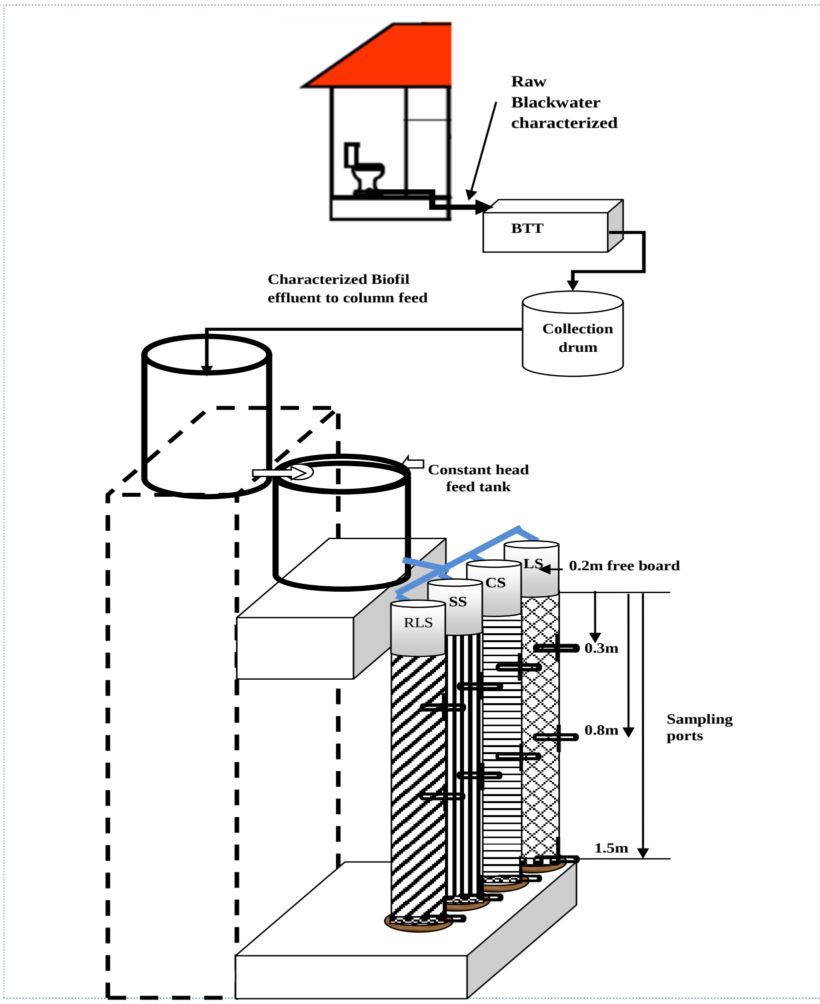

Figure 3-1: Scheme of the experimental soil column set-up

3.4.2.3 Physico-chemical and bacteriological characteristics

BOD_5, COD, TKN, nitrate, and nitrite and ammonia of the BTT effluent and filtered effluent samples through the soil columns were measured according to the Standard Methods for the Examination of Water and Wastewater (Clesceri *et al.*, 1998). Total dissolved solids (TDS) and total suspended solids (TSS) were determined by filtration and oven drying gravimetric methods. The total coliform numbers were estimated by the membrane Filtration Technique (Clesceri *et al.*, 1998).

3.4.3 Assessment of the effect of the solid loading rate on the treatment performance for optimization of the Biofil Toilet Technology (SO3)

The specific objective three (SO3) investigated the influence of different feed loading rate on the rate of decomposition of faeces in the BTT. The aim was to determine the optimum rate at which faecal matter can be added to the BTT, expressed as the amount of faecal material added per square meter of BTT surface per day (g feed m^{-2} day^{-1}). The study was conducted to give a better understanding of the effects the different feed loading rates have on the stabilisation process. Based on this, the maximum acceptable feed loading can be determined when the toilets are used continuously each day.

Prototype models of the BTT (comprising a porous filter to carry coconut fibre, faecal matter/tissue paper and earthworms) were setup as detailed earlier (Figure 2-2) to investigate three feed loading rates (1.80, 2.70 and 4.5 kg feed/m^2/day). These loading rates were determined based on 10 users/day, 15 users/day and 25 users/day respectively (Table 3-1). The three loading rates were designated as light, moderate and heavy. An average feed loading of 300 g/user/day was used as the generation rate (section 3.4.3.1). To achieve these loading rates in the experiment, the miniature BTT setup (having dimensions that are one-third the size of the original BTT) was fed with 195 g, 291 g and 485 g substrate respectively. Each setup had 50 mature earthworms (approx. 35g) and 200 g of coconut fibre. The combination of faeces to coconut fibre as per the different feed loading regimes (light, moderate and heavy) gave corresponding faecal matter: coconut fibre ratios of 1:1, 1.5:1 and 2.5: 1 respectively. Three replicates for each feeding rate were established.

Each of the loading rates had two controls: one control with faeces and coconut fibre only and the other with faeces only. The control with faeces and coconut fibre only was setup to monitor the contribution of the coconut fibre to the stabilization process while the control with faeces only was setup to monitor the contribution of the microbial population and/or tissue paper in the faecal matter to the stabilization process.

3.4.3.1 Feed loading rate determination

The following parameters were used for the calculation of the different loading rates:

i. Average solid loading rate (ASLR) = 300 grams/person/day
ii. Actual digester size/Experimental digester size = 3:1
iii. Total surface area of digester (TSAD) = 1.67 m^2 (i.e. 1.83 m by 0.91 m)
iv. Total surface area of experimental digester (TSAED) = 0.18 m^2 (i.e. 0.6 m by 0.3 m)

Table 3-1: Determination of solid loading rates

Calculation	Low loading	Moderate loading	Heavy loading	Unit	Remark	Code
	10	15	25		persons/day	A
(A) * (ASLR)	3	4.5	7.5	kg/day	Anticipated total generation rate	B
(B) / (TSAD = 1.67m^2)	1.80	2.7	4.5	kg/m^2/day	Anticipated solid loading rate (Actual)	C
(C)*(TSAED = 0.18m^2)/ (TSAD = 1.67m^2)	194	291	485	g/day	Feed to achieve solid loading rate (Study)	

3.4.3.2 Continuous loading

To mimic the situation where toilets are highly used daily, continuous feeding was designed and conducted for 14 days. Two moisture conditions representing full flush and microflush were used including the controls under the different loading rates for 12 prototype models of the BTT under each trial. The raw feed was analysed and grab samples from different parts and depths of the biosolids were also taken for C, N, TS and VS analyses. The C, N, TS and VS of the coconut fibre were also determined to investigate their contribution.

The mass readings of the experimental and control setups were also taken twice each day: before and after loading of each to determine the mass reduction of the faecal matter over the experimental period during stabilization.

3.4.4 Analytical procedure

3.4.4.1 Percentage faecal reduction determination

Percentage mass reduction was calculated using the equation:

$[(M_1 – M_2)/M_1)] \times 100$

Where;

M_1 = total faecal mass added;

M_2 = faecal mass remaining

3.4.4.2 Moisture content determination of biosolids

Typically, 50 % to 60 % moisture is considered optimum for the composting process. Water is the most commonly used as moisture source. Vermicompost samples (10.0 g) were weighed using the Brecknell balance. The samples were oven dried at a temperature of 105^{o}C for 24 hours and reweighed. The difference in weight expressed as the amount of water in the sample taken.

The percentage (%) moisture content was then calculated using the formula:

$[W_1\text{-}W_2/W_1] * 100\%$

Where

W_1 is the initial weight of sample before drying

W_2 is the final weight of sample after drying.

3.4.4.3 Total solids determination

The total solids content is a measure of the amount of material remaining after all the water has been evaporated.

Total dry solids content was determined by weighing 10 g of each sample into a Petri dish and designated W_1, oven dried for 24 hours at 105 ^oC and then reweighed, W_2.

The percentage of total dry solids is then calculated using the formulae;

% Total solids = $[W_2/W_1] * 100$ %

3.4.4.4 Organic matter and Ash content determination

Biosolid sample (10.0 g) was put into a dry porcelain crucible and dried for 24 hours at 105 ^oC. Samples were taken then transferred into an ignition furnace where the temperature was gradually increased to 550 ^oC and then maintained for 8 hours. The crucibles containing a grayish white ash were removed and cooled in a desiccator and reweighed.

The percentage ash and organic matter were then calculated by the differences in weight of the crucibles before and after combustion as follows:

% ash = $[(W_3-W_1)/W_2-W_1)] * 100$ % and

% Organic matter = [100 - % ash]

Where W_1 = Weight of the empty dry crucible

W_2 = the weight of the dry crucible containing the biosolids before ignition

W_3 = the weight of the dry crucible containing the biosolids after ignition

NB: The weight of the ash = $W_3 – W_1$

3.4.4.5 Carbon content determination

After heating at a temperature of 550 ^{o}C, all organic and inorganic carbon was burnt off and hence percentage carbon was calculated using the formula:

% Carbon = (100 - % ash)/1.72

3.4.4.6 Total Nitrogen determination

Well dried biosolids sample (0.2 g) was weighed into a Kjeldahl flask. To this was added 5 mL of concentrated sulphuric acid, 0.2 g of catalyst mixture (selenium powder and copper sulphate powder) and 1 gram of sodium sulphate. The mixture was heated in the digestion block until the solution was clear and digestion continued for 30 minutes. The samples were allowed to cool to the ambient temperature; then 60 mL of distilled water added to the digestion samples and transferred into distilling flasks. 20 mL of sodium hydroxide solution was added to the digested mixture to provide the necessary alkaline conditions for the release of ammonia. 200 mL of the mixture was then distilled into a conical flask containing 25 mL of blue boric acid mixture serving as the absorbent indicator. A change in colour from blue to green indicated the presence of ammonia. The solution in the conical flask was then titrated against standard 0.02 N HCL to grey end point. Blank was determined on reagents using the same quantity of standard acid in a receiving flask. Percentage nitrogen in each sample was calculated using the formula:

% N = {[(T-B) * N (0.1) * 14.007]/W * 1000} * 100 %

Where:

% N = Percentage nitrogen

T = titration volume for sample (mL)

B = titration volume for blank (mL)

W = weight of dried sample

N = Molar mass of HCL

3.4.5 Assessment of the toxicity effect and recovery rates of the vermin in the BTT to household chemicals reagents normally applied in cleaning of the toilet bowls (SO4)

In this specific objective, three different household cleaning chemicals notably used to clean toilets were used on the prototype Biofil Toilet Technology (BTT) to determine their toxic effects on the earthworms and degradation of faecal matter. The selection of these household chemicals was based on a simple survey of households (n=10) on the commonly used cleaning chemicals. The active ingredients in the three selected household chemicals were: chloroxylenol (C_8H_9ClO) in dettol; hydrogen chloride (HCL) in harpic and sodium hypochlorite (NaOCl) in bleach. The dilution of the stock concentration of the three different household chemicals was based on the microflush (i.e. 1 litre) and full flush (i.e. 9 litres) for flushing.

The toxicity test was conducted on five adult worms of *Eudrilus eugeniae* per each concentration since it is used in the BTT as a waste digester.

Key parameters determined under this specific objective included:

i. Time of paralysis;
ii. Time of death;
iii. Number or percentage of worms paralysed;

iv. Number or percentage of deaths of worms caused by the household chemicals;

v. Effect of the cleaning household chemicals on the rate of decomposition of the faecal material.

3.4.5.1 Household cleaning chemicals and experimental concentrations

The three household chemicals selected were diluted to obtain six different concentrations (C_1, C_2, C_3, C_4, C_5, and C_6) prepared from each and used for the toxicity test (n = 18) with a control using flushwater only (n = 3).

The first set of six concentrations was prepared based on the product usage specifications and amount of water used for dilution of the household chemicals before cleaning of toilet seats. These were termed "normal application" of the household chemicals. The corresponding concentration based on the normal application of the household chemicals was:

i. C_1 = 0.014 g/100mL;

ii. C_2 = 0.039 g/100mL;

iii. C_3 = 0.064 g/100mL;

iv. C_4 = 0.089 g/100mL;

v. C_5 = 0.114 g/100mL;

vi. C_6 = 0.139 g/100mL).

A second set of concentrations were prepared when the household chemicals were not applied according to the product usage specification. These are termed as "worse case" application with concentrations:

v. C_1 = 0.05 g/100mL;

vi. C_2 = 0.1 g/100mL;

vii. C_3 = 0.5 g/100mL;

viii. C_4 = 1.0 g/100mL;

ix. C_5 = 2.0 g/100mL;

x. C_6 = 3.0 g/100mL).

The two sets of household chemical concentration were applied under different experimental setups and compared.

All the two sets of concentrations (i.e. normal and worse-case application) were prepared from stock concentration of the three different household chemicals (chloroxylenol in dettol = 4.8 g/100mL; hydrogen chloride in harpic = 10 g/100mL and sodium hypochlorite in bleach = 3.5 g/100mL) as indicated on the product bottles. Different stock volumes of the household chemicals were diluted with flushwater to determine the six different concentrations mentioned above (under both normal and worse-case applications) and used for the toxicity test (Appendix A).

The final concentrations had their final volumes made to 33 mL to represent microflush regime and 600 mL to represent full flush regime. These volumes were determined based on a scale factor of 15:1 of the actual flush volume and the experimental flush volume. The concentrations were selected to cover the microflush and full flush regimes where 1.0 litre and 9.0 litres were used for flushing respectively. The final volume of the chemicals and different concentrations were poured in different perforated baskets containing the worms and monitored (Plate 3-2).

Calculations for the determination of dilution have also been presented in Appendix A.

3.4.5.2 Earthworms

In this specific objective, a total of 90 worms were used for each trial of experiment under both normal application test and worse-case application test. Five (5) worms per each of the six concentrations (C_1, C_2, C_3, C_4, C_5, and C_6) were used.

3.4.5.3 Test for paralysis and death

Spiked earthworms were placed on a tray and observed for paralysis or death. Mean time for paralysis of worm (min) was noted when no movement of any sort could be observed, except when the worm was shaken vigorously; the time of death of worm (min) was recorded after ascertaining that worms neither moved when shaken nor when given external stimuli (Partap *et al*., 2012).

Plate 3-2: Chemical preparation and experiment on Time of paralyses and death

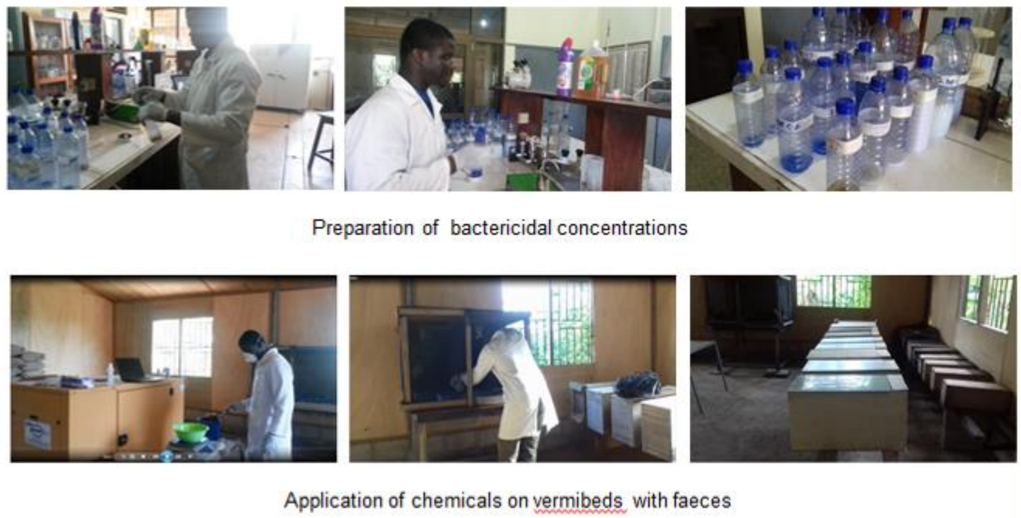

Plate 3-3: Chemical preparation and experiment on effect of chemicals on biodegradability

3.5 Statistical analysis

The results for all the analyses were subject to varying statistical tests to establish any trends, relationships and treatment effects that exist with the materials being assessed. Sieve analysis, density and permeability results were tested and verified as normally distributed data. Because the results were normally distributed, the statistical analysis proceeded with testing for trends and relationships. In addition, ANOVA and t-tests were conducted to determine if the use of an aggregate type as filtering membrane resulted in a significant difference in the removal of any of the contaminants. The t-tests were conducted using the two-tailed least significant difference (LSD) and differences were considered significant at an alpha value equal to 0.05 (Montgomery, 1997).

The results of the toxicity and robustness test were expressed as Mean ± SD of six worms in each group. Comparisons were made between standard against test treated group, $P< 0.05$ was considered significant. A Bonferroni corrected t-test value was also used in comparing same to increase the level of confidence in the data sets.

3.6 Data quality assurance and ethical considerations

The experiments were performed in triplicate where necessary and the average determined to ensure representative and reliable results. Standard Methods and Procedures for the examination of water and wastewater as described by (APHA, 1998) was followed for all analytical procedures. For quality assurance purpose, sampling bottles were washed thoroughly with detergent, clean tap water, rinsed with non-ionized water and finally sterilized prior to usage for next sampling. The samples were analysed immediately upon collection for most cases. However, in the event that the samples could not be analysed promptly, the samples were appropriately preserved by refrigeration.

Professional integrity and academic honesty were maintained throughout the study and to also safeguard the interest of all persons involved.

3.7 Experimental limitation

Due to limitation of biosolid volume available in the Biofil digester setup, the biosolids characteristics were determined at the beginning and after 7 days and 14 days of operation, with duplicate samples, for all experiments under the solid loading tests. There was a high reduction in mass of the biosolids over the experimental period.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

The summary of results of tests conducted during the experimental study is presented in this chapter with discussions to expand on their significance. The first part of the results focuses on the different porous filter composites and coconut fibre on contaminant removal from the blackwater. The second part looks at the treatment efficiency of subsurface infiltration using pre-treated effluent from the BTT. The experiment to evaluate effect of different solid loading rate on the treatment performance for optimization of the BTT is presented in the third part of the results and discussion. The last part focuses on the toxicity effect and recovery rates of the vermin in the BTT to household chemicals reagents normally applied in cleaning or disinfecting the toilet bowls.

4.1 Assessment of the effect of different porous filter composites and coconut fibre on contaminant removal from the blackwater (SO1)

This section presents results on specific objective one (SO1) which sought to assess the effect of different porous filter composites and coconut fibre on contaminant removal from the blackwater. Under this study, the performance of the current porous filter composite made from granite aggregates (GR) for the removal of contaminants during solid-liquid separation of blackwater in the BTT was compared with two alternative porous filter composites made from shredded polyethylene terephthalate (PET) and palm kernel shells (PKS).

To understand the capacity of the different porous filter composite to remove contaminants in the blackwater, their respective physical properties such as particle sizes, density, permeability and compressive strength were determined.

4.1.1 Particle size distribution, density and compressive strength

The grading curves for PKS, PET and GR (Figure 4-1) resulted in a uniformity coefficient (C_U) of 1.625, 1.848 and 1.510 with a corresponding effective aggregate particle size of 4.8 mm, 3.41 mm, 4.9 mm respectively.

The densities of the pervious composite specimens were 781.45 kg/m^3, 1171.3 kg/m^3 and 1944.34 kg/m^3 for PET, PKS and GR respectively. A study by Luck *et al.* (2006) suggested density ranges of 1739 - 2023 kg/m^3. Other recommended ranges between 1,570 and 2,000 kg/m^3 (Ghafoori and Dutta, 1995d; Tennis *et al.*, 2004) were proposed. Under the other specific objectives, the existing granite porous composite was used.

The compressive strength of the PET, PKS and GR were also calculated as 0.3 N/mm^2, 1.1 N/mm^2 and 5.6 N/mm^2 respectively.

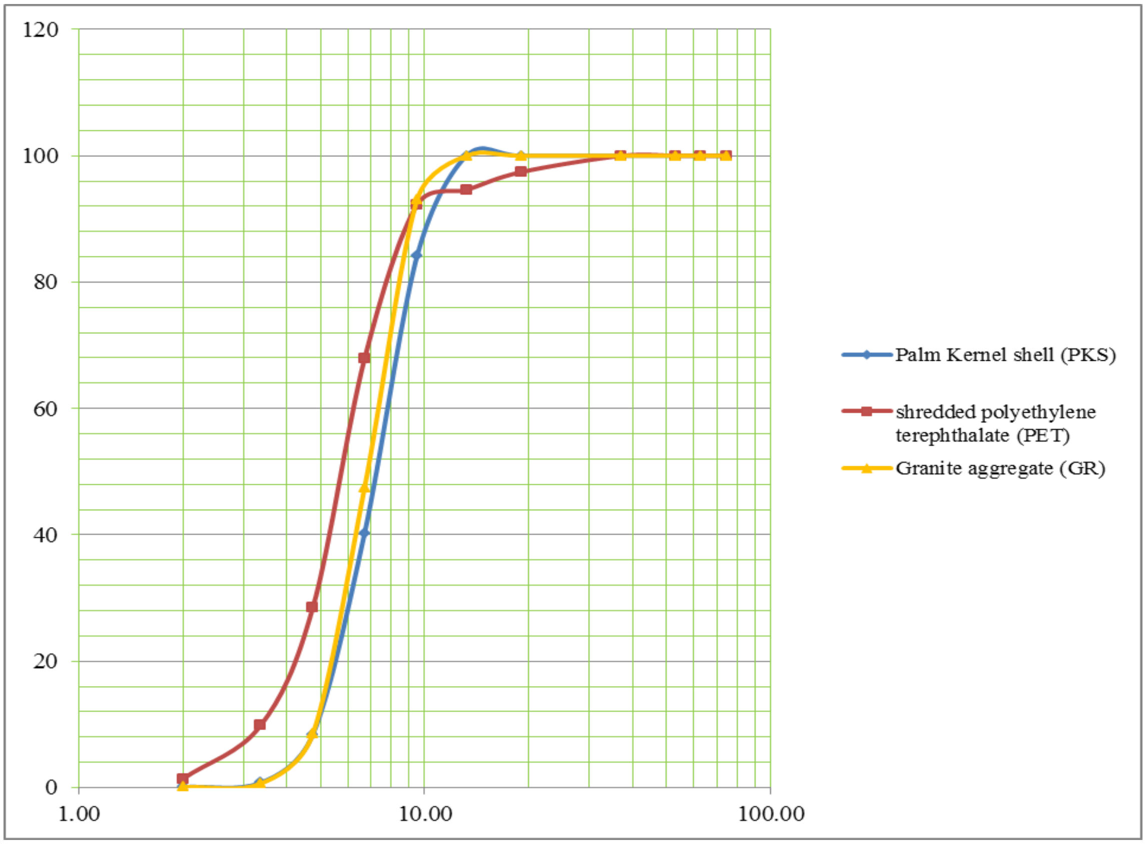

Figure 4-1: Grading curve of the different porous filter composites for solid-liquid separation of blackwater

4.1.2 Permeability

The permeability of the porous filter composites ranged between 0.0352 and 0.0390 cm/s. The GR aggregate had a significantly lower permeability (0.0352 cm/s) than the PET (0.0372 cm/s) and PKS (0.0390 cm/s) aggregates.

The results of the regression analysis on the specimen density and permeability (R^2 = 0.4642) suggests that if the density of the composite mixture were to increase, the permeability would be greatly reduced. The loss of permeability could be attributed to the lack of interconnected voids in the mixture at high densities as suggested by Luck *et al*. (2006).

4.1.3 Wastewater quality of composite-filtered effluent

4.1.3.1 pH

There was no significant variation ($p = 0.1662$) in pH values throughout the experiment after filtering the effluent through the porous composite filters. The pH of the influent blackwater and the strained effluent from the coconut fibre were similar. The pH was observed to have increased after filtration through the porous filter composites (Figure 4-2). This increase was most likely the result of available calcium carbonate in the cement (Luck and Workman, 2007). Additionally, the decomposition of the organic fractions of the wastewater, mainly by the microbes in the blackwater may have produced some mineralized organic materials (CO_3^{2-}, NH_4^+, and NO_3^-) that play an important role in altering the pH (Suthar & Tomar, 2011). The high urea content in urine which forms a major part of blackwater may also have contributed to the basic nature of the effluent (Owusu-Antwi *et al.*, 2015).

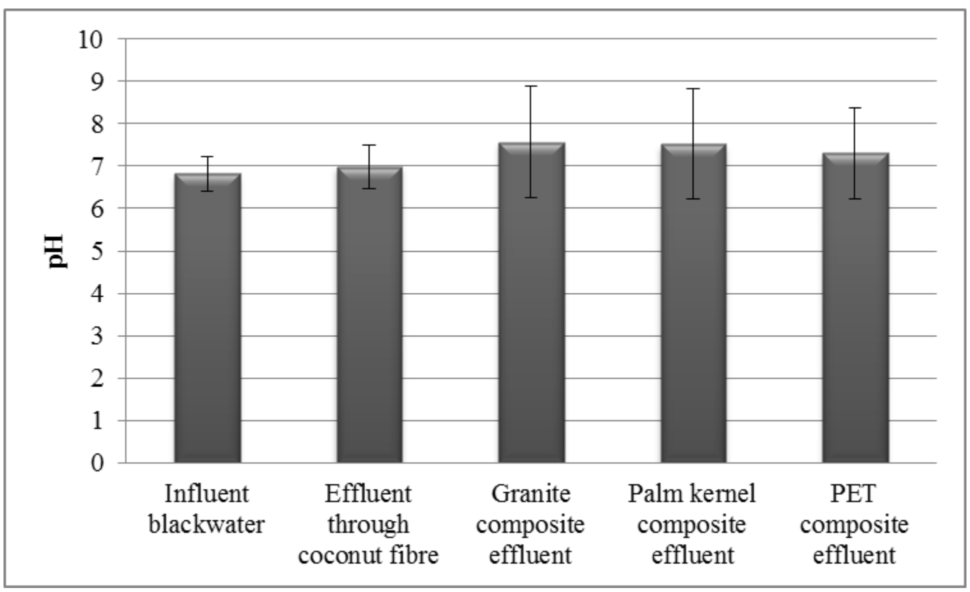

Figure 4-2: pH levels of influent and effluent through different porous filter composites

4.1.3.2 Electrical conductivity and Total dissolved solids

There was a general increase in the conductivity (Figure 4-3) and total dissolved solid (TDS) concentration (Figure 4-4) as the effluent run through the composite specimens. Electrical conductivity (EC) has been shown to indicate solute concentrations (e.g. nitrates) found in the effluent filtered with the porous filter composite (Luck and Workman, 2007). The presence of dissolved solutes might have contributed to the increase in the EC concentration. Adsorption plays a key role in the removal of dissolved contaminants during filtration in a medium (Schmoll *et al.*, 2006). Due to the high permeability of the composite specimens, there was low contact time to initiate any such adsorptive mechanisms at start-up. The filtration through the coconut fibre and porous filter composites might have also leached solute into the effluent resulting in the increase in the conductivity of the effluent.

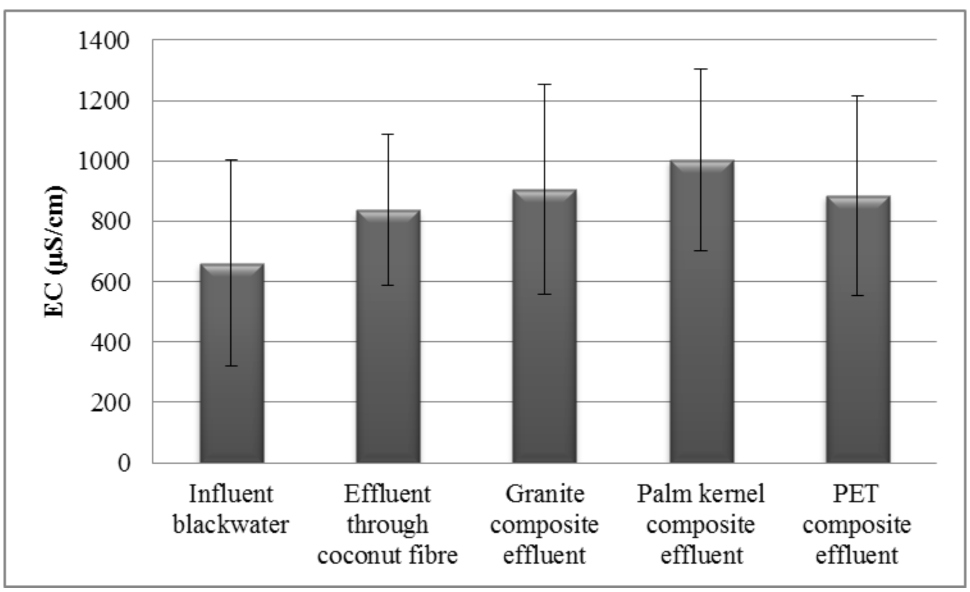

Figure 4-3: EC levels of influent and effluent through different porous filter composites

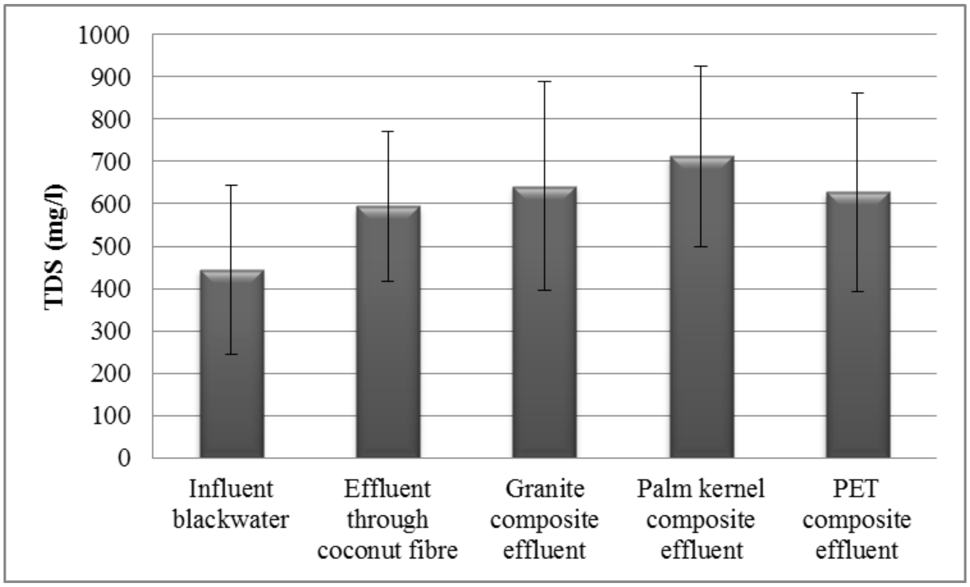

Figure 4-4: TDS levels of influent and effluent through different porous filter composites

4.1.3.3 BOD_5 and COD

There was a significant increase in BOD_5 (68 %) (Figure 4-5) and COD (30 %) (Figure 4-6) in the effluent filtered through the coconut fibre. COD/BOD ratios for the influent, effluent through the coconut fibre, granite, palm kernel shells and PET porous filter composites were 14.6, 6.7, 6.8, 7.3 and 7.3 respectively. A separate test run using only distilled water through the coconut fibre ascertained the leaching of solute in the effluent. Additionally, One-way ANOVA showed a high variation in BOD_5 concentration ($p=3.47 \times 10^{-6}$) within the samples. Further t-tests conducted on the samples indicated a significant variation between the BOD_5 concentration of the influent blackwater and the effluent through the coconut fibre. This indicates that high organic constituents in the residues of the faecal matter might have leached into the effluent. Particulates from the faecal matter are usually trapped in the pores of the composites and flushed out with continuous hydraulic loading.

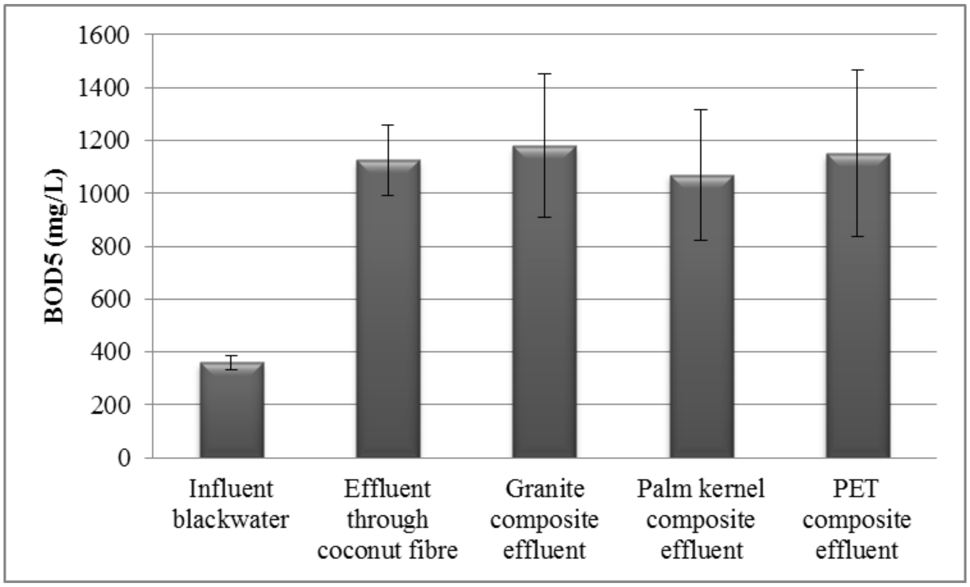

Figure 4-5: BOD_5 levels of influent and effluent through different porous filter composites

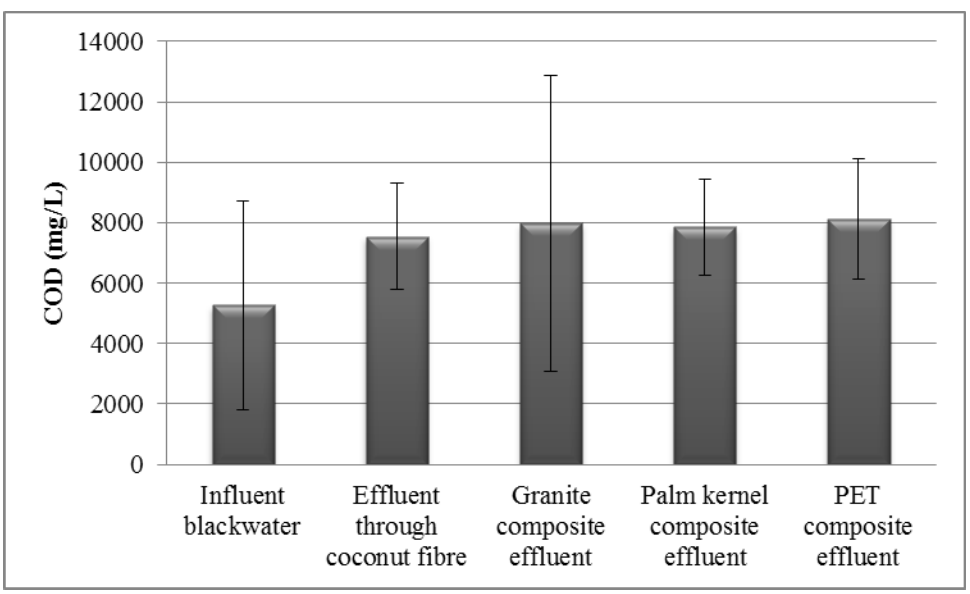

Figure 4-6: COD levels of influent and effluent through different porous filter composites

4.1.3.4 Total suspended solids

With respect to the total suspended solids (TSS), it was observed that there was an increase in the TSS concentration after filtration through the coconut fibre (33.4 %). Though there was a reduction in the TSS concentration after filtration through the porous filter composites using effluent through the coconut fibre; it was not statistically significant (p=0.730) (Figure 4-7). The chaff in the fibre due to the shredding process where washed down through the porous filters since they are generally smaller than the pores sizes in the composites. However, the coconut fibre was typically retained by the porous composite filters.

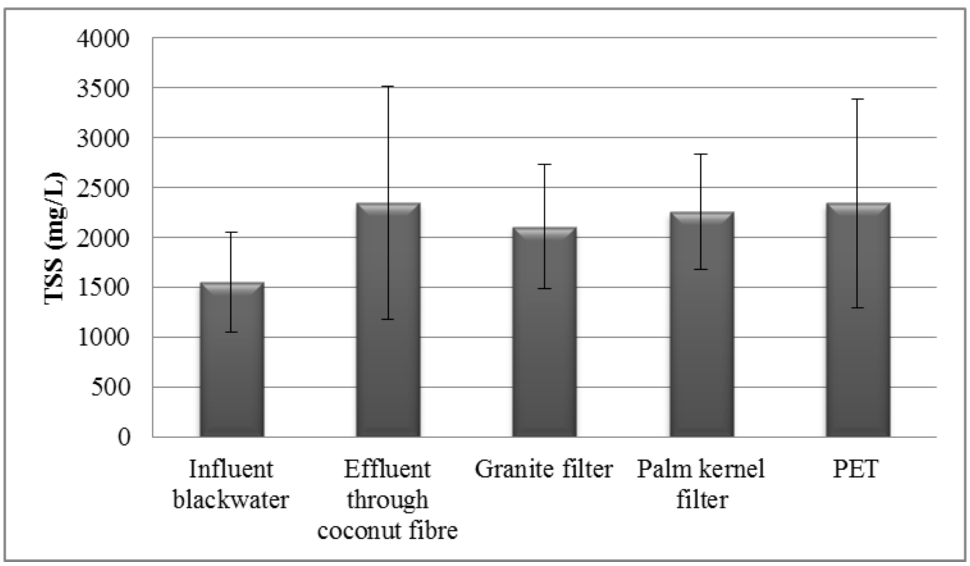

Figure 4-7: TSS levels of influent and effluent through different porous filter composites

4.1.3.5 Nutrient removal (Nitrogen and Phosphorus)

Generally, the porous filter composites were unable to reduce nitrogen concentrations effectively (Figure 4-8) (p value ranged from 0.302 to 0.9918). The total nitrogen (TN) had the highest concentrations in the effluents. The formation of ammonium ions after hydrolyses was observed to have increased generally which resulted in the production of nitrates and subsequent formation of nitrites. With the exception of the palm kernel composite, TN generally decreased in the effluent drained through the granite and PET composites. It is possible that the high permeability of the specimens did not allow for much interaction between the coconut fibre and the effluent emerging from the composites (Figure 4-8). Sato *et al.* (2010) in their study investigated the reduction in ammonia through possible adsorption unto the filter media of their packed beds. They indicated the low contact time as the limiting factor to the minimal reduction in ammonia levels. The potential for TN reduction in wastewater using composites were established by Sung-Bum and Mang (2004). The removal of the TN was attributed to the microorganisms attached on the porous composite.

The removal of total phosphorus (TP) using the porous filter composites resulted in significantly lower levels compared to the TN (Figure 4-9). Particulate trapping and absorption might likely be responsible for the TP reduction.

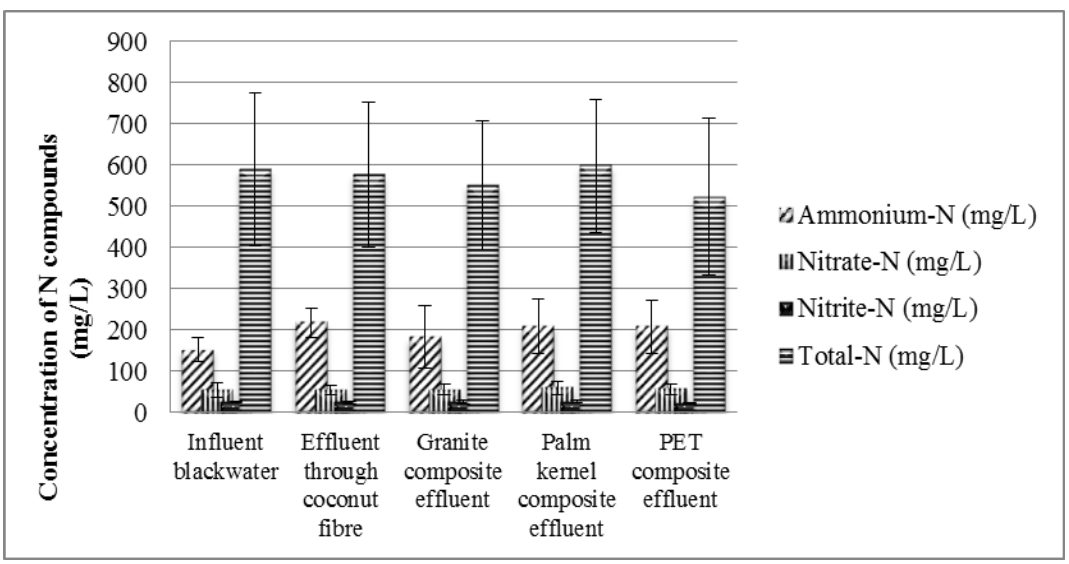

Figure 4-8: Performance of porous filter composites in nitrogen removal in blackwater

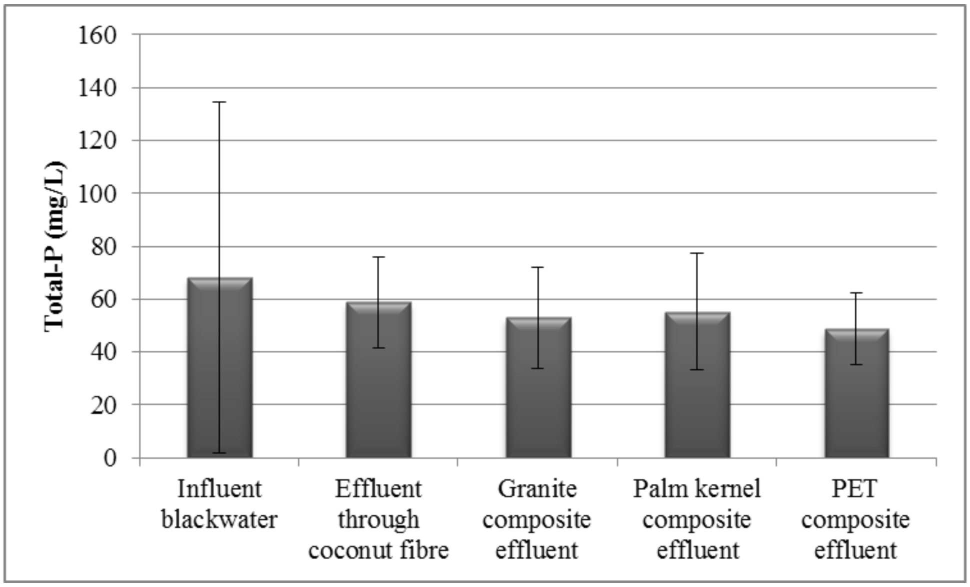

Figure 4-9: TP levels of influent and effluent through different porous filter composites

4.1.3.6 Microbial count

Effluent from the PKS gave the highest count of *Escherichia coli* of 26 x 10^8 cfu/100ml with corresponding other coliform count of 9 x 10^8 cfu/100ml. GR also recorded *Escherichia coli* of 26 x 10^8 cfu/100ml and other coliforms of 12 x 10^8 cfu/100ml. PET yielded the least coliform concentration with an *Escherichia coli* count of 6 x10^8 cfu/100ml and other coliform concentration of 4 x 10^8 cfu/100ml (Table 4-1). One-way ANOVA showed a very high variation in the counts of *Escherichia coli* colony forming units (cfu) ($p=8.334 \times 10^{-12}$). There was significant variation between the *Escherichia coli* population of the influent blackwater and the effluent from coconut fibre (p= 0.000373).

There was also a significant variation between *Escherichia coli* number between the effluent from coconut fibre and effluent from PET composite ($p=4.154 \times 10^{-5}$). The experiment was conducted within a temperature range of 24.5 – 29.4 ^oC.

Hydrophobic interactions between composite filtering media particles and microbial cells could have promoted attachment (Schaefer *et al.*, 1998) and thus, the reduction in the counts. Additionally, at higher temperatures bacteria are easily attached to polystyrene (Fletcher, 1997). Additionally, the coconut fibre, palm kernel shells (PKS) and granite (GR) might have provided surfaces for the microbes to multiply.

Table 4-1: Performance of porous filter composites in microbial removal from blackwater

Parameter	**No. of Samples**	**Coconut fibre**		**GR**		**PKS**		**PET**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Escherichia coli (x 10^8)	6	22	3	26	4	26	5	6	3
Other coliform (x 10^8)	6	13	5	12	3	9	4	4	5

4.2 Assessment of the treatment efficiency of subsurface infiltration using pre-treated effluent from the Biofil Toilet Technology (SO2)

This section presents results and discussions on the specific objective two (SO2). The pre-treatment of the BTT effluent during solid-liquid separation in the BTT have been presented. The characteristics of four common soils through which BTT effluent is discharged and their performance in the reduction of physico-chemical parameters in the BTT effluent have also been presented and discussed.

In this section, the use of the customised microflush seat connected to the BTT where up to 1 litre is used for flushing is termed “microflush BTT”. Similarly, the scenario where the regular water closet seat is connected to the BTT where between 6 – 9 litres of water are used for flushing is termed “full flush BTT”.

4.2.1 Physico-chemical and microbial characteristics of blackwater and BTT effluent

The characteristics of blackwater, effluent from the microflush BTT and full flush BTT have been outlined in Table 4-2. At a temperature range of 27.0 ^{o}C to 29.0 ^{o}C, the pH for the blackwater was typically neutral (6.92 ± 1.41) with the ensuing effluent from the microflush and full flush BTT recording pH values of 8.1 ± 0.67 and 7.8 ± 0.72 respectively. The decomposition of organic fractions of wastewater, mainly by microbes in water, produces mineralized organic materials (CO_3^{2-}, NH_4^+, and NO^{3-}) which play an important role in altering the pH (Suthar and Tomar, 2011). The high urea content in urine which forms a major part of blackwater may have contributed to the basic nature of the BTT effluent. Urea has been studied to hydrolyze rapidly in the presence of water by the action of enzyme urease to form ammonium ions (Orhon and Artan, 1994):

$(NH_2)_2CO + 2H_2O \Rightarrow 2NH_4^+ + CO_3^{2-}$ (Eq. 1)

The reduction of (i.e. NH_3-N, NO_3-N) was relatively low due to limited contact time for chemical transformation and precipitation. The increase in NH_4-N in the BTT effluent leading to the production of NH_3-N and NO_3-N can be attributed to the disposal of urine with faeces (Koné and Strauss, 2004). The urine fraction contributes 80 % of the total nitrogen concentration. In this fraction, >80 % consists of urea-nitrogen, which is readily converted to ammonia (Rose *et al*., 2015). The ammonium ions (NH_4+) produced during the hydrolysis of urea is also kept in equilibrium with ammonia (NH_3) according to the following reaction equation (Benefield *et al.,* 1982):

$NH_3 + H_2O \Rightarrow NH_4^+ + OH^-$ (Eq. 2)

The increase in the pH causes the formation of ammonia gas. Ammonia gas is very insoluble in water and will escape to the atmosphere (Metcalf and Eddy, 2003). In this study, the results indicate a reduction in the concentration of NH_3-N from the BTT which seems to agree with the phenomenon described. Additionally, NH_4-N in the presence of oxygen undergoes nitrification to form NO_3-N (Metcalf and Eddy, 2003). This is seen in the formation of NO_3-N most especially in the microflush (Table 4-2).

$NH_4^+ + 2O_2 \Rightarrow NO_3^- + 2H^+ + H_2O$ (Nitrifying bacteria) (Eq. 3)

The low concentration of NO_3-N in the full flush can be explained under two phenomena.

Contrary to expectation, the results showed very low concentration of NO_3-N (Full flush = 2.46 mg/L). This occurrence might possibly be due to denitrification process resulting from the development of unexpected anoxic conditions within the BTT. The BTT is normally aerated by a connecting vent. Depending upon the surrounding environment (i.e. installation of the vent pipe, non-sealing of the cover slabs etc.), the extent of aeration in the BTT can be influenced. Additionally, low filtration in the BTT could result in organic matter build-up which could lead to slight ponding:

$$6NO_3^- + 5CH_3OH \Rightarrow 5CO_2 + 7H_2O + 6OH^- + 3N_2 \text{ (Denitrifying bacteria)} \qquad \text{(Eq. 4)}$$

Although the BOD_5 concentrations in the microflush and full flush BTT effluents were reduced by 75 % and 87 % respectively compared with the blackwater values, their mean concentrations were greater than the GH-EPA permissible limit for discharge into open water bodies (There is no guideline limits for discharge into soils for On-Site Sanitation). The COD concentrations in blackwater were reduced by 76.9 % and 91.6 % in the microflush and full flush BTT respectively; the respective concentrations fell within the GH-EPA limit of 250 mg/L recommended for COD (Table 4-2). The COD/BOD ratio for blackwater, microflush and full flush were 3.0, 2.8 and 2.2 respectively.

Table 4-2**:** Wastewater characteristics of the feed blackwater and BTT effluent

Parameters	GH EPA**	Characteristic of Blackwater and Effluent from the BTT					
		Blackwater		Microflush		Full flush	
		Mean	SD	Mean	SD	Mean	SD
pH	6.0 - 9.0	6.92	1.41	8.11	0.67	7.83	0.72
Temp (ºC)		27.58	2.37	28.91	1.25	29.00	0.71
BOD_5 (mg/L)	50.0	761.55	675.78	184.01	60.41	98.27	127.69
COD (mg/L)	250.0	2268.35	2167.12	523.54	167.73	218.56	344.41
COD/BOD		3.0		2.84		2.22	
TDS (mg/L)	1000.0	984.00	953.79	311.75	136.44	1000.00	469.00
TSS (mg/L)	50.0	1247.00	1741.83	1550.29	250.38	883.31	1090.44
Turbidity (NTU)	75.0	342.67	322.67	64.17	8.65	18.70	13.53
EC (ᶣScm)	1500.0	2150.00	1629.87	899.38	337.39	2237.64	1485.94
Ammonia as TKN (mg/L)	1.0	33.23	16.70	0.49	0.25	14.43	6.61
Nitrate (mg/L)	50.0	28.93	55.38	153.83	24.28	2.46	1.97
TP (mg/L)	2.0	32.04	45.97	0.07	0.02	16.18	26.80
Total coliform (cfu/ml)	400.0	5.35E+07	8.28E+07	2.42E+05	5.73E+05	4.66E+07	7.97E+07
Escherichia coli (cfu/g/dw)	10.0	1.88E+07	2.61E+07	1.74E+04	2.53E+04	2.48E+06	3.61E+06
Helminth eggs (ml/L)	<1.0	0.25	0.50	ND	ND	ND	ND

** Ghana EPA guideline values for wastewater discharge into natural water bodies

The high concentration of BOD_5, COD, and TSS in the blackwater can be attributed to the anal cleansing materials (i.e. toilet paper). The pollution potential of toilet paper as reported by Almeida *et al.* (1999) contributes as much as 706 and 546 mg per sheet for COD and TSS concentrations respectively. Their removal from the blackwater by the BTT is mainly accomplished through the solid-liquid separation (i.e. physical straining). The COD/BOD ratio of 3:1 suggests that part of the organic matter content is difficult to degrade biologically due to the presence of refractory or non-biodegradable substances contributing a larger proportion of the COD in the sample (Asia and Akporhonor, 2007). Different researches agreed that occurrence of COD/BOD ratios in the range of 1.5 - 2.0 implies there exist high levels of bio-degradables and therefore could lead to removal of organics (Samudro and Mangkoedihardjo, 2010). Secondly, particulates of organic matter may be flushed into the voids of the composites and trapped. The high reduction in coliform counts in the influent seems to be associated with the filtration of TS by the composites. TS generally provides adsorption sites for these microbes and is removed from the liquid portion of the blackwater (Ariffin, 2009). It was noticeable despite the high reduction in coliforms; the effluent did not meet the standard for discharge into open bodies. The presence of food substrate forms a basis for coliforms to quickly multiply and increase in their counts (Monroy *et al*., 2009).

4.2.2 Filter media used in soil columns

Four different soil media comprising red lateritic soil, sandy soil, clayey soil and loamy soil were selected and applied for this infiltration experiment. All the soils were generally acidic with permeability ranges (Table 4-3) between 0.001 k (Clayey soil) and 0.0230 k (Sandy soil). Similarly, the bulk densities of the soils ranged between 1,272.82 kg/m^3 and 1,592.43 kg/m^3. The detailed characteristics of the four soils have been presented in Table 4-3.

Table 4-3**:** Characteristics of Soil Used

Column soil types	Constituent particle size percentages (%)				Bulk density (kg/m^3)	Permeability coefficient (cm/s)	pH
	Clay < 0.002 mm	Silt 0.002-0.06 mm	Sand 0.06-2 mm	Gravel > 2 mm			
Red laterite soil	38.20	21.50	40.30	0	1,367.94	0.0005	5.55
Sandy soil	0	0	99.71	0.29	1,592.43	0.0230	5.66
Clay soil	23.5	65.68	10.82	0	1,272.82	0.0001	4.07
Loamy soil	10.5	78.75	10.75	0	1,336.38	0.0003	6.02

Notes: RLS: red lateritic soil; SS: sandy soil; CS: clay soil; LS: loamy soil

All the soils had particles sizes in the range of clay and silt (Table 4-3) which constitutes the majority of fines in the soil types. The red laterite soil and clayey soils had the greater percentage of the fines (Clayey soil was not considered in the analyses due to heavy clogging). The removal of contaminants from the wastewater during filtration through the soil columns may have been influenced by the particle sizes of the different soils (Figures: 4-13; 4-14; 4-15). These conform to reports where grain sizes of soils were very crucial in the removal of bacteria and other contaminants in wastewater through the mechanism of straining (Matthess *et al.*, 1985). This finding is in agreement with results reported by Ausland *et al.*, (2002) and Stevik *et al.*, (1999) where they described the straining ability of their soil media in removing bacteria from wastewater. Silt and clay have pore sizes smaller than the range of sizes reported for most bacterial cells. Straining can thus be a mechanism in limiting the bacterial movement through these materials (Matthess *et al.* 1985). During unsaturated flow, transport takes place in the smallest pores, and straining can be more effective than during saturated flow through the same filter media (Stevik *et al.*, 2004).

4.2.3 Physico-chemical characteristics of wastewater samples in the soil columns

In the bid to address the second specific objective, infiltration experiments were run to assess the purification of BTT effluent through soil columns using four different soils [red laterite soil (RLS), sand soil (SS), loamy soil (LS) and clayey soil (CS)]. Filtrates collected from the three sampling ports (0.3 m, 0.8 m, 1.5 m) along the soil columns were analyzed for pH, conductivity, TDS, COD, TSS, BOD_5, NH_4-N, NO_2-N, NO_3-N, faecal, and total coliform. As a result of the high clogging in the clayey soil, adequate filtrates were not obtained for analyses. Results of clayey soil have not been considered in the analyses.

4.2.3.1 pH

The pH of the influent and effluent from the soil columns were generally basic within a range of 6.5 to 8.86. The effluent sampled at a depth of 1.5 m from the sandy soil column was the only one in the acidic regime (Figure 4-10). There was no significant difference between the pH values in the soil columns ($p = 0.053$). The Generally basic pH in the effluent can be attributed to the hydrolysis of urea to ammonium with the release of carbonates (Orhon and Artan, 1994). The acidic nature observed in the 1.5 m depth of the sandy soil can be due to two phenomena: the probable formation of CO_2 due to the depletion of oxygen by microbial metabolism and the subsequent utilization of organic acids produced during decomposition by microbial metabolism. Additionally, the presence of NO^{-}_{3} and NO^{-}_{2} ions in the sandy soil at depth 1.5 m (Figure 4-16) which are weak bases, are reported to cause ionic acidity (Garg *et al.*, 2006).

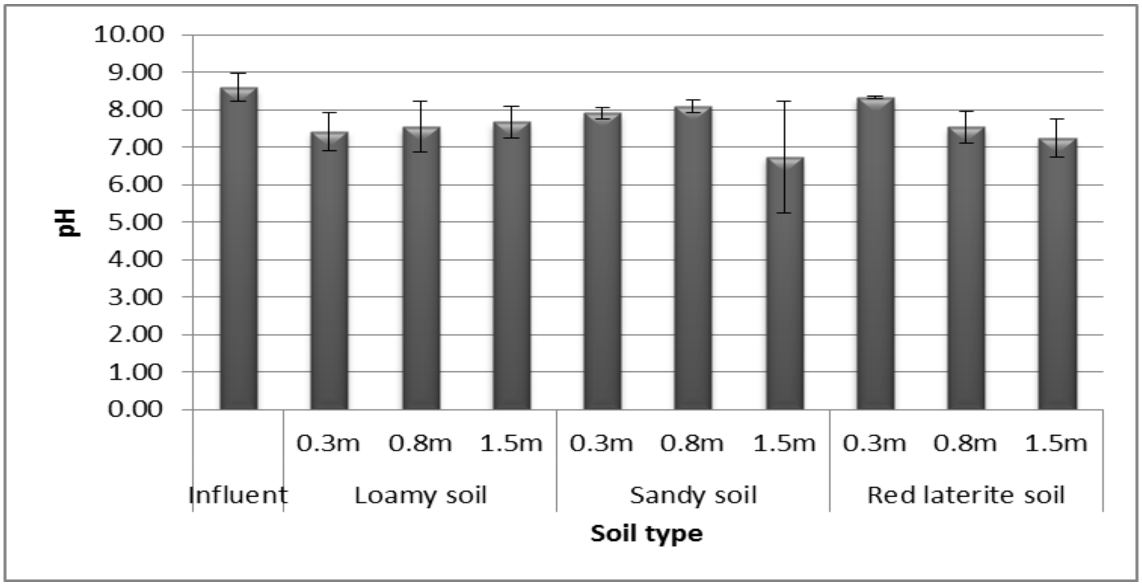

Figure 4-10: pH levels of influent and effluent in different soil columns

4.2.3.2 Conductivity

The relevance of conductivity gives an indication of the proportion of exiting ions that are in dissolution. This study showed that the RLS had the highest capacity to remove the dissolved ions. Conductivity concentration generally varied at different depths of the soil columns with the lowest value of 417 µS/cm measured at a depth of 1.5 m in Red laterite soil (Figure 4 – 11). Throughout the experiment, a minimum average temperature of 28.2 ^{o}C and maximum 31.8 ^{o}C (mean deviations of 0.3 to 1.8) was recorded. The concentration at 1.5 m in the red laterite soil was significantly lower than at 0.3 m (p=0.00303). The reduction in conductivity concentration was observed to be increasing with depth. The large adsorptive surface area might have contributed to the reduction. This was evident at a depth of 0.3 m in the red laterite soil. The conversion of NO_3 into diatomic molecular nitrogen (N_2) has also been reported to decrease the conductivity levels in domestic wastewater (Sharma *et al.*, 2013).

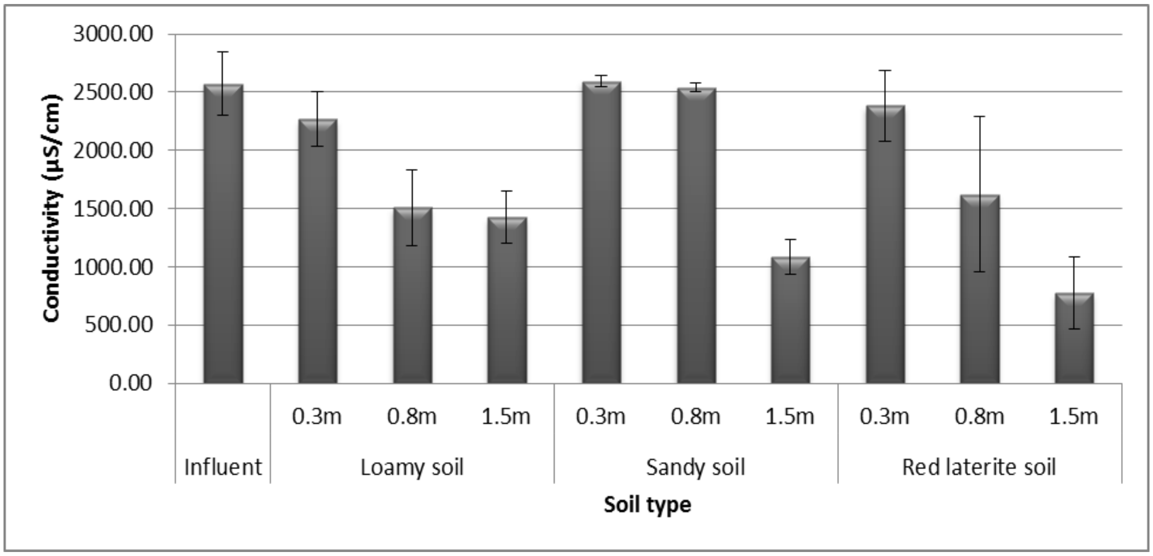

Figure 4-11: Performance of different soil columns in conductivity removal

4.2.3.3 Total dissolved solids

TDS concentration decreased with depth (Figure 4-12). The influent TDS concentration (1200-1500 mg/L) reduced to 500 mg/L in the RLS at a depth of 1.5 m. Loamy soil, sandy soil, and red laterite soil recorded an average of 50 %, 60 %, and 80 % TDS removal respectively at the maximum depth of 1.5 m. The RLS demonstrated good percentage removal at depth of 1.5 m. This confirmed the high conductivity reduction by the RLS (Figure 4-11 and 4-12) which could be attributed to ion adsorption capacity of the RLS. The results indicated a statistically significant reduction of TDS along the depth of soil columns.

Adsorption is key in the reduction of dissolved contaminants during infiltration in the soils (Schmoll *et al.,* 2006). Short circuiting may partly be the cause of TDS levels showing higher values at some depth. At depths beyond 0.3 m, the RLS performed better at reducing TDS concentrations in the effluent notably at a depth of 1.5 m.

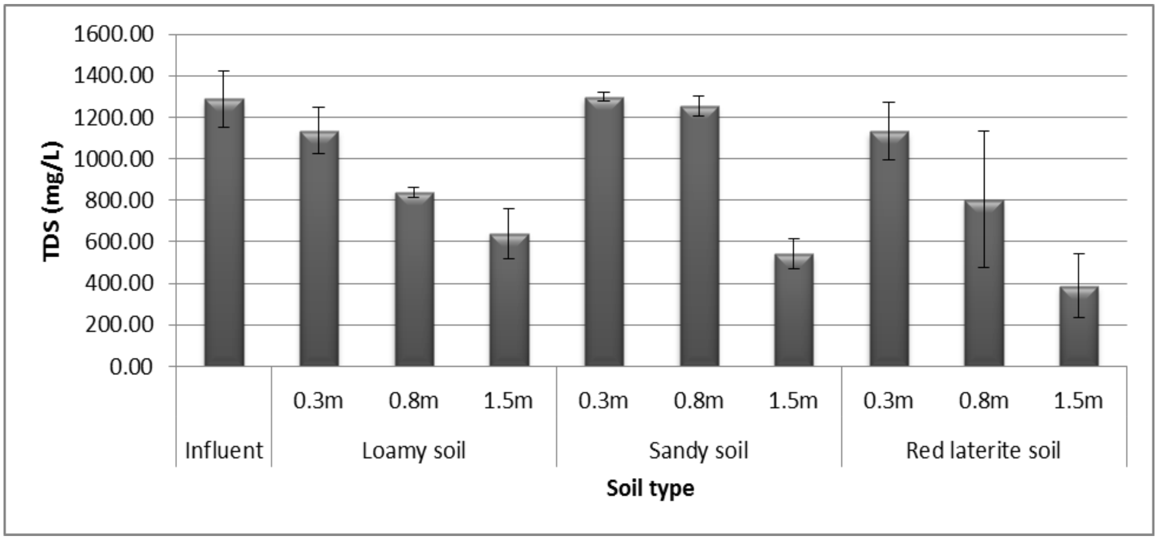

Figure 4-12: Performance of different soil columns in TDS removal

4.2.3.4 BOD, COD and TSS

BOD_5 concentrations were significantly reduced in the red laterite soil (Figure 4-13). The ANOVA conducted for the different soil columns was significant (p= 1.45E-07). Very notably amongst the lot was the fact that the BOD_5 concentration at 0.3 m (p= 0.0041), 0.8 m (p= 0.0040) and 1.5 m (p= 0.0039) within the red laterite soil were significantly lower than the influent concentration; showcasing the best performance in terms of BOD_5 removal (Figure 4-13).

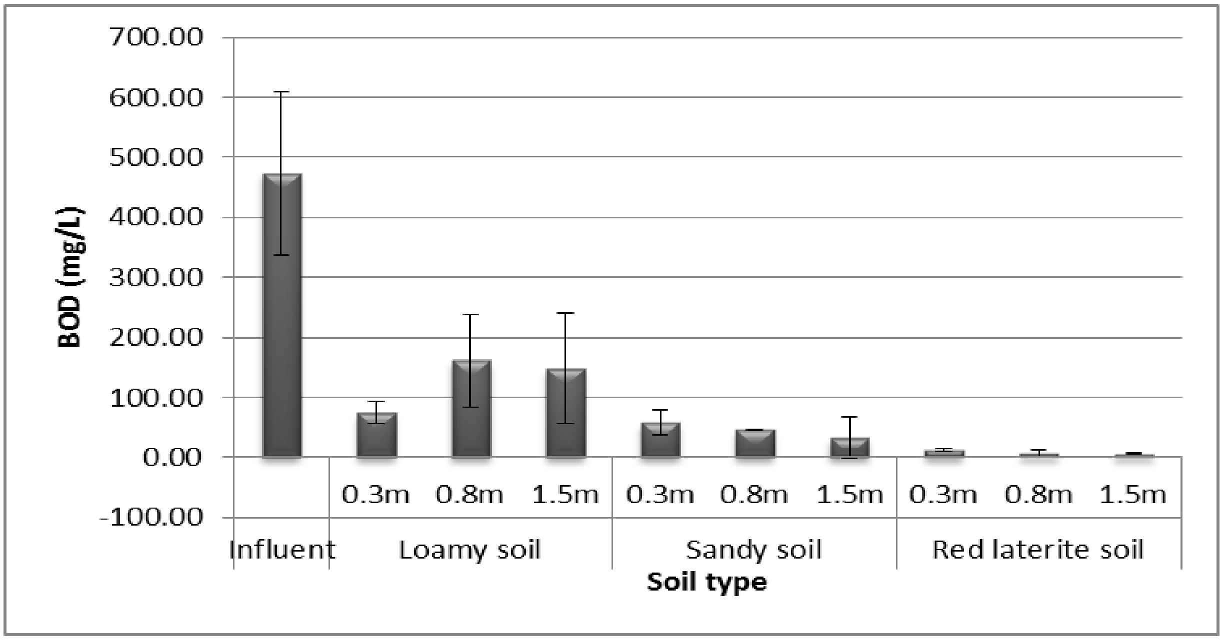

Figure 4-13: Performance of different soil columns in BOD_5 removal

Generally, COD concentrations decreased with increasing depth (Figure 4-14). However, there was a rare increase in the COD concentration at depth 1.5 m in the sandy soil. This might be attributed to possible short circuiting. The red laterite soil contributed to a COD reduction of 84 % in the influent concentration (Figure 4-14). The red laterite soil performed better at all the sampling points. A Bonferroni corrected t-test showed that there was significant difference between the concentrations at 0.8 m and 1.5 m of the soil columns ($p=0.013$).

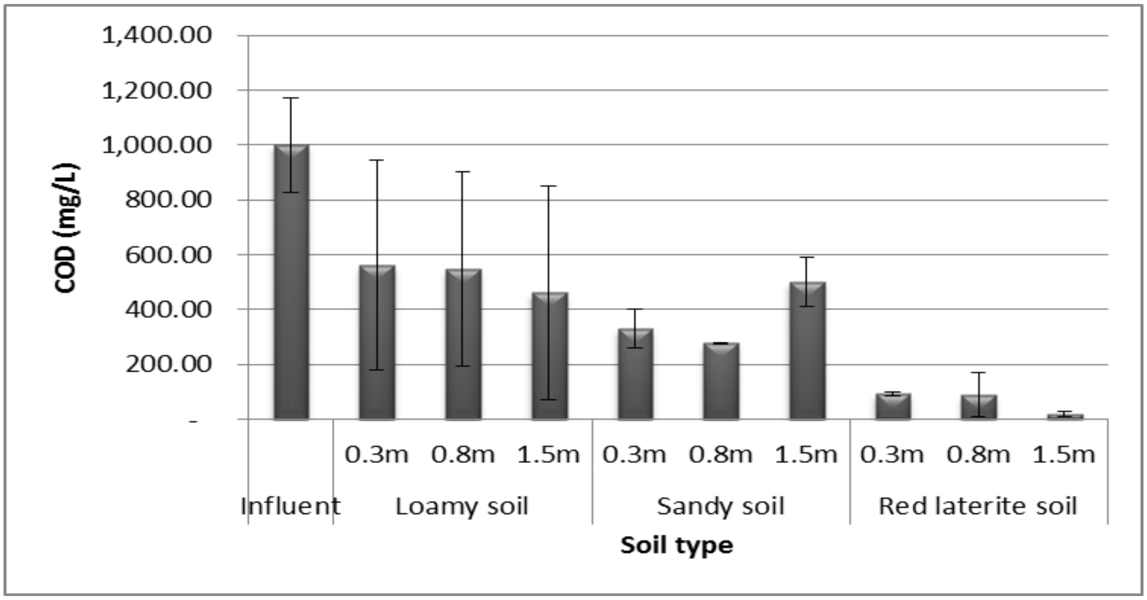

Figure 4-14: Performance of different soil columns in COD removal

Similarly, TSS concentrations were reduced by 90 % in the influent by the red laterite soil at a depth of 0.8 m (Figure 4-15). The ANOVA for the soil columns was significant (p=8.02E-09).

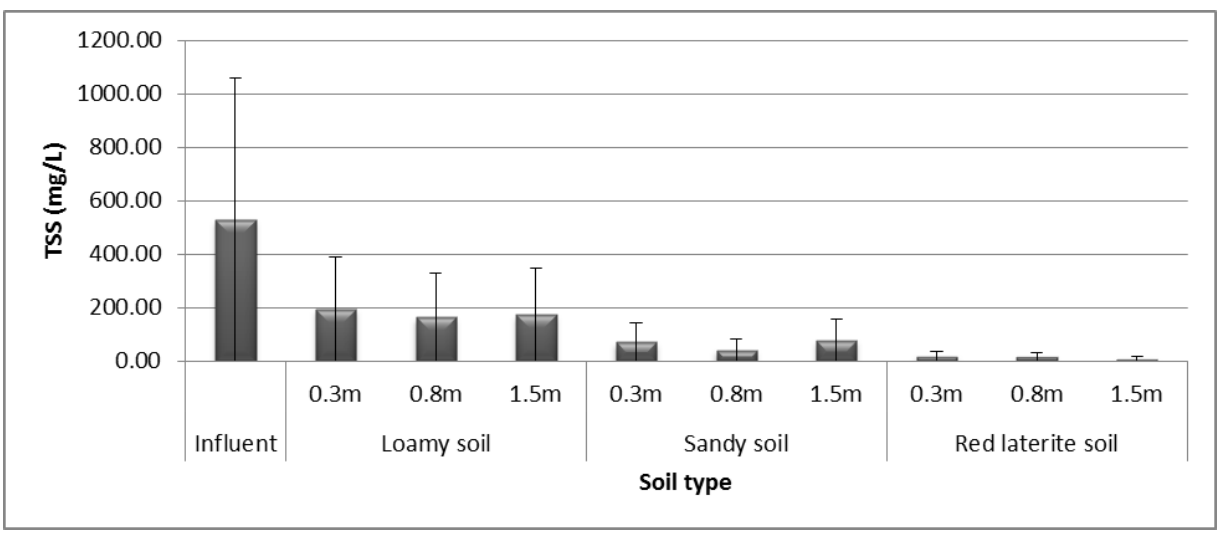

Figure 4-15: Performance of different soil columns in TSS removal

The amount of effluent samples collected during the experiment showed that the red laterite soil has a relatively slower infiltration rate than the other soil columns, thus increasing the contact time for contaminant interaction with the soil media. TSS, BOD_5, and COD might have been effectively reduced due to the longer interaction with the soil media by enhancing microbial reaction. Infiltration rate has a direct impact on the contact time and hence contaminant removal is most pronounced in the first 1.5 m depth in the vadose zone (Drewes and Fox, 1999). Generally, the soil columns attained their optimum performance by way of TSS, BOD_5, and COD removal at depth up to 0.8 m. TSS in particular can easily be removed during soil passage when there is clogging and head loss develops (Sharma *et. al.,* 2011). Suspended solids are also removed by filtration through the upper soil layer and the largest part is mostly composed of volatile suspended solids (Idelovitch *et al.,* 2003).

4.2.3.5 Nutrients

Though the nutrient levels in the effluent from the BTT had high concentrations of T-N and NH_4-N up to 250 mg/L, NO_3-N were seen to have low concentrations in the effluent through the soil columns (0.06 mg/L) (Figure 4-16). There were significant reduction in the nutrient concentrations within the first of 0.8 m. NO_3-N and a NO_2-N concentration in both the influent and effluent were generally less than 50 mg/L, but observed to increase at a depth of 1.5 m within the soil columns, notably in the sandy soil. Red laterite soil column was effective in reducing the concentrations of T-N and NO_3-N in the BTT effluent compared to the other soil columns. It has been reported that the composition of the biodegradable nitrogen compounds change forms as it moves through soils due to natural biological processes that occur (Babel *et al.,* 2009). These changes are usually facilitated by nitrification and simultaneous denitrification during soil infiltration (Güngör and Ünlü, 2005) depending on the redox potential (Fox *et al.,* 2001a). The denitrification process may have been triggered by the levels of carbon source, nitrate-N and anoxic condition (sufficient BOD_5 level) in the soil. The generally low concentrations of NO_3-N in the soil column seem to suggest the existence of anoxic conditions within the first 1.5 m vadose zone of the different soils. Typically, biological activities in wastewater with high total oxygen demand will utilize all the dissolved oxygen leading to anoxic conditions in the saturated zone (Pescod, 1992). The resulting anoxic conditions promote carbon degradation and denitrification with nitrate as the electron acceptor. Dissolved oxygen is rapidly depleted in the vadose zone and this usually causes the redox potential to decrease. The decreasing redox potential usually converts nitrate to nitrogen gas which escapes into the environment (Fox *et al.,* 2001a). Sharna *et al.* (2011) also confirmed the loss of nitrates through denitrification process.

The re-generation of NO_3-N at a depth of 1.5 m can be attributed to a possible re-aeration of the gravel supporting base of the soil columns experimental setup through the outflow nozzle.

Under aerobic conditions, nitrification usually takes place in the unsaturated zone and part of the nitrogen adsorbed on soil particles undergoes nitrification (Fox, *et al.,* 2001b). A rare scenario was noticed in the sandy soil where the T-N seemed to increase in the sandy soil. Usually, limited dissolved oxygen in soil columns accelerates the conversion of T-N to NO_3-N most especially at depth 1.5m in the sandy soil. This phenomenon is confirmed with the sudden drop in pH in the sandy soil at depth 1.5 m (Figure 4-10). Bacteria involved in the second stage nitrification might have been inhibited by the drop in pH causing elevation of the TN concentration, due to possible accumulation by continuous inflow of the influent TN (Anthonisen *et al.,* 1976). The operation of the soil column test to depict normal flushing at the household introduces a regime of wet and dry cycles in the soil. It has been shown that it is possible to achieve some nitrification and denitrification during soil infiltration with appropriate wetting and drying cycles (Fox *et al.* 2001a, b; Crites *et al.* 2006).

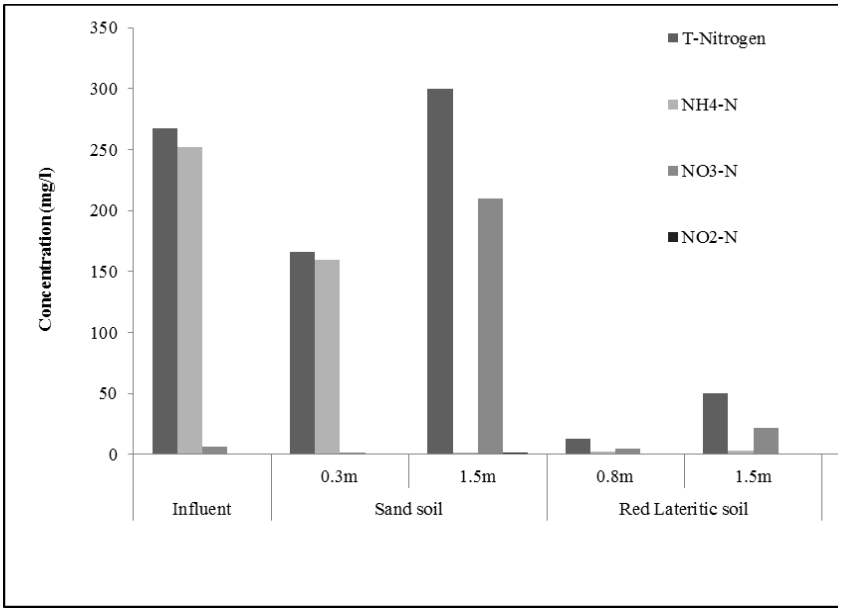

Figure 4-16: Performance of different soil columns in nitrogen compound removal

Red laterite soil performed well in the reduction of phosphorus concentrations (Figure 4-17). The reduction can be attributed to adsorption onto iron and aluminium containing minerals and/or precipitation with these minerals (Reemtsma *et al.*, 2000). Laterite soils generally have a high content of iron oxides and oxyhydroxides that have zeta potentials to enhance adsorption at pH beyond 6. Iron ions also have high affinity to phosphate groups (Gidigasu, 1976) and take them out of solution.

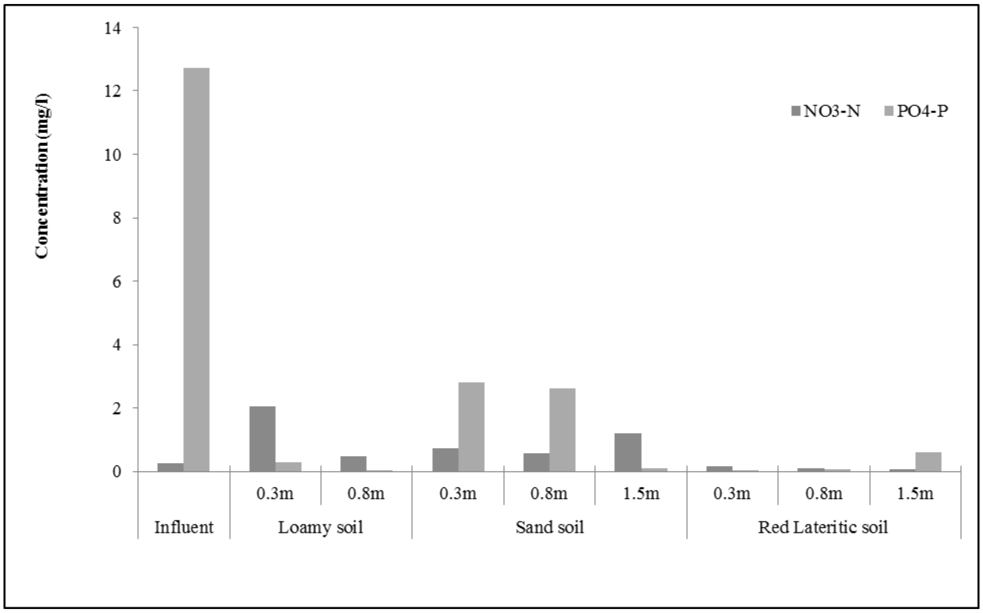

Figure 4-17: Performance of different soil columns in phosphate removal

4.2.3.6 Pathogen loads in the soil columns

The levels of *Escherichia coli* applied as feed onto the different soil columns was 5.42 x 10^7 cfu/100ml (Figure 4-18). RLS performed well in the reduction of *Escherichia coli* (p= 3.17E-07). The Bonferroni corrected t-test value was used to test the significance of the soil columns. In the case of the sandy soil, the counts of other coliforms at 0.3 m (p= 0.0167), 0.8 m (p= 0.0165) and 1.5 m (p= 0.0167) were significantly lower than the influent counts. Similarly, the counts for other coliforms in the red laterite soil at 0.3 m (p= 0.0166), 0.8 m (p= 0.0165) and 1.5 m (p= 0.0165) were significantly lower than the influent counts (Figure 4-19).

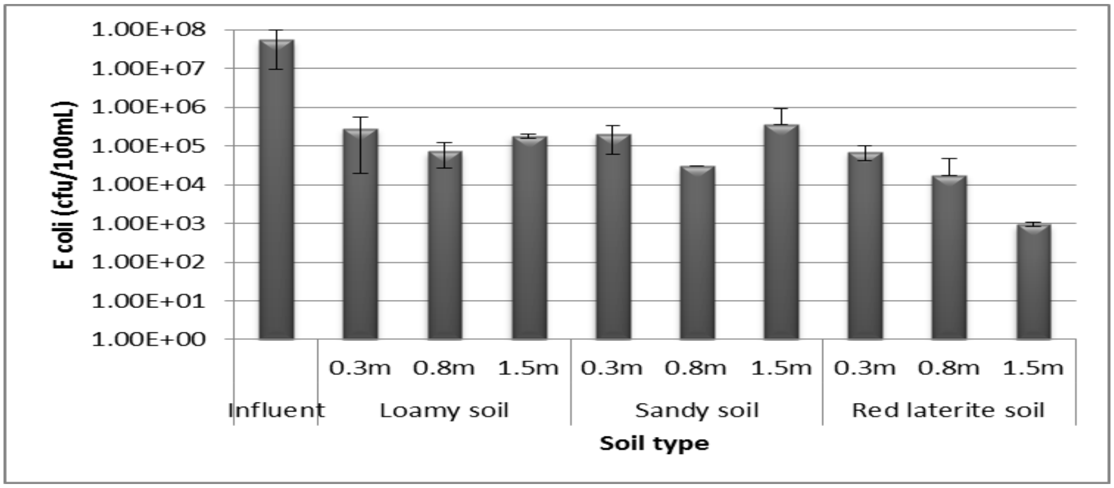

Figure 4-18: Performance of different soil columns in *Escherichia coli* removal

Other coliform reduction showed a significant difference (p= 0.0028) in the soil column. Based upon the Bonferroni corrected T-test value, the total coliform counts at depths 0.3 m, 0.8 m, and 1.5 m were significantly lower than the influent counts for all soils used in the infiltration experiment (Figure 4-19).

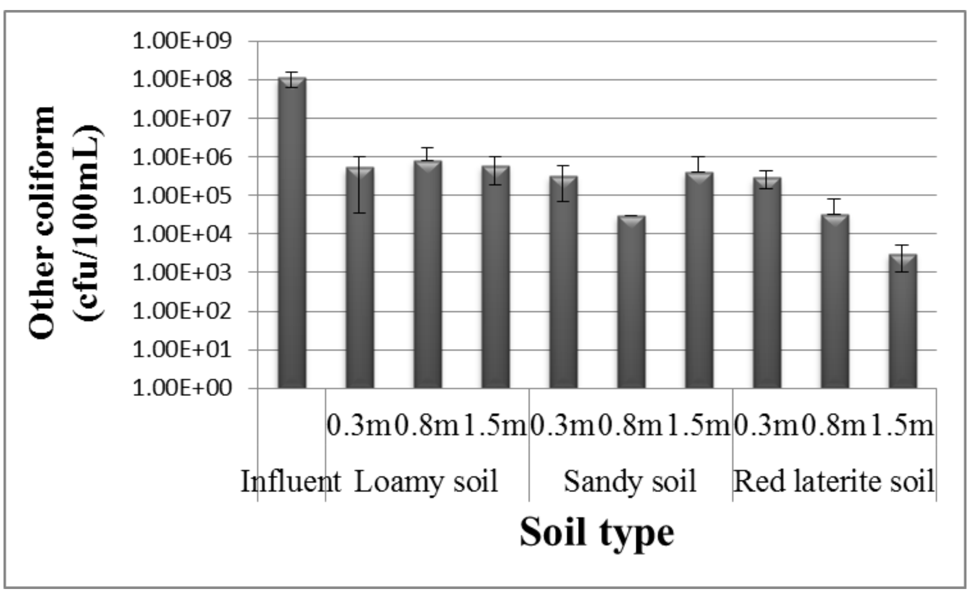

Figure 4-19: Performance of soil columns in other coliform removal

The reduction in other coliform levels can be associated to the removal of suspended particles and adsorption within the filter bed. Normally, the adsorption of coliforms to soil media is influenced by the organic matter content, the degree of biofilm formation, and electrostatic attraction between the coliforms and particle-surfaces (Stevik *et al.,* 2004). The study seemed to suggest that the microbes though reduced, multiplied quickly under the experimental conditions.

Red laterite soil was effective in the reduction of contaminant values below the guideline values recommended for effluent discharge into the environment (GH-EPA, 2003). Areas with high water tables should have infiltration systems made from red laterite pellets to enhance contaminant reduction in effluent before discharge into the sub-surface soil.

4.3 Assessment of the effect of the solid loading rate on the treatment performance for optimization of the Biofil Toilet Technology (SO3)

This section presents results on the specific objective three (SO3), which sought to assess the effect of three different solid loading rates (i.e. faecal matter) designated as light, moderate and heavy with a corresponding usage of 10 persons/day, 15 persons/day and 25 persons/day respectively. The test also sought to compare the decomposition of faecal matter under the different solid loading rates (light, moderate, heavy) using two hydraulic loading: (1) microflush (where up to 1 litre of water was used for flushing) and; (2) full-flush (where 9 litres of water was used for flushing).

Under the experimental setup (i.e. decomposing faecal matter in the presence of coconut fibre and earthworms), the microflush and full-flush setups under the different loading regimes were presented. Thus we have three configurations: (a) light loading under microflush termed "light microflush", moderate loading under microflush termed "moderate microflush" and heavy loading under microflush termed "heavy microflush" and; (b) light loading under full-flush termed "light full-flush", moderate loading under full-flush termed "moderate full-flush" and heavy loading under full-flush termed "heavy full-flush". Two control tests were also presented both using the three different loading rates: (1) faeces only and; (2) faeces in the presence of coconut fibre only.

The solid loading rates were applied continuously each day throughout the experiment.

4.3.1 Continuous loading

It has been reported that the organic loading rate and solid loading rate applied during start-up are among the important parameters that influence the design parameter of a reactor and subsequently, the effective treatment of the waste sludge. The BTT was continuously subjected to different faecal matter loads for 14 days to observe the robustness to heavy loading and its ability to decompose and stabilize the solids. The result of the carbon content, nitrogen content, total solid content, volatile solid content and stability ratios (C/N and VS/TS) have been presented in the subsequent sections.

4.3.1.1 Carbon content of biosolids

The result of the carbon content of the biosolids under continuous addition of faeces to the BTT has been presented in Figure 4-20. An ANOVA test on the results showed significant difference (p= 0.000205) between the groups. A Bonferroni corrected t-test value was used to assess the level of significance between the groups. The carbon content of the raw faeces compared with that of the biosolids in the microflush showed that the carbon content in the heavy loading was significantly lower (p= 0.0000020) than in the light microflush (p= 0.0194) and moderate microflush (p= 0.155). The comparison of the carbon content in the faecal matter with the light full-flush, moderate full-flush and heavy full-flush showed a significant difference in the moderate full-flush (P= 0.0025). There was significant difference between the carbon content in the raw faeces and the controls (faeces + coconut fibre only): light (p= 1.47E-05), moderate (p= 2.15E-04) and heavy (p= 2.67E-04). However, there was no significant difference in the carbon content of the microflush and the full-flush experimental setups. The carbon content in the raw faeces, coconut fibre and experimental setups were generally high in the range of 40 - 50 %. There was no significant variation in the carbon content of the raw faeces and the controls. The coconut fibre had very high carbon content compared to the faeces (p= 4.32E-08).

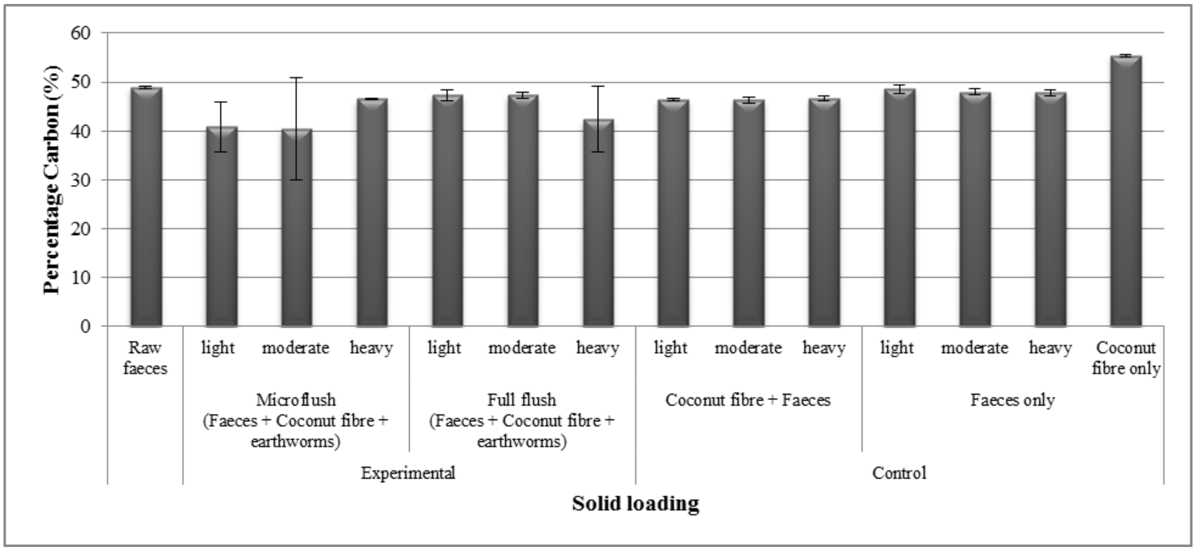

Figure 4-20: Carbon content under continuous loading with different solid loading rates

Generally the carbon contents of the biosolids fell within the wide range value of 8–50 % as suggested by Gotaas (1956). However, only the light microflush and moderate microflush were within the range of 15.67–39.43 % as reported by Bernal *et al.* (1998a) for composts prepared with a wide range of organic wastes. The generally high carbon content in the experimental and control setups can be attributed to the accumulation of carbon due to the continuous addition of faecal matter in all setups and the presence of coconut fibre in the experiment. The start-up faecal matter had tissue paper which serves as a rich source of carbon for decomposition. The coconut fibre played a key role in the overall carbon content of the setup.

The reduction in carbon content in the experiment as compared to the control could be attributed to the decomposition of the starting material (faecal matter and tissue paper) which is due to the transformation into carbon dioxide as reported by Cofie *et al.* (2009) under aerobic conditions. This observation may be used to explain the decrease in carbon content of the setups since faeces are mostly made up of organic carbon and undergo degradation (Geigy, 1962); and the carbon content of the coconut fibre are mostly inorganic and not easily broken down (Goulart *et al.*, 2000). The earthworms in the experiment might also have contributed to the carbon levels. The reduction in organic carbon has also been reported to be associated with bioconversion of organic material through cellulolysis by earthworm–microbe interaction (Ndegwa and Thompson, 2000). Earthworm mineralization of organic carbon results in loss of carbon from the substrates in the form of CO_2. Earthworm activity significantly decreases organic carbon levels in waste and accelerates the waste stabilization process (Suther, 2007). The hydraulic loading did not play any role in the level of carbon under this study. The heavy loading influenced the levels of carbon in the biosolids. The heavier the loading, the more the carbon content was reduced. It can be concluded carbon is not readily lost at start-up.

4.3.1.2 Nitrogen content of biosolids

The nitrogen (N) contents in the raw faeces were generally high. The N content of the experimental averaged 16 % compared to the 27 % in the faeces corresponding to a loss of 40.7 %. The coconut fibre only had the lowest N content. The N content of the microflush, full-flush and control setups with coconut fibre; though having similar N content trends had significantly lower levels than the raw faeces and control with faeces only. It can be observed that the N contents increased from the light loading up to the heavy loading (Table 4-21). It can also be observed that the experimental setups had lower N contents than those without earthworms. There was a significant difference in the groups ($p= 4.04E-11$). A Bonferroni corrected t-test value ($p= 0.0035$) was used to compare the level of significance in the groups. Comparing the raw faeces and the experimental, the light ($p= 6.79E-04$) and moderate ($p= 9.84E-04$) loading under the microflush setup showed significant difference. However, in the full-flush regime only the light loading had a significant difference in the nitrogen content (p=

9.14E-04). There was no significant difference between the faeces and the controls. The percentage reduction in the nitrogen content in the faeces with coconut fibre was high compared to the faeces only. The coconut fibre had the lowest nitrogen content (p= 8.31E-06).

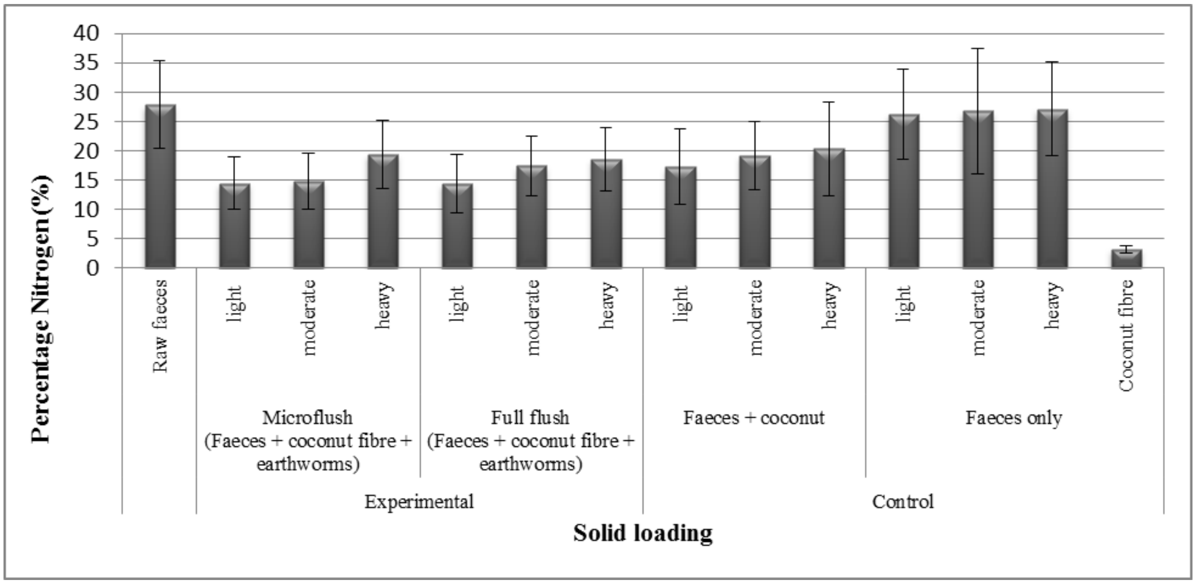

Figure 4-21: Nitrogen content under continuous loading with different solid loading rates

The high N content in the raw faeces can be attributed to the presence of urine in the form of ammonia. The continuous addition of the faeces to the BTT also resulted in an increase in the N content. The biggest contributor to the total nitrogen excreted is the urine fraction, contributing 93 % to the total nitrogen concentration (Geigy, 1962). In this fraction 84 % consists of urea-nitrogen, which is readily converted to ammonia (Geigy, 1962). Only 10 - 20 % of N content has been reported to be attributed to faecal matter (Lentner *et al.*, 1981; Vinnerås *et al.*, 2006).

Since there was no significant difference between the controls (faeces + coconut fibre and faeces only), the reduction in the N content can be attributed to the mineralization of organic matter with the contribution from earthworms. Earthworms have been reported to accelerate microbial mediated nitrogen transformation during the process of vermicomposting. The decrease in nitrogen concentration during the process due to release of ammonia, has been investigated by Guest *et al.* (2001). It is reported that at high pH, N content is lost in the form of ammonia (Geigy, 1962). These results conformed to results by Yadav *et al.* (2010); where during vermicomposting of source-separated human faeces, N contents were lost in the form of ammonia at high pH. The increase in pH is as a result of the release of carbonates due to the hydrolysis of urea (Orhon and Artan, 1994).

Light loading exhibited rapid loss of NH_3 as compared to the heavy loading. Li *et al.* (2012) also revealed a decrease in removal efficiency of nitrogen and ammonium with increasing solid loading rate partly due to overloading of their system. The hydraulic loading did not have a significant influence on the N content of the biosolids.

The overall N content loss under this study confirms the work by Benitez *et al.* (1999) which reported that 36 % nitrogen content was lost during the vermicomposting of sewage sludge.

4.3.1.3 C/N ratio of biosolids

The C/N ratio of the biosolids under continuous loading resulted in generally lower values in all the setups particularly in the raw faeces. The C/N of coconut fibre was high. The light loading had higher C/N ratios and this decreased with increased loading rates. Setups with coconut fibre had higher values of C/N than the raw and the control with faeces only (Figure 4-22).

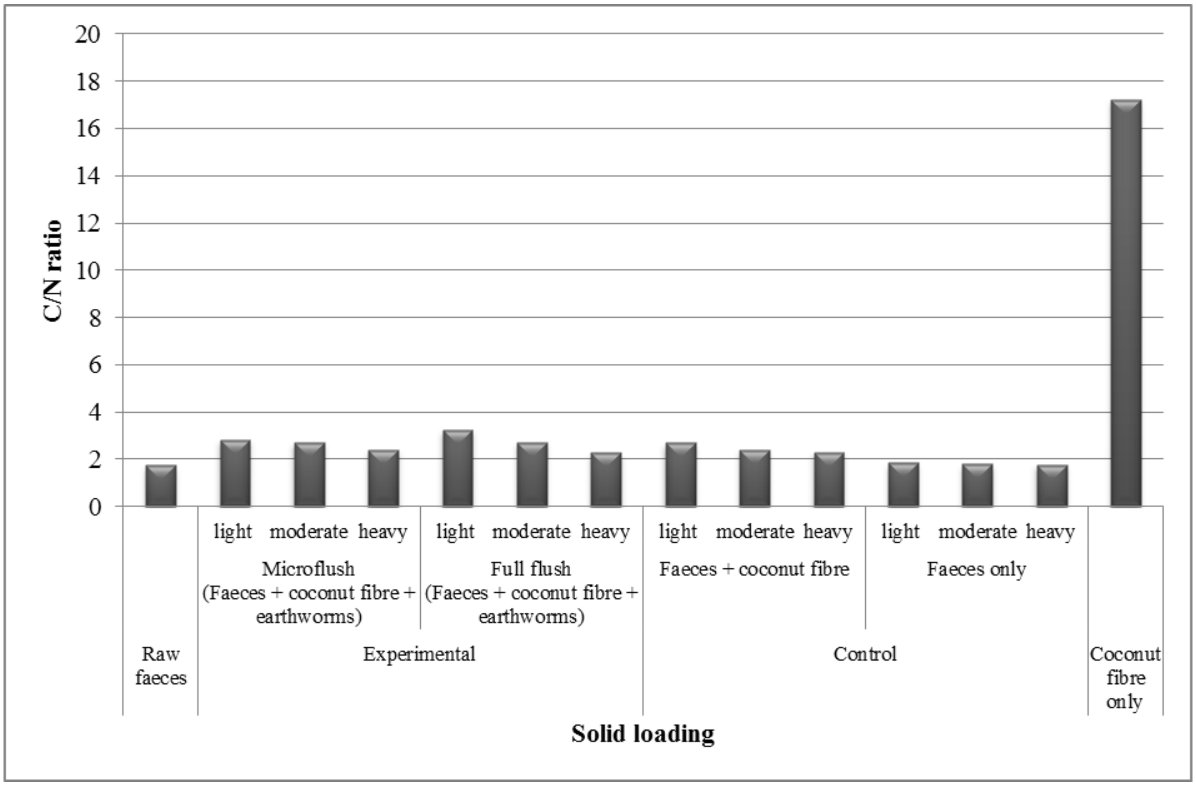

Figure 4-22: C/N ratio of biosolids under continuous loading with different solid loading rates

The high N content of the start-up and presence of carbon rich materials in the faecal matter (tissue paper and coconut fibre) is confirmed by the C/N ratios of raw faeces and the ensuing biosolids under this study. Joseph (1999) reported composting need 30 parts of carbon and 1 part of nitrogen in balanced diet. If the nitrogen content was very high then excess nitrogen will be lost in the form of smelly ammonia, and at low C/N ratio the nitrogen loss would be high with the possibility of going up to 60 %.

It can also be concluded that the high carbon content released with faeces helps with the degradation. This phenomenon also results in the decrease of the C/N ratio. It can be seen from the results that contribution of the coconut fibre in the degradation process is crucial at the early usage of the BTT. The presence of earthworms might have played a significant effect on the C/N ratio of the biosolids with time.

The C/N ratio of the coconut fibre was very high due to the low N content and high carbon content in the coconut fibre. The C/N values in this experiment also conform to the limit of 12 as suggested by Bernal *et al.* (1998a). The C/N ratio decreases with time as the nitrogen remains in the system, but carbon is released as carbon dioxide (Kitsui and Terazawa, 1999). Vermicomposting is associated to fast rates of decomposition and mineralization of the organic matter and accelerates the decrease of the C/N ratio (Kaushik and Garg, 2003). A C/N ratio less than 20 indicates an advanced degree of maturity in organic waste (Senesi, 1989). Based on the C/N values, the biosolids were satisfactorily stabilised even at the early usage of the BTT.

4.3.1.4 Total solid content of biosolids

Generally there was significant difference between the groups (p= 4.21E-27). The coconut fibre had the highest Total Solid (TS) content to the raw faeces, experimental and control setups (Figure 4-23). A Bonferroni corrected t-test value of 0.00357 was used to compare the level of significance between the individual groups. There was a general increase in the TS content in the experimental and control setup compared to the raw faeces used. Significant difference in the TS content compared with the raw faeces was only seen in the low regimes of the microflush (p= 0.000099). The light and heavy loading of the control (i.e. faeces + coconut fibre) showed significant difference. A level of significance was only seen in the moderate regime of the control (i.e. faeces only) compared with the raw faeces. There was no significant difference between the microflush and full-flush experimental setups. Similarly there was no significant difference between the two controls. There was no significant difference between the experimental (microflush and full-flush) and the controls (Figure 4-23).

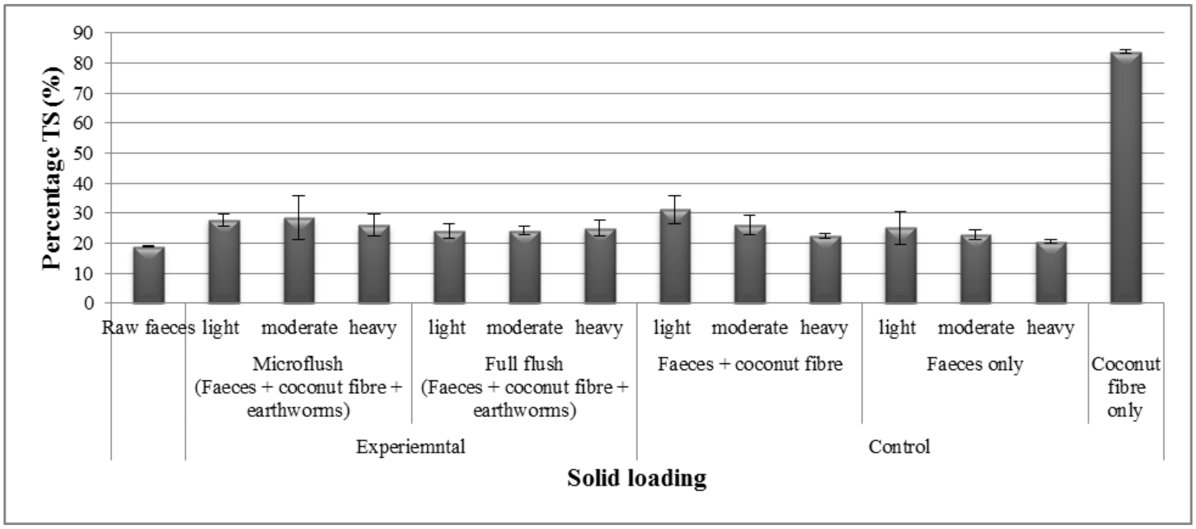

Figure 4-23: Total solid content under continuous loading with different solid loading rates

The increase in the TS content can be attributed to continous accummulation in the BTT. The coconut fibre might have also contributed to the overall TS of the biosolids during the study. However, hydraulic loading did not influence the TS contents under the study.

4.3.1.5 Volatile solid content of biosolids

Volatile Solid (VS) values in the raw faeces were significantly higher. Comparing the VS values between the microflush and full-flush experimental setups indicated a reverse trend with VS decreasing from light to heavy loading while increasing from light to heavy in the full-flush setup. The control setups had similar trends with the moderate loading having slightly higher values and the heavy loading having lower VS values in both cases. The coconut fibre had the least value for VS content. An ANOVA showed a significant difference between the groups (p= 0.000291). A Bonferroni corrected t-test value of 0.003571 was used to test the level of significance between the individual groups. There was no significance between the experimental setups of the microflush and the raw faeces. Similarly, there was no significant difference in the VS content in the light ($p= 0.041$), moderate ($p= 0.090$) and heavy ($p= 0.42$) loading under the full-flush setups by comparing with the Bonferroni corrected t-test value ($p = 0.003571$). The controls compared with the raw faeces did not show any level of significance in the VS contents. There was a significant difference in the VS content of the coconut fibre compared to the raw faeces ($p= 0.0031$). Comparing the VS content of the microflush with the full-flush did not show any significant difference at the different loading regimes; light ($p= 0.0066$), moderate ($p= 0.15$) and heavy ($p= 0.306$) though the percentage reduction in the full-flush was high (Figure 4-24). Similarly, there was no level of significance between the controls (i.e. faeces + coconut fibre vs faeces only). Comparing the three loading rates under the microflush with the control (i.e. faeces only) did not show any level of significance in the VS content. However, there was a significant difference in the light loading under the full-flush ($p= 0.00289$) as against the moderate ($p=0.00563$) and heavy ($p= 0.289$) (Figure 4-24).

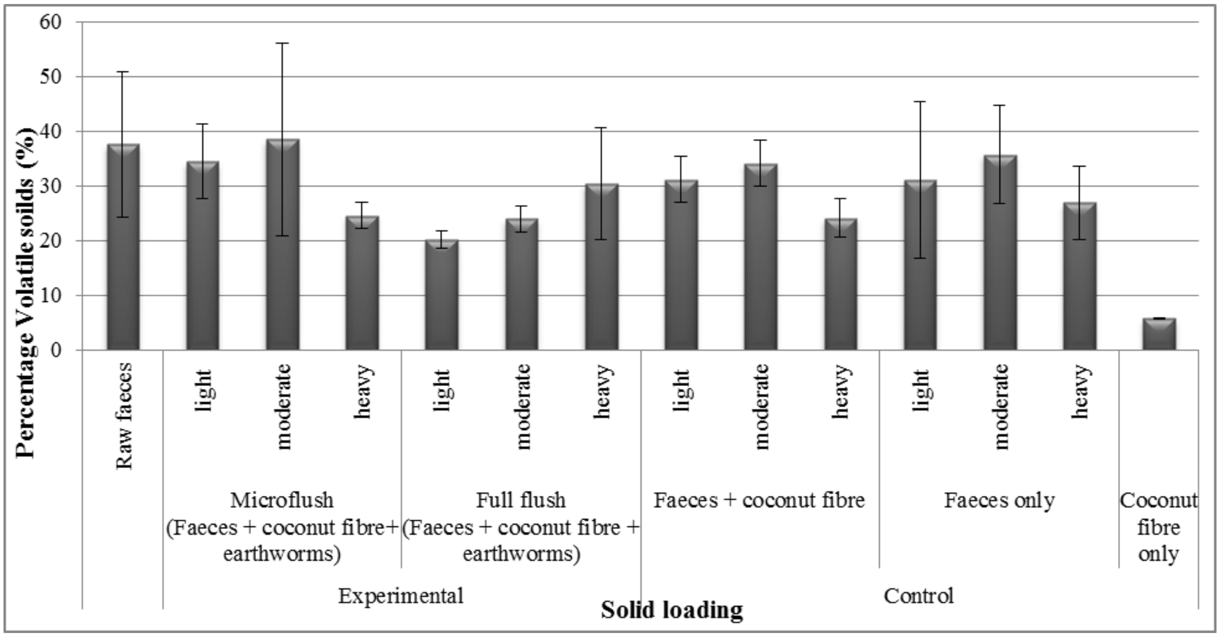

Figure 4-24: Volatile solid content under continuous loading with different solid loading rates

The generally high values of VS can be attributed to the low inorganic content of the stock feed. The decrease in VS values in the full flush setup can be attributed to faster degradation of organic contents in the biosolids as a result of increasing the surface area of the biosolids with the turbulence in flushing. This phenomenon is in line with similar observation reported by Cofie *et al.* (2009). Additionally, the microflush and control setups having their heavy loading with lower VS values could be attributed to the increased microbial activities in the biosolids due to heavy accumulation of organic contents thus lowering rapidly the VS values. Cofie *et al*. (2009) also indicated that the VS decreases during the process of composting through microbial activity by converting organic contents into carbon dioxide and ammonia resulting in the increase of the ash or inorganic component.

It has also been shown that a high percentage of organic matter favours growth of earthworms. When the earthworm population is high, the process of decomposition of organic matter is accelerated and the humification is carried out in a short time due to the action of microorganisms contained in the excreta of earthworms (Martínez, 1997).

The percentage reduction of 8.3 % in the low loading of the experiment conformed to prevailing studies. Hartenstein & Hartenstein (1981) reported a 9 % reduction in volatile solids over 4 weeks of sludge vermicomposting by earthworms. Fredrickson *et al.* (1997) found a reduction in volatile solids of 30 % in compost after 4 months of conventional composting, whereas the reduction was 37 % after only 2 months of vermicomposting.

4.3.1.6 VS/TS ratio of biosolids

The VS/TS ratio of the experimental setups ranged from 0.84 to 1.34 (Figure 4-25), indicating the degree of stabilization of the faeces at start-up in the different solid loading rates. The controls had a VS/TS range from 1.0 to 1.55. A high VS/TS ratio was observed for the heavy loading in the full flush setup but a reverse was observed in the microflush setup. The VS/TS ratios were generally high for the raw faeces and control of faeces only and high for the moderate and heavy loading. VS/TS values were typically low for the light loading.

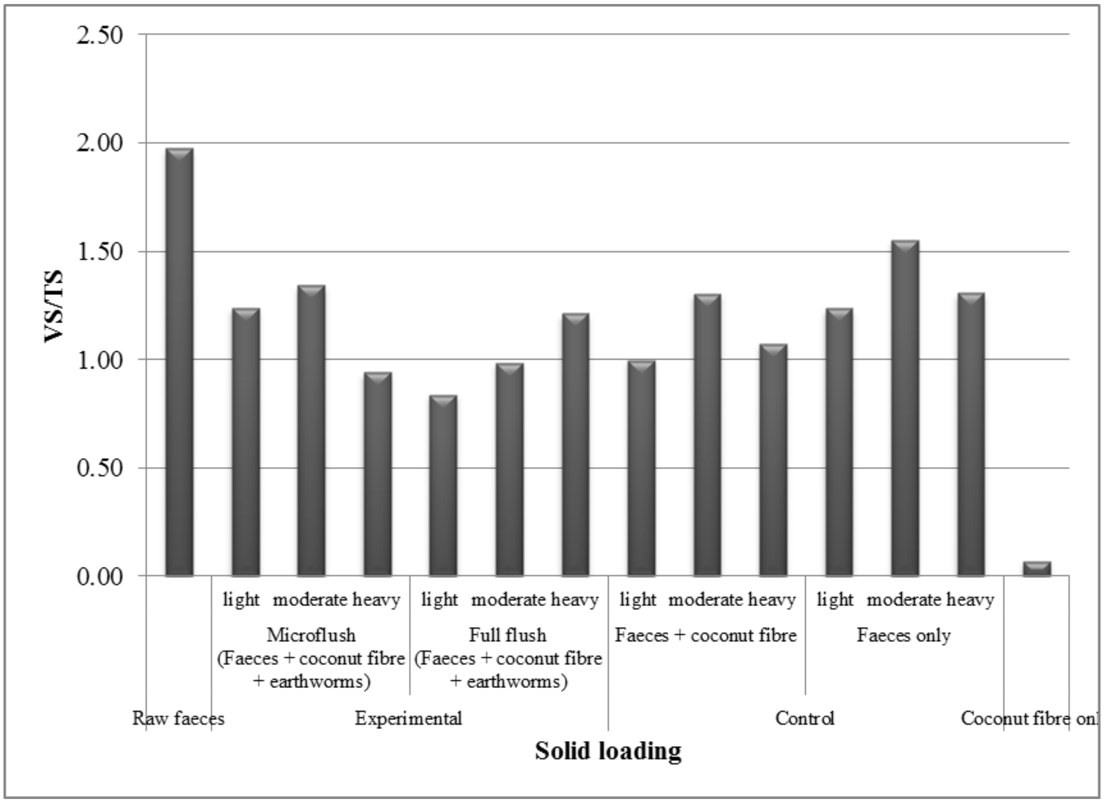

Figure 4-25: VS/TS ratio of biosolids under continuous loading with different solid loading rates

It has been reported that the VS/TS ratio greater than 0.4 and less than 0.6 is favourable for better reactor performance (Ghangrekar *et. al.,* 2005). From the results it can be deduced that the amount of organic matter in the faeces was degraded by 37.4 %, 32.2 % and 52.5 % in the light, moderate and heavy microflush respectively. In the case of the full-flush, organic matter degradation was 57.6 %, 50.0 % and 38.9 % in the light, moderate and heavy full-flush. In the case of the control (coconut fibre + faeces only), the amount of organic matter was degraded by 49.5 %, 33.8 % and 45.0% in the light, moderate and heavy loading respectively. Degradation of organic matter in the control (faeces only) was reduced by 37.9 %, 21.7 % and 33.8 % in the light, moderate and heavy loading respectively.

It can be concluded that organic matter degradation by the BTT was high at start-up and the faeces was highly degradable.

4.3.1.7 Mass reduction under continuous feeding at start-up

Mass reduction is important when assessing technology's suitability for on-site sanitation, as it is directly related to the necessary size of the system and emptying frequency (Furlong *et al.*, 2014).

An ANOVA conducted on the data sets did not show any significant difference between the faecal mass reductions at start-up under the different solid loading rates ($p = 0.786$). The mass reduction was estimated at between 2 – 10 % for all loadings (Figure 4-26). The mass reduction was generally low from day one with an average of 2 %, and gradually increasing to 8 % by day seven.

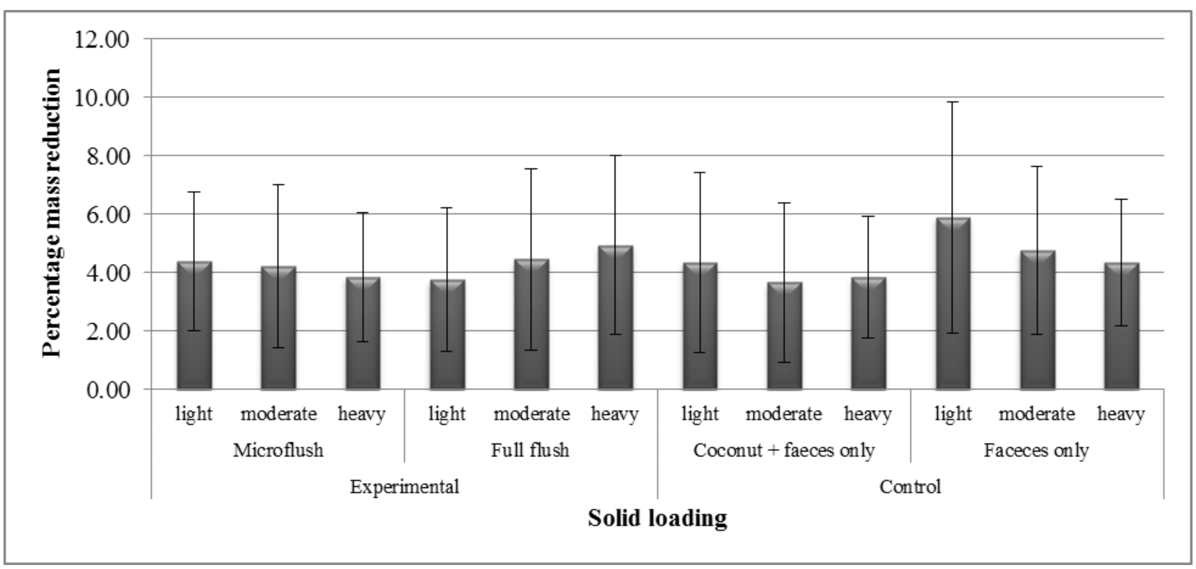

Figure 4-26: Percentage mass reduction of faeces under different loading at start-up

The faecal mass reduction at start-up was not influenced by the hydraulic loading, the presence of bulking material and earthworms and the solid loading. A study by Furlong *et al.* (2014) under continuous loading also indicated that the type of bedding material did not influence the mass reduction of their vermifilters. It is worth noting that in this study, the BTT was put under stress by not allowing the earthworms to acclimatise to the new environment with the intention of testing its robustness at start-up. A number of studies have shown high mass reduction but at long cumulative effect of solid loading where the environment conditions have stabilized. Under the test results, it could be confirmed that the continuous feeding under the low (10 users/day), moderate (15 users/day) and high (25 users/day) did not affect the BTT by causing filling up and total failure of the technology. The study suggested the rapid reduction of faecal mass during the fallow period when the BTT was not used.

4.4 Assessment of the toxicity effect and recovery rates of the vermin in the BTT to household chemicals reagents normally applied in cleaning of the toilet bowls (SO4)

This section presents the findings and discussions under the fourth specific objective which sought to investigate the toxicity effect of household chemical reagents on the Biofil toilet technology when applied normally in cleaning toilet bowls. The three notably cleaning chemical reagents used were chloroxylenol in dettol, hydrogen chloride in harpic and sodium hypochlorite in bleach.

The presence of chemoreceptors along the body makes earthworms highly sensitive to chemicals in their environment, and their mobility abilities allow them to avoid unfavourable environments (Udovic and Lestan, 2010). It is however difficult to study earthworm behaviour under field conditions because of inherent variability caused by spatial differences, as well as complex interactions, both biotic and abiotic (Auclerc *et al.*, 2011). To understand the effect of household chemicals on the BTT, a number of commonly used household cleaning chemicals were studied on the BTT. According to Loureiro *et al.* (2005), acute tests do not provide an insight into the effect of contaminants on population dynamics and most of the chronic tests are often time consuming and labour intensive. To determine quick answers to chemical contamination problems, many authors have resorted to avoidance behaviour tests where earthworms can choose or avoid a given media (Hund-Rinke *et al.,* 2003). Under this study, parameters such as time of paralysis, percentage paralysis and deaths, and stability of the contaminated substrate or the waste processing rate were used to assess the effects of these household chemicals on the BTT.

The experiment was conducted under two regimes: (1) application of cleaning chemicals in low concentrations of the active ingredient when applied normally for cleaning toilet bowls;

(2) application of high concentrations of the active ingredient when applied under a worse-case. The essence of the applications was to test the robustness of the vermin (i.e. the worms in the BTT).

4.4.1 pH of household chemicals

According to Posthuma *et al.* (1997) and Meharg *et al.* (1998), pH plays a key role in the determination of toxicity of earthworms. In this study, the pH of the ensuing chemicals was used to explain the levels of toxicity to the earthworms together with other constituents in the household chemicals. The three chemical cleaning reagents used to achieve this specific objective were dettol, harpic and bleach. The respective active ingredients in the dettol, harpic and bleach were chloroxylenol, hydrogen chloride and sodium hypochlorite. The typical ranges of the sodium hypochlorite concentrations prepared for dosing were moderately acidic to basic (pH: 6.49 ± 0.007 to 7.20 ± 0.042). The sodium hypochlorite stock had a pH of 7.15 ± 0.283. The pH of the stock chloroxylenol and hydrogen chloride were 7.07 ± 0.035 and 5.59 ± 0.056 respectively. The pH of the different concentrations of the diluted active ingredients used in the experiment has been presented in Table 4-4.

Though ammonia is a key factor contributing to the toxicity of earthworms and cannot be overruled, the study did not consider it since above a pH of 5, nitrification is very rapid with the release of ammonia (Aciego Pietri and Brookes, 2008).

Table 4-4: pH of stock and diluted concentrations of household chemicals used in the experiment

Concentration	Chloroxylenol (Dettol)		Hydrogen chloride (Harpic)		Sodium hypochlorite (Bleach)	
Code	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Stock	7.07	0.014	5.59	0.057	7.15	0.283
C1	7.015	0.035	5.99	0.085	6.49	0.007
C2	7.185	0.021	5.58	0.014	6.53	0.000
C3	7.765	0.021	5.46	0.078	6.59	0.035
C4	7.895	0.007	5.48	0.014	6.96	0.042
C5	7.89	0.014	5.49	0.007	7.2	0.042
C6	8.01	0.014	5.70	0.014	7.1	0.495

4.4.2 Application of low concentration of chemical reagents

Spiking of the worms of the Biofil toilet technology under low concentration was done according to the product specification of the disinfectants and practice by households. In this study, we termed the low concentration application as "normal application". Details of the method of cleaning toilets based on interactions with households have been described in the methodology.

4.4.2.1 Percentage paralysis and Death

The results obtained from the low concentration tests recorded no deaths of the earthworms for all the three household chemicals. However, paralysis of earthworms was observed for chloroxylenol and hydrogen chloride application at concentrations of 0.114 g/100mL and 0.139 g/100mL respectively (Figure 4-27). These concentrations fell within the microflush regime. The control test comprising the application of only flush water without disinfectants did not have any paralytic and fatal effect on the earthworms.

It was observed that 20 percent of earthworms were paralysed at chloroxylenol concentrations of 0.114 g/100 mL and 0.139 g/100 mL. In the case of hydrogen chloride, 13.3 % and 40 % paralysis occurred at concentrations of 0.114 g/100mL and 0.139 g/100mL respectively (Figure 4 – 27).

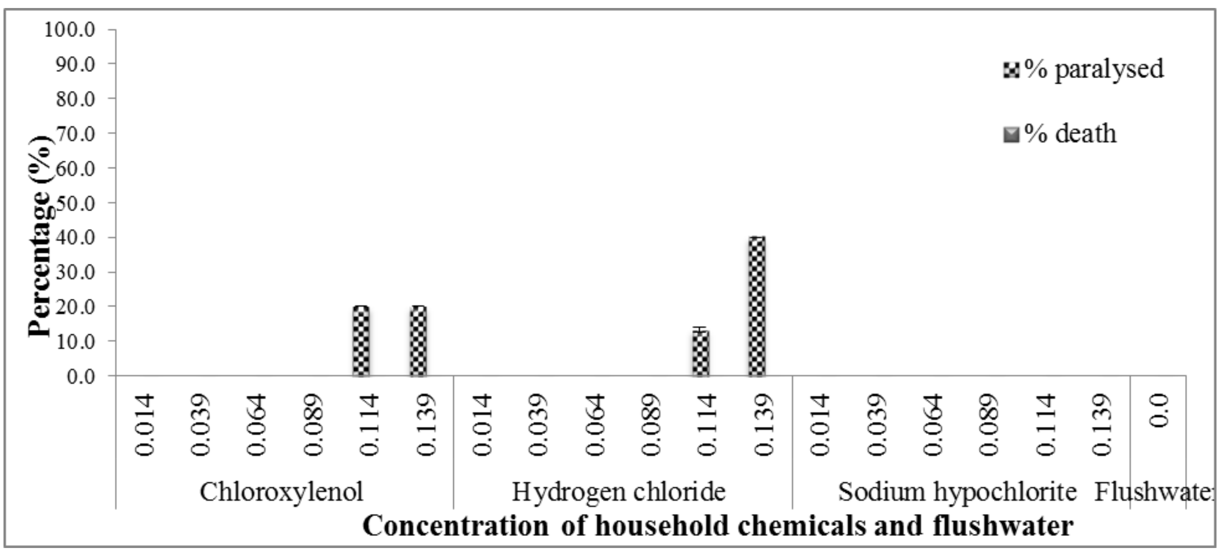

Figure 4-27: Effect of household chemicals on earthworms at low concentrations

The results showed a 100 % survival in the normal application of the household chemicals. This can be attributed to the favourably pH range of the applications and the concentrations of the ensuing dilutions used for cleaning. The pH of the concentrations used was not harsh on the earthworms. Posthuma *et al.* (1997) in their study stated that pH is the most important abiotic factor in determining toxicity. High dilution of the chemical reagents (full flush regimes) was seen to reduce the toxicity effect of the household chemicals on the earthworms. It is expected that during cleaning of toilets and depending on the availability of water in the house, the household chemicals will be heavily diluted by water as a result of continuous rinsing. This phenomenon will be seen in the case of the low flush option (microflush) since the usual practise is to use buckets of water since there is no direct connection to piped water for flushing (in this study, the microflush concentrations were based on the amount of water used for the microflush – up to 1 litre).

In the case of the chloroxylenol and hydrogen chloride, there were no significant difference on the effect of the applications at 0.114 g/100 mL and 0.139 g/100mL for both chloroxylenol and hydrogen chloride (40 % paralysis).

4.4.2.2 Time of paralysis, death and recovery

The corresponding times for paralyses at the low chemical application of the household chemicals to depict regular cleaning of toilets, indicated a wide time range for paralysis to occur after the application of the chemicals. Since there were no deaths after applying all three household chemicals, Table 4-28 only presents the time of paralysis and time taken to recover after paralysis.

Applications with Chloroxylenol resulted in an average time of 62 ± 2.88 mins to cause paralysis of the earthworms at concentration of 0.114 g/100mL and 0.139 g/100mL. In the case of the Hydrogen chloride application, earthworms spiked at concentration of 0.114g/100mL were paralysed after 62 ± 2.89 mins of application while the earthworms spiked at 0.139 g/100mL were paralysed after 43 ± 2.89 mins (Figure 4-28).

It took a time of 8.33 ± 2.89 mins to recover from the paralysis at a concentration of 0.114 g/100mL of the chloroxylenol. Additionally, earthworms that were paralysed by the chloroxylenol at the concentration of 0.139 g/100mL were able to recover after a time of 10.67 ± 1.15 mins. The earthworm paralysed at concentration 0.114 g/100mL of hydrogen chloride were able to recover at a time of 13.33±2.89 mins and those at 0.139 g/100mL recovered at 16.67 ± 2.89 mins (Figure 4-28).

An ANOVA conducted on the time taken for paralysis (p= 3E-24) and recovery (p= 1.17E-11) to occur was significant. A t-test was conducted on the chloroxylenol and hydrogen chloride to determine the significant difference in the paralysis of the earthworms and their recovery. Comparison within groups showed that at concentrations 0.114 g/100mL and 0.139g/100mL of the chloroxylenol, there was no significant difference in the time taken for paralysis and their recovery (p=0.5). Similarly, there was no significant difference at concentration 0.114g/100mL and 0.139g/100mL of the hydrogen chloride (p= 0.090). A similar result was noticed for the comparison between the groups.

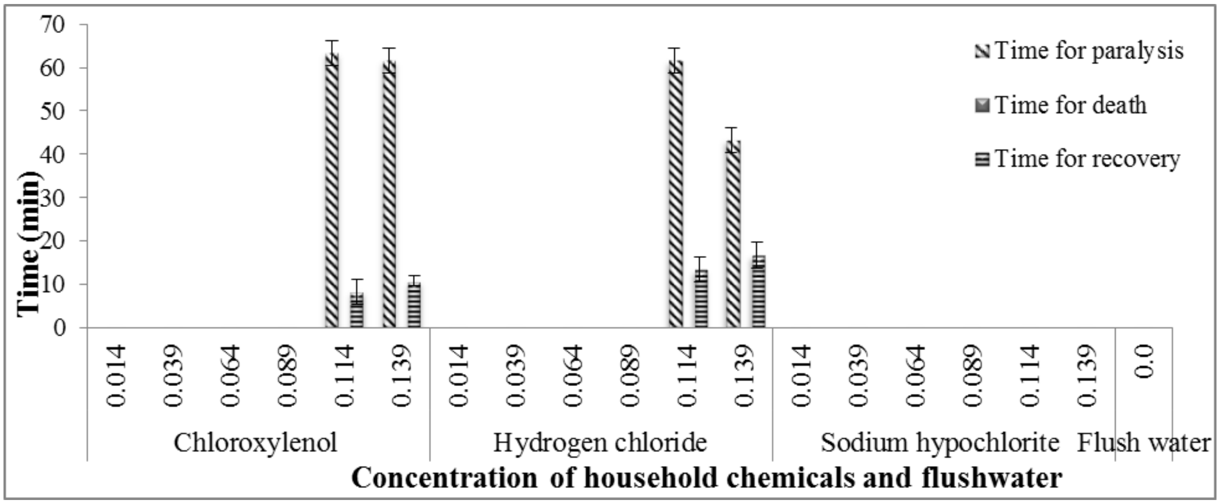

Figure 4-28: Time taken for paralysis and death of earthworms spiked with household chemicals at low concentrations

4.4.2.3 Determination of lethal concentration (LC_{50})

There were no deaths recorded regarding the normal application of the household chemicals: hence an LC_{50} could not be generated for earthworms exposed to the household chemicals under normal application.

4.4.3 Application at high concentration of the chemical reagents

Based on the fact that some users of the BTT may purposefully or accidentally use high concentrations of the cleaning chemicals/disinfectants, the tests were repeated with higher application to test the robustness of the system though these concentrations are not attained during normal cleaning. The concentrations were increased for C_1, C_2, C_3, C_4, C_5 and C_6 by 72 %, 61 %, 87 %, 90 %, 93 % and 95 % respectively; using stock concentrations of the cleaning reagents.

4.4.3.1 Percentage paralysis and Death

Chloroxylenol application at high concentrations (0.05 g/100mL) resulted in no paralysis and death. These concentrations fell within the full flush regime. Application of 0.1 g/100mL caused 10 % paralysis and 20 % death of the earthworms. At concentrations 0.5 g/100mL, 1.0 g/100mL, 2.0 g/100mL and 3.0 g/100mL, more than half of the earthworms were paralysed (Figure 4-24). Similarly 40 – 60 % deaths were recorded at concentrations 0.5 g/100mL, 1.0 g/100mL and 2.0 g/100mL. At concentration 3.0 g/100mL chloroxylenol, all the earthworms died (Figure 4-29).

Household chemical application using the hydrogen chloride resulted in no deaths for concentrations 0.05 g/100mL to 2.0 g/100mL (Figure 4-29).

Application using the Sodium hypochlorite resulted in no deaths for all six concentrations. Only concentrations 2.0 g/100mL and 3.0 g/100mL caused 30 % paralysis in the earthworm population (Figure 4-29). An ANOVA conducted on the resulted showed a significant difference in the population of deaths ($p= 0.0105$). The deaths caused by the hydrogen chloride were seen to be significantly lower than in the Chloroxylenol ($p=0.034$). However there was no significant difference in the number of paralysis ($p= 0.334$). Similarly, the concentration of Sodium hypochlorite at high application did not have a lethal effect on the earthworms. Deaths were caused in the chloroxylenol and hydrogen chloride. Their deaths were characterized by coiling of their body, after which the body was rigid and sometimes reddened swellings appeared on the body surface (Appendix B: Plate 17).

Though the pH values in the hydrogen chloride were moderately acidic and lower compared to the chloroxylenol, the presence of isopropyl alcohol in the dettol may have contributed to the paralysis and death of the earthworms. A study by Sarkar *et al.* (2013) revealed the high toxicity of hexadecytrimethyl ammonium chloride (organoclay) to earthworms.

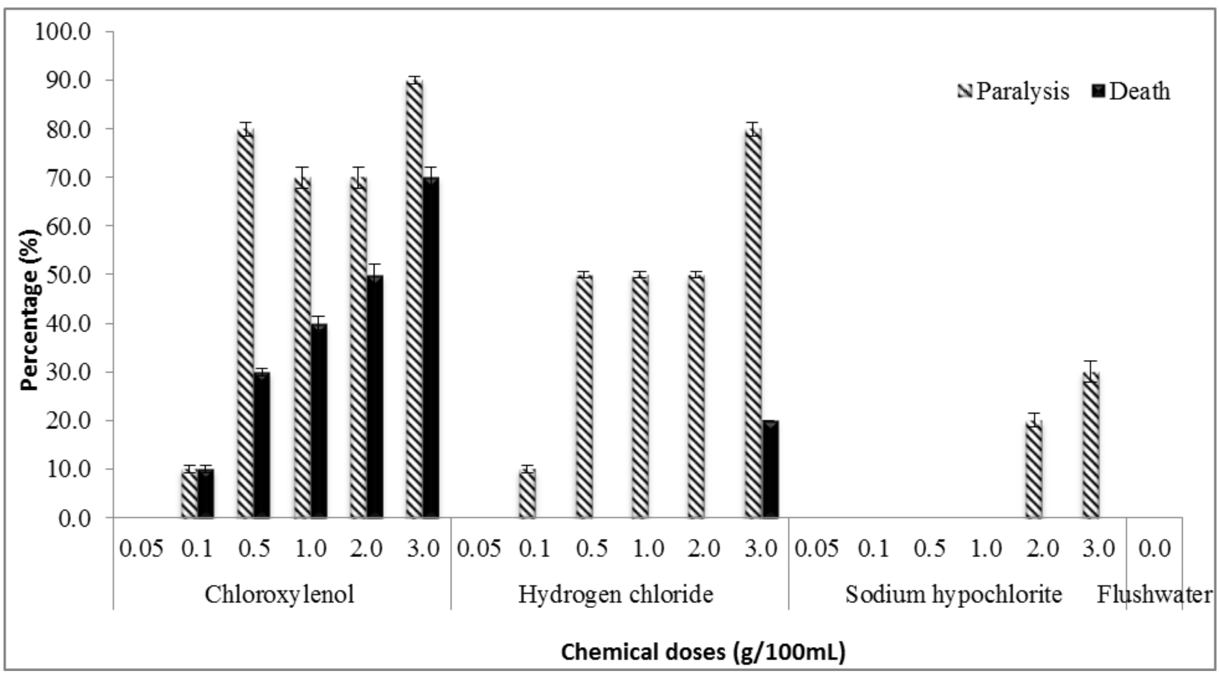

Figure 4-29: Effect of household chemicals on earthworms spiked at high concentrations

4.4.3.2 Time of paralysis, death and recovery

The results obtained for the three household chemicals at high concentrations to determine the time of paralysis, death and recovery of the adult *Eudrilus eugeniae* have been presented in Figure 4-30.

It was observed from the results that the stronger the concentration of the household chemicals, the faster the time of the paralysis and the shorter the time for death. This phenomenon was typically seen in the hydrogen chloride concentrations (Figure 4-30). In the hydrogen chloride application, earthworms spiked at concentration of 0.1 g/100mL were paralysed after 61 ± 0.71 mins of application while the earthworms spiked at 0.3 g/100mL were paralysed after 13 ± 2.89 mins (Table 4-30). Generally, longer time for paralysis effects were seen in the low concentrations within the full flush regimes (0.05 g/100mL, 0.1 g/100mL and 0.5 g/100mL) in all three household chemicals. The most paralyses effects and time of death were recorded in concentrations within the micro-flush regime (1.0 g/100 mL, 2.0 g/100mL and 3.0 g/100 mL). Applications with Chloroxylenol resulted in paralysis from concentration 0.1 g/100mL to 3.0 g/100mL. A maximum time of 42 ± 2.88 mins and a minimum of 10 ± 0.71 mins were recorded to cause paralysis of the earthworms at concentration of 0.1 g/100mL and 3.0 g/100mL (Figure 4-30). Paralysis caused by sodium hypochlorite occurred only at concentrations 2.0 g/100mL and 3.0 g/100mL with corresponding times of 38 ± 4.24 mins and 28 ± 3.54 mins respectively. Paralyses in the sodium hypochlorite at concentration 2.0 g/100mL and 3.0 g/100mL were able to recover at a time of 5.0 ± 0.00 and 24 ± 5.66 mins respectively (Figure 4-30). Additionally, the time taken for paralyses effect was also seen to be longer in the higher concentrations of sodium hypochlorite (i.e. 2.0 g/100mL and 3.0 g/100mL) as compared to the other chemicals.

The time taken for death of the earthworms occurred at 40 ± 7.07 mins when dosed with hydrogen chloride at 3.0 g/100mL. Generally, it took an average of 63.8 ± 4.66 mins for the application of household chloroxylenol to cause death of the adult earthworms for concentration 0.1 g/100mL to 3.0 g/100mL. There were no deaths caused by the sodium hypochlorite. Sodium hypochlorite, the key ingredient in bleaches which are effective disinfectants are considered safe for both septic systems and groundwater as long as they are used in concentrations listed on the product labels (Schwartz *et al.,* 2004). Current research shows that the majority (87 % to 94 %) of these chlorinated compounds are degraded or removed by septic systems. As a result, the formation of chlorinated compounds from the normal use of hypochlorite bleach is not considered a threat to human health or the environment (Schwartz *et al.,* 2004).

Comparatively, the results suggested chloroxylenol had a faster paralyses effect on the worms compared to hydrogen chloride and sodium hypochlorite. The results seemed to suggest that the chloroxylenol was the strongest household chemicals. Deaths were recorded over a wide range of concentrations within the microflush and full flush regimes (Figure 4 – 29).

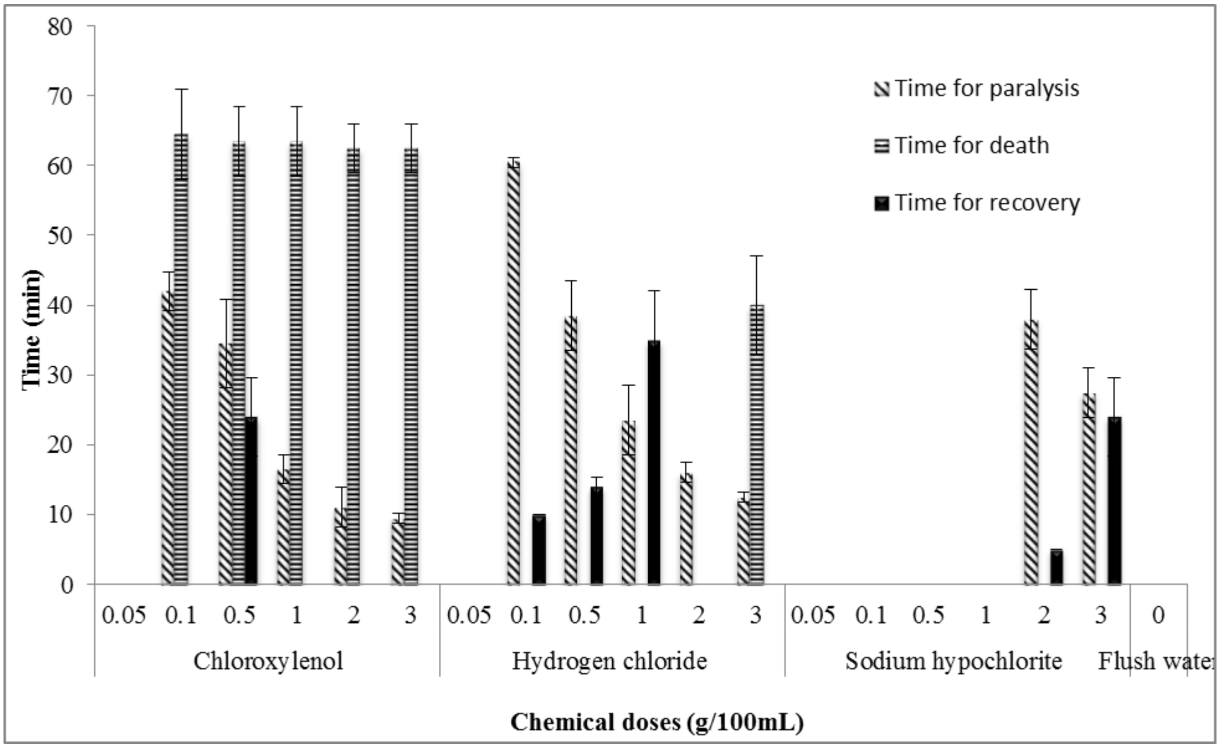

Figure 4-30: Reaction time of earthworms to household chemical at high concentration

4.4.3.3 Determination of lethal concentration (LC_{50})

The lethal concentration at 50 % is defined as the dose required to kill half the members of a tested population after specified test duration. The LC_{50} was calculated only for chloroxylenol due to the number of deaths recorded by the concentrations dosed (Figure 4-31).

The calculated LC_{50} for the high application of chloroxylenol was calculated as 1.72 g/100mL. Details of the calculations have been presented in Appendix D.

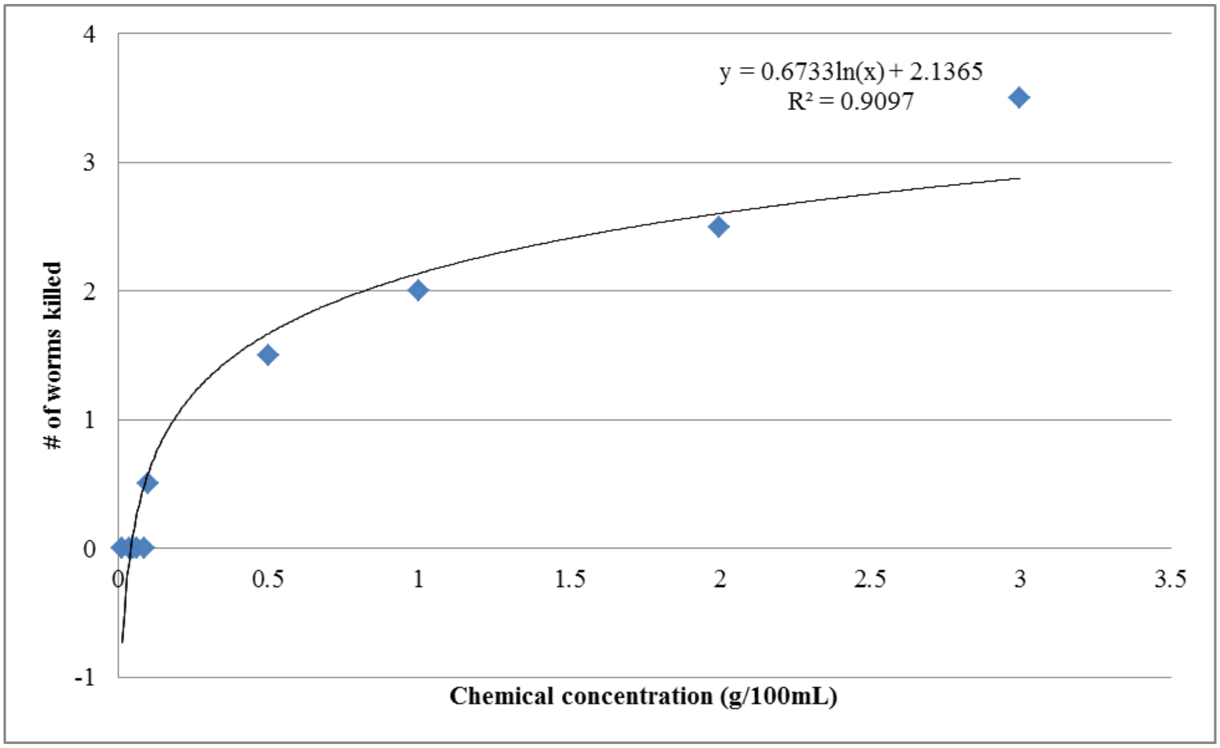

Figure 4-31: Correlation of chloroxylenol concentration with the number of worms killed

5 CONCLUSION AND RECOMMENDATIONS

The conclusion of the study and accompanying recommendations are presented in this chapter.

5.1 CONCLUSION

SO1

The primary function of the porous filter composites was for solid-liquid separation. The PET porous composite was the most effective in limiting microbial growth in the effluent.

SO2

Red laterite soil was the most effective in the reduction of contaminants within the soil columns. Up to 80 % contaminant removal was achieved for all the different soil columns within the top 0.3 m depth of the soil columns.

SO3

Organic matter was degraded by 32.2 % to 52.5 %. Carbon content of the biosolids was within the suggested limits of 8 % - 50 %. Carbon was generally high due to the accumulation as a result of high carbon content in the feed (tissues paper) and coconut fibre in the biosolids. The biosolids were generally stable due to the high carbon content. The heavier the loading, the higher the reduction in carbon and VS content. VS reduction in the low loading (8.3 %) within a week conformed to prevailing studies. VS reduction was influenced by the surface area for microbial and earthworms' activities (seen in the full flush) and the bulkiness of the faecal matter (seen in the heavy loading). Light loading exhibited rapid loss of N than in the heavy loading (Overall there was 40.7 % N loss). The stability of the biosolids was dependent on the feed; heavy loading did not influence the stability of the faecal matter. Hydraulic loading did not play any role in the reduction of carbon and TS content. The current minimal loading of 10 people per day per standard digester is ideal. The BTT is robust since it could withstand heavy loading at start-up; it has proven to be a feasible technology.

SO4

There was a 100 % survival rate of the spiked earthworms under normal application; the concentration of chloroxylenol (Dettol), hydrogen chloride (Harpic) and sodium hypochlorite (Bleach) at normal application was not lethal to the earthworms. Time of paralysis and recovery was within 60 mins and 20 mins respectively. The pH of the ensuing concentrations used to spike the earthworms was within the acceptable limits for earthworms to thrive and mostly basic; ammonia might not have contributed to the mortality if earthworms since it was lost at high pH. Sodium hypochlorite did not have any influence on the mass reduction of the biosolids.

5.2 RECOMMENDATIONS

- The clogging effect of the porous composites with time should be studied to determine the optimal stage for replacement.
- The biofilm formation on the pervious composites should be characterised over a time of operation.
- Shredded PET or other light weight and inexpensive coarse aggregates should be considered as porous filter composites for solid-liquid separation in the BTT.
- A filter should be designed and placed after the porous filter composites to reduce further the BOD_5, COD, and nutrient and pathogen levels in the ensuing effluent especially in areas with high water table. The red laterite soil should be considered as a filter line in the BTT design; configurations of pellets of red laterite soil and/or hard pan laterite should be developed and their performance evaluated for contaminant removal to prevent frequent clogging when used as a possible filter media in the BTT re-design.
- A study should be conducted to monitor the microbial loading in BTT effluent under different hydraulic loading rates.
- The study strongly recommends a study on the effect of different anal cleansing material on faecal matter degradation.
- The role of coconut fibre in the neutralization of the toxic effect of household chemicals should be further studied.

5.3 CONTRIBUTION TO KNOWLEDGE

- The study has provided information on what happens with the BTT effluent on different prevailing soils for future utilization of the results in the design of filtration systems for further treatment of effluent; this can be compared to infiltration of leachate by other toilet facilities (e.g. septic tanks, pit latrines) in literature and future studies.
- The study has provided information on the toxicity of household chemicals on earthworms as compared to the already existing information on chemical impacts on microbial population in septic tanks. This will be also useful for the manufacturer in the enhancement of the design of the BTT.
- The study has provided information on the details of the BTT as an alternative technology to septic tanks and other toilet facilities

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APPENDICES

Appendix A: Tables and Figures (Data)

Solid loading test

Percentage faecal mass reduction under continuous solid loading at start-up

Description	Experimental						Control					
	Microflush			Full flush			Coconut + faeces only			Faeces only		
	Low	Moderate	Heavy	Low	Moderate	Heavy	Low	Mod.	Heavy	Low	Moderate	Heavy
Day 1 (morning - evening)	1.79	1.15	1.09	2.14	1.09	1.44	0.59	0.83	2.27	8.61	5.39	5.73
Day 1 (evening - morning)	3.52	2.34	2.34	2.07	1.65	2.12	1.48	1.43	2.71	4.71	5.34	5.42
Day 2 (morning - evening)	4.13	1.42	1.87	1.83	1.20	1.90	10.04	1.05	1.48	3.78	3.26	2.82
Day 2 (evening - morning)	6.52	2.89	1.64	2.05	1.65	3.11	1.47	1.42	2.54	2.50	2.16	2.33
Day 3 (morning - evening)	5.50	3.09	3.37	3.02	2.40	4.47	1.54	1.33	2.28	8.27	7.43	6.96
Day 3 (evening - morning)	7.37	5.99	4.98	4.24	4.75	6.89	3.13	2.49	3.50	3.66	3.06	3.34
Day 4 (morning - evening)	7.53	7.60	5.92	5.50	6.03	9.22	4.15	2.72	2.76	7.95	6.14	5.95
Day 4 (evening - morning)	7.48	6.30	5.05	5.08	5.35	7.56	4.17	3.71	4.60	3.60	3.51	3.41
Day 5 (morning - evening)	5.55	7.44	4.51	5.63	6.64	7.65	5.89	6.56	4.36	6.15	5.48	5.87
Day 5 (evening - morning)	6.77	6.62	6.66	6.17	8.55	8.87	9.24	8.59	6.87	5.33	5.12	5.39
Day 6 (morning - evening)	3.72	4.24	3.61	3.81	5.69	4.52	4.79	4.79	3.69	3.03	2.56	2.76
Day 6 (evening - morning)	4.27	5.75	5.62	5.44	8.18	7.31	7.42	6.52	5.80	5.58	4.66	3.39
Day 7 (morning - evening)	2.07	3.71	3.45	3.37	4.96	4.09	4.58	4.14	4.11	4.26	3.06	2.75
Day 7 (evening - morning)	5.54	9.99	9.21	10.47	11.82	10.04	9.42	9.82	9.82	19.56	14.29	10.15
Day 8 (morning - evening)	1.62	2.03	3.01	1.73	2.35	2.17	3.58	3.34	3.95	5.49	4.33	3.32
Day 8 (evening - morning)	0.63	0.72	1.58	0.72	1.78	1.36	1.24	1.82	2.17	3.73	2.49	2.16
Day 9 (morning - evening)	0.65	0.74	1.66	0.74	1.83	1.43	1.31	1.92	2.30	4.09	2.68	2.29
Average	**4.39**	**4.24**	**3.86**	**3.77**	**4.47**	**4.95**	**4.35**	**3.67**	**3.84**	**5.90**	**4.76**	**4.36**
SD	**2.39**	**2.78**	**2.19**	**2.47**	**3.11**	**3.06**	**3.10**	**2.73**	**2.09**	**3.96**	**2.87**	**2.15**

Stability ratios for continuous solid loading at start-up

Sample code	Description			%Volatile matter	%Total Solids	VS/TS	%Ash	%Carbon	%Nitrogen	C/N
R1P	Raw faeces			37.56	19.01	1.98	15.51	49.00	27.88	1.76
MFPL	Experimental	Microflush (Faeces + coconut fibre + earthworms)	Low	34.44	27.76	1.24	29.70	40.87	14.43	2.83
MFPM			Mod	38.46	28.63	1.34	30.40	40.47	14.83	2.73
MFPH			High	24.53	26.03	0.94	19.88	46.58	19.40	2.40
FFPL		Full flush (Faeces + coconut fibre + earthworms)	Low	20.16	24.09	0.84	18.64	47.30	14.48	3.27
FFPM			Mod	23.91	24.25	0.99	18.55	47.35	17.42	2.72
FFPH			High	30.37	25.05	1.21	27.07	42.40	18.58	2.28
CCPL	Control	Faeces + Coconut fibre	Low	31.09	31.21	1.00	20.14	46.43	17.27	2.69
CCPM			Mod	34.08	26.10	1.31	20.20	46.40	19.18	2.42
CCPH			High	24.13	22.47	1.07	19.64	46.72	20.33	2.30
CFaPL		Faeces only	Low	31.01	25.11	1.23	16.40	48.60	26.28	1.85
CFaPM			Mod	35.67	22.97	1.55	17.42	48.01	26.80	1.79
CFaPH			High	26.88	20.58	1.31	17.81	47.79	27.10	1.76
RCCH	Coconut fibre only			5.80	83.82	0.07	4.58	55.41	3.22	17.22

Toxicity test

Toxicity preparation under normal application

Flushing + cleaning Volume (Actual)	S/N	Dilution factor by actual	Ratio of Actual: Exp. (15:1)	(V_1) Volume of stock to fetch (mL)			Volume of flush water to ADD (mL)		
				Dettol	**Harpic**	**Bleach**	**Dettol**	**Harpic**	**Bleach**
		(C_2) Concentrations of spiking solution (%)	(V_2) Final volume of spiking solution (mL)	C_1 = 4.8% (4.8g/100mL) Chloroxylenol	C_1=10% (10g/100mL) Hydrogen chloride	C_1=3.5% (3.5g/100mL) Sodium Hypochlorite	C_1 = 4.8% (4.8g/100mL) Chloroxylenol	C_1=10% (10g/100mL) Hydrogen chloride	C_1=3.5% (3.5g/100mL) Sodium Hypochlorite
Full flush (7L)	1	0.014	600	1.75	0.84	2.40	598.25	599.16	597.60
	2	0.039	600	4.88	2.34	6.69	595.13	597.66	593.31
	3	0.064	600	8.00	3.84	10.97	592.00	596.16	589.03
Microflush (2L)	4	0.089	33	0.61	0.29	0.84	32.39	32.71	32.16
	5	0.114	33	0.78	0.38	1.07	32.22	32.62	31.93
	6	0.139	33	0.96	0.46	1.31	32.04	32.54	31.69

Toxicity preparation under worse case application

Flushing regime	**S/N**	**Dilution factor by actual**	**Ratio of Actual : Exp. (15:1)**	**(V_1) Volume of stock to fetch (mL)**			**Volume of distilled water to ADD (mL)**		
				Dettol	**Harpic**	**Bleach**	**Dettol**	**Harpic**	**Bleach**
		(C_2) Concentrations of spiking solution	(V_2) Final volume of spiking solution (mL)	C_1 = 4.8% (4.8g/100mL) Chloroxylenol	C_1=10% (10g/100mL) Hydrogen chloride	C_1=3.5% (3.5g/100mL) Sodium Hypochlorite	C_1 = 4.8% (4.8g/100mL) Chloroxylenol	C_1=10% (10g/100mL) Hydrogen chloride	C_1=3.5% (3.5g/100mL) Sodium Hypochlorite
Full flush (9L)	1	0.05	600	6.25	3.00	8.57	593.75	597.00	591.43
	2	0.1	600	12.50	6.00	17.14	587.50	594.00	582.86
	3	0.5	600	62.50	30.00	85.71	537.50	570.00	514.29
Microflush (0.5L)	4	1.0	33	6.88	3.30	9.43	26.13	29.70	23.57
	5	2.0	33	13.75	6.60	18.86	19.25	26.40	14.14
	6	3.0	33	20.63	9.90	28.29	12.38	23.10	4.71

Datasets of faecal mass of experimental setups spiked with household chemicals

S/N	Codes	Mass of empty vermibed	Mass of empty bed + Net	Mass of bed + net + fibre (100g)	Mass of bed + net + fibre + faeces	Mass of bed + net +fibre +faeces + worms	Mass of vermibed after spiking - start	Mass of vermibed after 7 days
	Faeces only							
1	Beach C1	2.528	2.545	2.644	2.839	2.837	2.872	2.735
2	Beach C2	2.267	2.278	2.378	2.549	2.545	2.578	2.439
3	Beach C3	2.228	2.239	2.338	2.512	2.509	2.544	2.39
4	Beach C4	2.132	2.143	2.24	2.451	2.448	2.455	2.353
5	Beach C5	2.626	2.644	2.745	2.938	2.938	2.948	2.867
6	Beach C6	2.969	2.985	3.083	3.275	3.27	3.276	3.209
7	Harpic C1	2.352	2.372	2.47	2.683	2.684	2.752	2.613
8	Harpic C2	2.404	2.421	2.522	2.718	2.717	2.751	2.635
9	Harpic C3	2.196	2.209	2.31	2.51	2.51	2.527	2.4
10	Harpic C4	0.19	0.205	0.304	0.518	0.523	0.538	0.458
11	Harpic C5	0.194	0.21	0.31	0.517	0.522	0.537	0.465
12	Harpic C6	0.19	0.207	0.307	0.514	0.52	0.536	0.471
13	Dettol C1	0.194	0.209	0.309	0.516	0.521	0.587	0.441
14	Dettol C2	0.192	0.207	0.306	0.508	0.512	0.57	0.46
15	Dettol C3	0.194	0.209	0.309	0.509	0.513	0.588	0.497
16	Dettol C4	0.192	0.207	0.307	0.518	0.522	0.547	0.472
17	Dettol C5	0.678	0.853	0.951	1.166	1.138	1.18	1.084
18	Dettol C6	0.687	0.85	0.949	1.152	1.139	1.169	1.102

Faecal mass reduction of solids spiked with household chemicals

S/N	Codes	Mass of vermibed after spiking - start	Mass of vermibed after 7 days	% Mass reduction
1	Faeces only	-	-	3.34
2	Bleach C1	2.872	2.735	4.77
3	Bleach C2	2.578	2.439	5.39
4	Bleach C3	2.544	2.39	6.05
5	Bleach C4	2.455	2.353	4.15
6	Bleach C5	2.948	2.867	2.75
7	Bleach C6	3.276	3.209	2.05
8	Harpic C1	2.752	2.613	5.05
9	Harpic C2	2.751	2.635	4.22
10	Harpic C3	2.527	2.4	5.03
11	Harpic C4	0.538	0.458	14.87
12	Harpic C5	0.537	0.465	13.41
13	Harpic C6	0.536	0.471	12.13
14	Dettol C1	0.587	0.441	24.87
15	Dettol C2	0.57	0.46	19.30
16	Dettol C3	0.588	0.497	15.48
17	Dettol C4	0.547	0.472	13.71
18	Dettol C5	1.18	1.084	8.14
19	Dettol C6	1.169	1.102	5.73

Appendix B: Photographs on research

Porous filter composite test

Plate 4: shredded PET, quarry granite aggregates and crush palm kernel shells for fabrication of porous filter composites

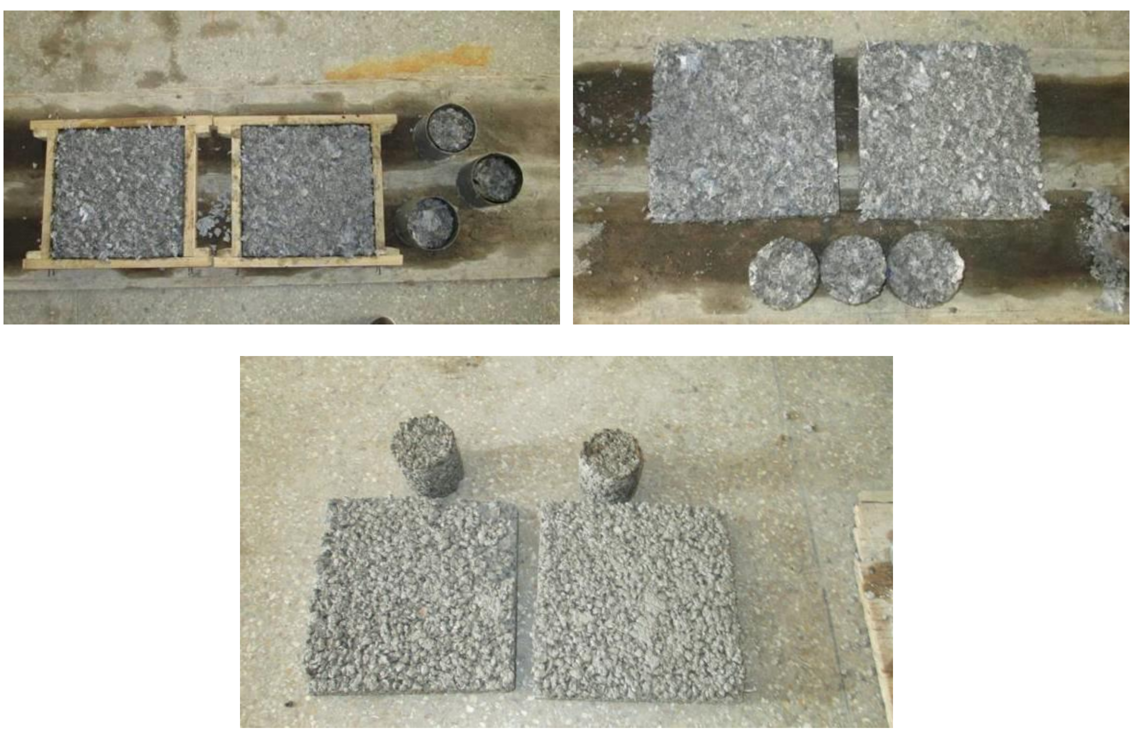

Plate 5: Porous filter composites casted for filtration test

Plate 6: Determination of porous filter composite strength; filtration of blackwater through porous filter composites

Plate 7: Effluents through coconut fibre; PET, granite and palm kernel porous filter composites

Subsurface infiltration test using different soil columns

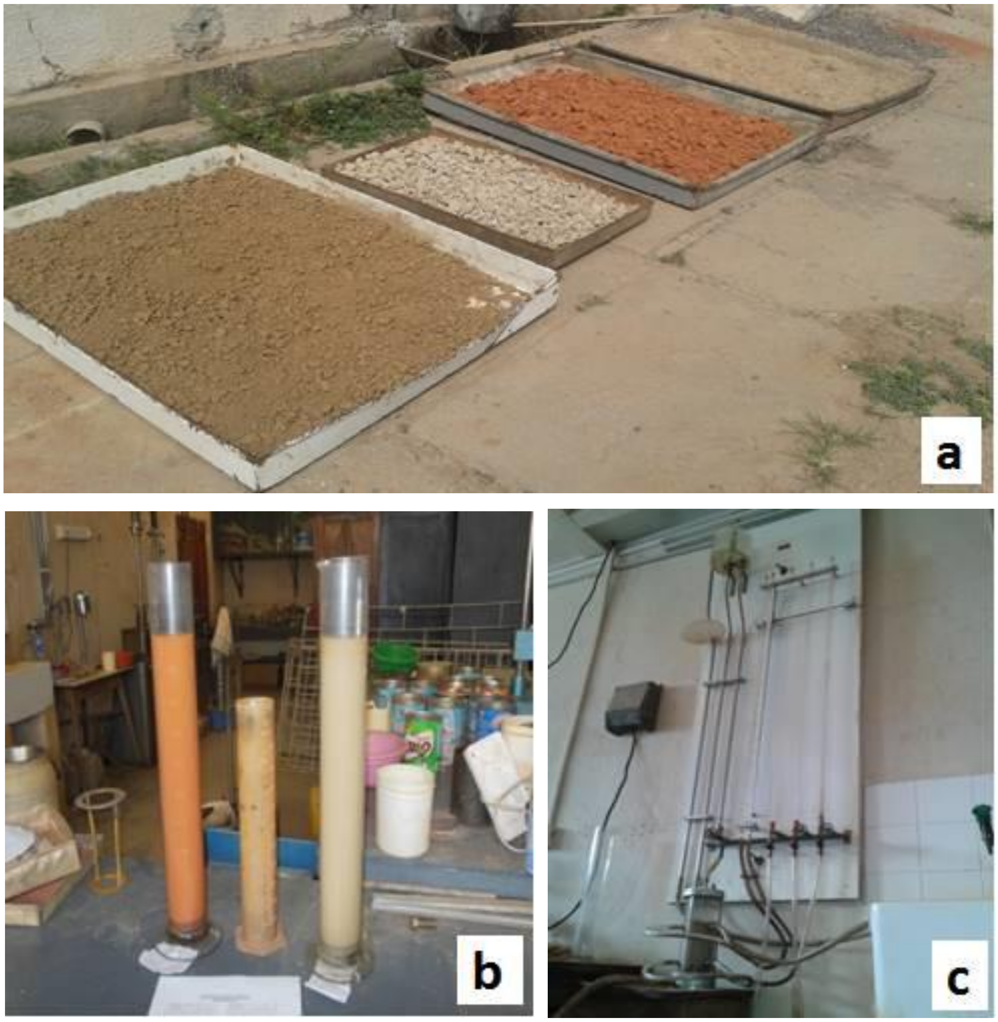

Plate 8: Soil characterization and preparation for use as column filling material: (a) Soil preparation; (b) hydrometric analysis set-up; and (c) permeability apparatus

Plate 9: Field sampling of Biofil effluent from existing installation

Plate 10: Experimental soil column set-up

Solid loading test

Plate 11: Vermiculturing of earthworms and porous filter composites for experiments

Plate 12: Fabrication of miniature BTT and hand counting & weighing of earthworms

Plate 13: Solid loading of miniature BTT with faeces & weighing of biosolids during vermicomposting

Plate 14: Vermicomposting, sampling and laboratory analyses of biosolids

Toxicity test

Plate 15: Household chemical concentration preparation and determination of pH of diluted chemical reagents

Plate 16: Hand sorting of earthworms for toxicity test (time of paralysis & death)

Plate 17: Assessment of paralysis and death in spiked earthworms; toxicity effect of household chemical reagents on earthworms

Appendix C: Achievement during PhD

Paper publications

1. Owusu-Antwi, P., Buamah, R., Kuwornu, S. I., Essandoh, H., Awuah, E., Anno, A. K. (2017). Nutrient and Microbial Reduction Properties in Pervious Composites for Blackwater Treatment, *Management Studies*, Vol. 5, No. 3, 212-218. doi: 10.17265/2328-2185/2017.03.006

2. Owusu-Antwi, P., Buamah, R., Essandoh, H., Molla, A. S., Awuah, E., Anno, A. K. (2015). The Potential of Subsurface Infiltration for the Treatment of Biofil Toilet Technology Effluent, *Management Studies*, December 2015, Vol. 3, No. 11-12, 281-299. doi: 10.17265/2328-2185/2015.1112.003

Conference papers

1. Owusu-Antwi, P., Buamah, R., Essandoh, H., Awuah, E., Anno, K. (2013). Occurrence of On-site Sanitation Technologies in Poor Urban Communities in Ghana, Ghana Institute of Engineers.

Drafted papers

1. A comparative assessment of paralysis and death of *Eudrilus eugeniae* by different household chemicals (Chloroxylenol, Hydrogen chloride, Sodium hypochlorite)
2. A comparative study of household chemical application and blackwater stabilization: A case of the Biofil Toilet Technology

Appendix D: LD_{50} Calculation for Chloroxylenol

Logarithmic

e = 2.718281828459045……..

y = 0.6733In(x) + 2.1365 ……………………. (Logarithmic Eq.: Figure 4-31)

Where:

y = half the number of earthworms used

x = concentration of chloroxylenol required to kill half the population of earthworms used (g/100mL)

0.3635 = 0.6733In(x)

x = e (exp.) 0.5398

x = 1.715

Appendix E: Cost of BTT products

BTT Product	# of User	Description	Cost ($)	Remark
Standard digester with drainfield, vent & 2 year warrantee	10		595	Residential
Large digester with drainfield, vent & 2 year warrantee	15		640	Residential
Special digester with drainfield, vent & 2 year warrantee	25+		880+	Schools, institutions, hotels, restaurants etc.
Standalone full flush (Privy, flush seat, hand wash basin, large digester, drainfield, vent, 2 year warrantee)	10		1200	Security post, event centres, parks & gardens
Standalone microflush (Privy, microflush seat, hand wash basin, large digester, vent, 2 year warrantee)	10	 	950	Low income (Residential), schools

**Standard septic tank (3.0 m x 1.8 m x 2.1 m); blockwork wall, reinforced concrete roof slab, cover slabs and soakaway costs between $1,200 – $1,500