SCIENTIFIC AND MANAGEMENT SUPPORT FOR VENTILATED IMPROVED PIT LATRINES (VIP) SLUDGE CONTENT

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EXAMINER'S COPY

Submitted in fulfilment of the academic requirements for the **degree of Doctor of Philosophy** in the School of Chemical Engineering University Of KwaZulu-Natal, Durban

DECEMBER 2011

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DEDICATION

For

Mercy and Daniel

DECLARATIONS

I, **Babatunde Femi Bakare**, declare that

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As the candidate's Supervisors we have approved this thesis for submission

Dr KM Foxon

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Prof. CA Buckley

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ABSTRACT

This thesis presents a scientifically based approach into the management of ventilated improved pit latrine sludge before and when the pit becomes full. The purpose of this study was to investigate processes within VIP latrines in order to understand the nature of sludge that is dug out of pits and thus be able to propose suitable disposal options for the sludge.

The components of this research work includes; an investigation into sludge accumulation rates in ventilated improved pit latrines, the characterization of ventilated improved pit latrine sludge collected at different locations within the pit, investigation into the entrenchment of ventilated improved pit latrines sludge for agroforestry and the efficacy of commercial pit latrine additives on ventilated improved pit latrine sludge content. Three hypotheses were proposed: that (i) significant biological stabilization occurs in a pit latrine with time, such that further biological treatment of sludge dug out of pits is not appropriate, (ii) VIP latrine sludge can be used in deep row entrenchment for agroforestry since the sludge contains nutrients that are available to plants, and that the sludge is sufficiently stable to not cause a negative environmental impact; and (iii) through biological action of microorganisms present in pit latrine additives (biological products), the overall mass of pit latrine contents could be reduced much faster than could be achieved by natural degradative processes mediated by microorganisms already available in the pit latrine contents

The main findings of this research work were:

- The overall average sludge accumulation rate obtained in this research work was 31 ± 10 ℓ/person·year. By comparing this value with an estimated volume of material (600 ℓ/person·year or more) added to the pit by an individual, indicates that only 5 % of the materials added to the pit by an individual per year eventually accumulate as sludge and out of this 5 % only 1 % of the estimated solids volume accumulates as sludge. This

clearly suggests that significant biological stabilization must have occurred in the pit latrines investigated with time.

- Laboratory characterization of collected sludge from various pit latrines indicated that, characteristics of sludge varied significantly within a pit and between different pits. It was observed that below the surface layer in a pit additional stabilization of sludge content does exist and the degree of stabilization within a pit increases from the surface layer of the pit down through the bottom layer of the pit. It was also found that the material buried well below the pit surface, to be specific sludge samples from the bottom of the pit are well stabilized.
- Unlike the disposal of VIP latrine sludge into wastewater treatment works or anaerobic digestion of VIP latrine sludge, deep row entrenchment of VIP latrine sludge for agroforestry was found to be a feasible and potentially beneficial disposal and/or reuse option for VIP latrine sludge.
- Neither laboratory trials nor field trials provided any evidence that the use of pit additives can significantly reduce the rate at which sludge accumulates in VIP latrines or reduces the volume of sludge in the pits.

It was concluded that the sludge content in pit latrines have naturally undergone significant degradation, this challenges the common assumption that pit latrines act only as storage vessels for faecal waste in which no biodegradation takes place. Consequently the option for the disposal of pit latrine sludge are limited by the characteristics of the sludge, thus based on the characteristics of pit latrine sludge obtained in this study further biological treatment of sludge dug out of pits is not appropriate; Rather deep row entrenchment of VIP latrine sludge for agroforestry seems to be an appropriate option for the disposal of VIP latrine sludge.

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LIST OF ABBREVATIONS

ANOVA	Analysis of Variance
BH	Borehole
COD	Chemical oxygen demand
DWAF	Department of Water Affairs and Forestry
EWS	eThekwini Municipality Water and Sanitation
FSA	Free and Saline Ammonia
TKN	Total kjeldahl nitrogen
TLB	Tractor Loader Backhoe
TS	Total Solids
TSS	Total Suspended Solids
VIP	Ventilated Improved Pit latrine
VS	Volatile Solids
WHO	World Health Organization
WRC	Water Research Commission
WWTP	Wastewater treatment plant

1 INTRODUCTION

According to the South African Government Strategic framework for Water Services (DWAF, 2003), the provision of adequate, appropriate, effective and sustainable sanitation facilities for all South Africans is a necessity. Ventilated Improved Pit (VIP) latrines have been identified as the minimum acceptable level of sanitation in South Africa. These VIP latrines were design mainly for the accumulation of faecal sludge without bio-processing of the sludge within the pit. At present, while the government of South Africa is still struggling to provide basic sanitation facilities for all, a considerable number of existing ones (i.e. conventional pit latrines and VIP latrines) are full and require immediate emptying.

While some Municipalities/Water Service Authorities are actively putting in programmes to manage the accumulated sludge, many are only focussed on providing this sanitation system to address the current backlogs without any serious thought on how to deal with the sludge that would accumulate over the years. However, some options which have been proposed to deal with accumulated sludge when the pits becomes full are all on the basis that pit contents that are dug out of the pit are not very different to the materials that are added to the pit and therefore the appropriate disposal/treatment options for the accumulated sludge would be similar to treatment options used for fresh sanitation waste. The options which have been proposed for the disposal/treatment of accumulated pit latrine sludge are:

- Disposal to wastewater treatment plant
- Anaerobic digestion
- Composting
- In situ "treatment" with a biological product (pit additives)

However, previous research (Buckley *et al*, 2008 and Nwaneri, 2009) suggests that significant degradation does occur within the pit. Therefore the basis of proposing the above treatment options is not appropriate.

Thus, the purpose of this research work was to investigate processes within pit latrines in order to understand the nature of material that is dug out of pits and thus be able to propose suitable disposal options for the sludge under South Africa conditions. An understanding of the rate of accumulation of sludge in pit latrines and the biological degradation processes occurring in VIP latrines would facilitate better management of VIP latrines and its sludge contents during their life span and upon emptying.

At the beginning of this research work, an opportunity arose to investigate the possible use of deep row entrenchment techniques for agroforestry as a means of both disposal and possibly beneficial reuse of the sludge. Hence, if the findings of previous research (Buckley *et al*, 2008 and Nwaneri, 2009) that significant stabilization occurs in a pit is correct, then pit contents dug out would be relatively stable but would contain certain amounts of nitrogen and phosphorus which might be available as plant nutrients. Thus, the research work was extended to investigate the fate and impact of VIP latrine sludge in deep row entrenchment as a possible disposal option and as an appropriate means for managing fairly well stabilized sludge. In situ "treatment" of pit contents with biological products was also investigated because of the various claims from the manufacturer of these products that the rate at which sludge accumulates within the pit or pit contents could be reduced by adding these biological products to pit contents.

Therefore the main hypotheses of this research work were:

- That significant biological stabilization occurs in a pit latrine with time, such that further biological treatment of sludge dug out of pits is not appropriate,
- That VIP latrine sludge can be used in deep row entrenchment for agroforestry since the sludge contains nutrients that are available to plants, and that the sludge is sufficiently stable to not cause a negative environmental impact, and
- That through biological action of microorganisms present in pit latrine additives (biological products), the overall mass of pit latrine contents could be reduced much faster than could be achieved by natural degradative processes mediated by microorganisms already available in the pit latrine contents.

1.1 OBJECTIVES OF THIS STUDY

To test for the validity of the main hypotheses of this research work, the following objectives were set out:

- To determine sludge accumulation rate in ventilated improved pit latrines over their life span through field investigations which could be use for pit design and maintenance.
- To investigate the physical, chemical and biological characteristics of sludge contents from different locations within the ventilated improved pit latrine.
- To monitor changes in the characteristics of sludge buried in trenches and also monitor the effect of sludge buried in trenches on surrounding ground water.
- To investigate and quantify the effect of pit additives on sludge contents in ventilated improved pit latrines, through laboratory and field investigation.

1.2 THESIS STRUCTURE

The research work and findings are covered in the following 8 chapters of this thesis. **Figure 1.1** is a schematic representation of this thesis.

Chapter 1 outlines the context of the research work. The main hypotheses and objectives of the research work are presented.

Chapter 2 defines the context of the problem through a review of literature related to this study. An overview of relevant literature on VIP latrine designs, characteristics of sludge contents in pits, processes occurring within pit latrines, pit additives, pit emptying methods, description of the sludge disposal and handling guidelines, description of the different disposal options available for pit latrines sludge content are presented.

Chapter 3 presents the work done and investigations carried out in determining sludge accumulation rate in ventilated improved pit latrines within the eThekwini Municipality.

Chapter 4 presents the physical, biological and chemical characteristics of sludge content from a number of ventilated improved pit latrines within the eThekwini Municipality.

Chapter 5 describes the applicability of a VIP sludge entrenchment technique under typical South African environmental conditions; results of changes in the sludge content buried in trenches and the effect of sludge burial on ground water are presented.

Chapter 6 presents the investigations carried out on the potential use of pit additives to reduce accumulation rate in VIP latrines taking into consideration both laboratory and field trials.

Chapter 7 describes and discusses the broad impact of the results presented in the previous chapters

Chapter 8 presents the conclusions and recommendation for future research.

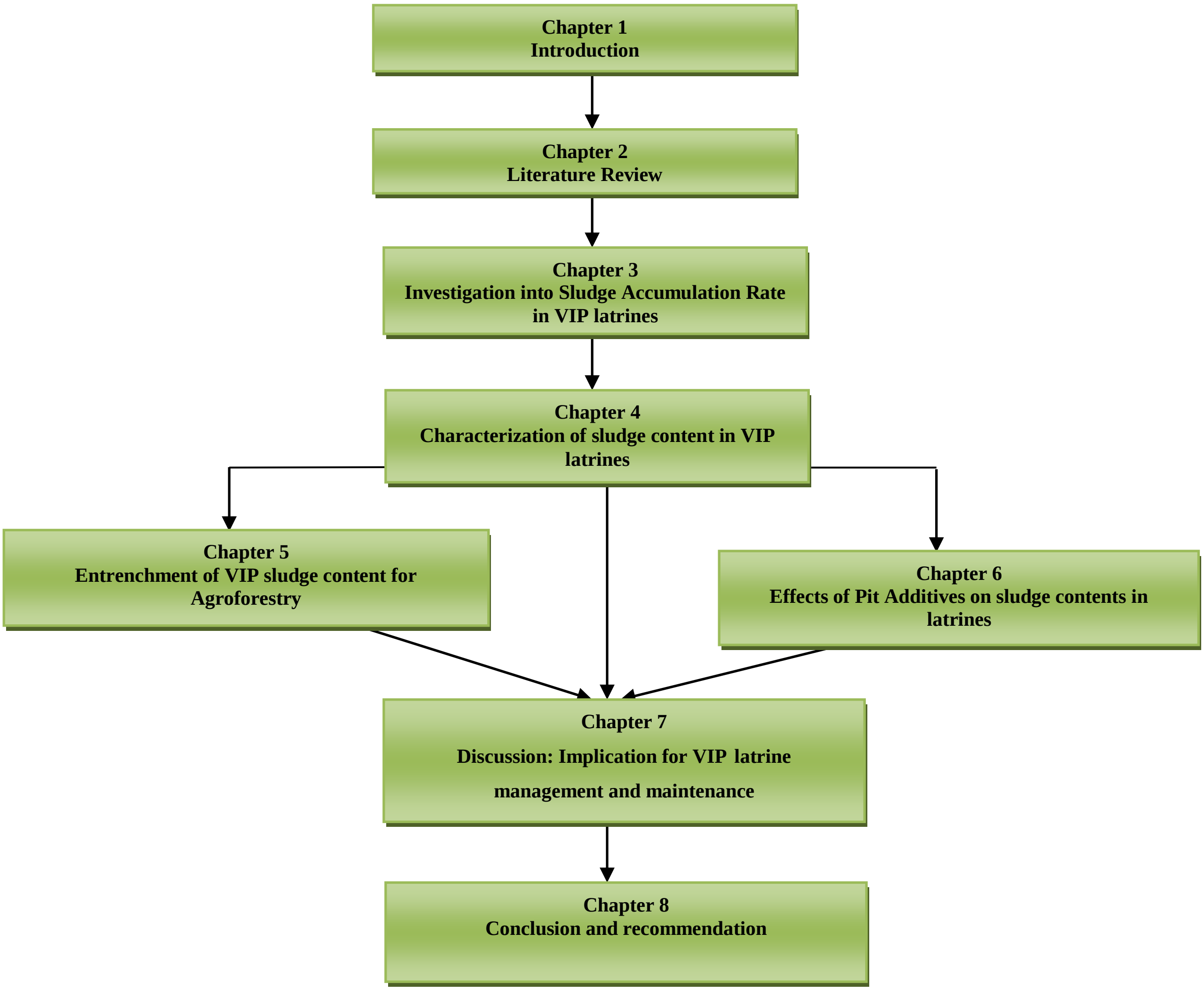


Figure 1.1: Schematic Layout of the thesis.

2 LITERATURE REVIEW

This chapter defines the context of the problem through a review of literature related to this study. A review of relevant literature on VIP latrine design, operation and maintenance, characteristics of sludge contents in pits, processes occurring within the pit latrines, pit emptying methods, management of sludge within the pit latrines and the disposal options of pit latrine sludge when the pit become full is presented.

2.1 THE VIP LATRINE

Ventilated Improved Pit latrines are used as an accumulation system for stabilizing faecal matter, urine and other materials added depending on household habits (Chaggu, 2004) and functions as containment for digestion of fresh faeces and storage of the digested faeces. They are designed primarily for the storage of the digested solids (Mara, 1996). **Figure 2.1** is a typical structure of a basic ventilated improved pit latrine. Ventilated improved pit latrines differ from traditional pit latrines in that they are equipped with a tall vertical vent pipe which has a fly screen fitted to the top. This vent pipe serves as a medium by which odours and flies are controlled by drawing airflow into the pit via the pedestal and out of the vent pipe above head height (Mara, 1984).

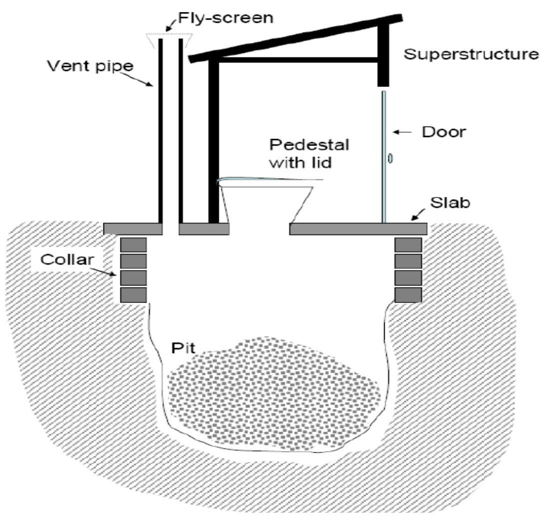


Figure 2.1: Basic structure of a VIP (Buckley *et al*, 2008)

A ventilated improved pit latrine is comprised of several components as indicated in **Figure 2.1;** the following sections present a brief description of these components.

2.1.1 The Pit

The pit is usually a single pit or an alternating twin pit. The pit may be either unlined or lined in open-joint brickwork or block work (Mara, 1984). This lining help prevents the soil from collapsing during emptying operations or during heavy rains (Mara, 1984), while the open vertical joints allow liquid (including urine) to drain into the soil (Mara, 1984). According to Bester and Austen (2000), the pit is usually circular or rectangular and may be built slightly above the surrounding ground to provide sufficient depth. The main function of the pit is to allow for the collection and storage of faeces such that the faeces are biologically degraded producing methane, carbon dioxide, and hydrogen sulphide gas which are liberated from the pit through the vent pipe (Mara, 1984). According to Mara (1984), the effective pit working volume (V_s) is calculated as:

$$V_s = \text{Sludge accumulation rate (R)} \times \text{number of users (n)} \times \text{design life (y)} \quad \textbf{[2.1]}$$

Mara (1984) quotes values for the solid accumulation rate in pit latrines to be between 0.02 and 0.06 m^3 per person per year depending on the location of the water table. For dry pits (i.e. those above the water table), values of solid accumulation rates quoted from Mara (1984) are typically between 0.03 and 0.06 m^3 per person per year and for wet pits (i.e. those penetrating the water table) values of solid accumulation rates are typically between 0.02 and 0.04 m^3 per person per year. It is always necessary that an empty volume of 0.5 m^3 is added to the calculated effective pit volume when designing the pit. This would prevent the pit from reaching its capacity at the end of the expected design life (Mara, 1984).

2.1.2 The Cover Slab

The cover slab is normally built using reinforced concrete which covers the pit. Two holes are attached to the cover slab; one for the pedestal and the other for the vent pipe (Cairncross and Feachem 1996; Mara, 1984). The cover slab provides support for the superstructure as well as the vent pipe and also prevents the exposure of faeces to the atmosphere and odours and flies from escaping to the surrounding environment (Cairncross and Feachem 1996).

2.1.3 The Superstructure

The superstructure is usually built with bricks and it is best to build the superstructure in the same general style as the house (Mara, 1984). According to Buckley *et al*, (2008) the superstructure provides privacy to the users, protects the pit from rain and sun, and provides shadow over the pedestal. This is important for preventing flies that are newly formed from leaving the pit itself and also for channelling air through the pedestal to the vent pipe thereby controlling faecal odours (Mara, 1984).

2.1.4 The Screened Ventilation pipe

The screened ventilation pipe controls both odour and flies and it is necessary that it stands upright so as to allow penetration of light into the pit in order to ensure good fly control (Mara, 1984). According to Cairncross and Feachem (1996), the screened ventilation pipe must be 500 mm above the roof of the superstructure in order to permit enough wind-induced air circulation for odour control. The screen apertures must not be greater than 1.2 × 1.5 mm, this would prevent flies and mosquitoes from passing through (Mara, 1984).

According to Cairncross and Feachem (1996) and Mara (1984), wind passing across the top of the screened ventilation pipe causes a pressure drop across the top of the vent pipe by a venturi effect. This results in a net pressure drop between the pit and the top of the pipe and causes air to rise up the vent pipe. This continual circulation of air effectively eliminates the odours emanating from the faecal material in the pit. The screen material attached to the ventilation pipe plays an important role in preventing flies and mosquitoes from entering and leaving the pit.

According to Mara (1984), flies are attracted to the top of the screened ventilation pipe by odours emanating from faecal material in the pit and are prevented from getting inside the pit by the screening material attached to the ventilation pipe. Nevertheless, some flies may eventually manage to enter into the pit through the superstructure or the pedestal; they will instinctively fly towards the direction of light penetrating from the screened ventilation pipe where they will eventually be trapped by the screening material attached to the ventilation pipe and will eventually fall down and die in the pit (Cairncross and Feachem, 1996; Mara, 1984; DWAF, 2003).

2.2 CHARACTERISTICS OF PIT LATRINE SLUDGE

The major composition of the sludge in any particular pit latrine, if appropriately used for its purpose will include faeces, urine and anal cleansing materials. **Table 2.1** presents characteristics of faeces extracted from various publications (It should be noted that not all these studies looked at fresh human faeces. This could be seen especially by the difference in the COD values between the first two and the last three references). The data by Palmquist and Jönsson (2003) was obtained from measured accumulated material in a urine diversion toilet system while Chaggu (2004) presents data compiled from a variety of sources. The last three references used fresh faeces in their analyses.

Table 2.1: Characteristics of faeces adapted from various literatures

Parameter	Units	Palmquist (2003)	Chaggu (2004)	Lopez (2002)	Almeida (1999)	Nwaneri (2009)
Moisture	% of wet mass	86	66-85	81.8	79.2	78
Volatile solid	% gVS/gTS	-	-	84.4	-	84
Total COD	mg COD/g dry mass	364	253	1 450	1 380	1 130
Biodegradability	% mgCOD/ mgCOD	-	-	80	-	74

In reality, the contents of any particular pit consist of a wide range of material. It is therefore impossible to predict the material composition of any particular pit without physically observing what is in the pit or digging out the contents of the pit since many households make use of the pit for different purposes; either for their basic sanitation needs or for both their sanitation needs and discarding of solid refuse. **Figure 2.2** shows two pit latrines with different sludge composition based on different user habits.

A large variety of materials in addition to faeces such as newspaper, magazines, broken glass, bottles, rags, plastic bags, and a range of other household waste materials could be found in the pit.

(a) Q section Umlazi

(b) Mariannhill

Figure 2.2: Typical content of pit latrines from two pit in different communities in eThekwini Municipality

It has been widely documented that the variety of materials which are discarded into pits may have a significant effect on the efficiency of the degradation processes occurring in the pit and also this could make pit emptying significantly difficult to perform (Cotton *et al*, 1995; Franceys *et al*, 1992; Mara, 1984; Still, 2002). About 10 to 20% of the material composition in a pit can be made up of non-degradable solid waste; this value may be lower or higher depending on the household habits (Still, 2002). **Table 2.2** presents typical characteristics of VIP latrines sludge content.

Table 2.2: Characteristics of VIP latrines sludge contents (Buckley *et al,* 2008)

	Parameters	Units	Average	Min	Max	n	C of V
Total	COD	mg/g wet weight	105	46	199	21	45
		mg/g dry sample	445	71	987	17	58
	Moisture	% of wet sample	76	29	81	13	6
	Total Solids	% of wet sample	33	19	71	17	54
	Organic Solids	% of solids	36	6	62	17	48
	Inorganic Solids	% of solids	64	38	94	17	26
	Biodegradability	%Biodegradable	50	47	56	5	8
Soluble[1]	COD	% of total COD	31	7	91	7	97
	Nitrate	mgN/g wet sample	0.028			**1**	

Based on the fact that a wide range of material can be found in a pit latrine and also the surrounding environmental conditions, it would be expected that there will be a considerable variation in the organic content, moisture content, non-biodegradable content and micro-organism population of different pits (Buckley *et al*, 2008). This could be observed by the significant variations in the values presented for all determinants as presented in **Table 2.2.**

According to the theory proposed by Buckley *et al* (2008), the faecal sludge portion within any pit latrine comprises of four theoretical categories as shown in **Figure 2.3**.

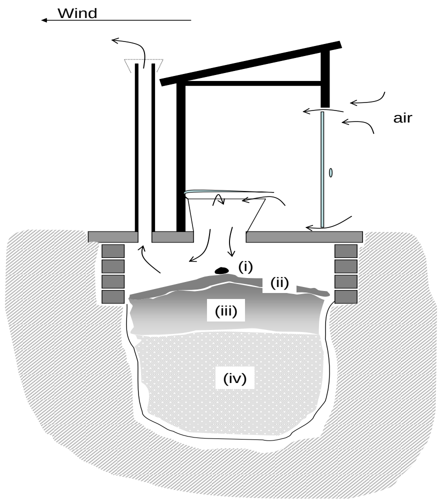


Figure 2.3: Diagram showing the different theoretical layers within a pit latrine. (Buckley *et al* 2008).

The first category (i) is the layer containing fresh faecal sludge in which readily biodegradable components are still present and in which rapid aerobic degradation is taking place, the second category (ii) is the layer in which aerobic degradation of hydrolysable organic material takes place at a rate limited by aerobic hydrolysis of complex organic molecules to simpler compounds; the third category (iii) is suggested to be an anaerobic layer due to the occlusion of oxygen by covering material. Anaerobic degradation in this layer is controlled by the rate of anaerobic hydrolysis of complex organic molecules to simpler molecules; and finally the fourth category (iv) is the lowest and bottom layer of the pit, here sludge component has attained a significant degree of stabilization and no further stabilization of organic material occurs within the remaining life span of the pit.

2.3 PROCESSES OCCURRING IN VIP LATRINES

Two categories of processes can be said to be taking place within the pit i.e. non-biological processes and biological processes (Foxon *et al*, 2006). The non-biological processes within the pit (also referred to as physical processes) involve the accumulation of sludge within the pit, transport of solubilised materials and moisture within and out of the pit and the compaction of materials in the pit. Biological processes taking place within the pit involve the microbial degradation of the organic material resulting in the production of gases which are liberated via the vent pipe into the atmosphere and soluble components that infiltrate with the liquid contents of the pit into the surrounding soil (Franceys *et al*, 1992; Mara, 1984).

2.3.1 Non-Biological Processes/Physical Processes in Pit Latrines

According to Buckley *et al*, (2008), the physical processes taking place in a pit is categorized into two which are: (i) accumulation of sludge in the pit; and (ii) hydraulic flow patterns of soluble components into and out of the pits via the walls and the base of the pit. However compaction of materials at the bottom of the pit as a result of faeces or new material added to the pit could also be described as a physical process taking place in the pit (Buckley *et al*, 2008). This may result to moisture been squeezed out of the pit materials, breakdown of intact cells with time, reduction in sludge volume within the pit latrine and improved control of water flows within the pit (Buckley *et al*, 2008; Cotton *et al*, 1995).

2.3.1.1 Sludge Accumulation rates

Ventilated improved pit latrines are meant to contain mainly human faeces, urine and the type of anal cleansing material used by the households. According to Vinnerås (2002), an individual produces between 0.12 – 0.40 litres of faeces and 0.6 – 1.5 litres of urine per day. Averaged over a year, this amounts to 110 litres of faeces and 440 litres of urine per person per year: a total volume of 550 litres of excreta per person per year. Natural bacteria present in faeces and urine degrade the available organic material found in the materials deposited in the pit. According to Franceys *et al*, (1992), the degradation of the material deposited in the pit gradually reduces the volume and/or mass of the materials present in the pit, however, the number of people using the pit, the use of biocidal or oxidative chemicals to overcome odour liberated from the pits, and the deposition of rough papers, plastics, bottles and other non biodegradable household refuse, can cause the rapid accumulation of solids in a pit (Still, 2002). Still (2002), also reported that the disposal of household refuse into pit latrines contributed significantly to the rate of sludge accumulation, by as much as 10 to 20 % increase in the rate at which sludge accumulates in pit latrines. According to WHO (2004), sludge accumulation rates in pit latrines do not only depend on these factors; climatic and socio-economic factors may also play a major role in the rate at which sludge accumulates in pit latrines and these differ from one country to another and even within the same country. Climatic conditions and also individual diet has a direct influence on the quantity and composition of faeces and urine produced. The type of diet of an individual affects the chemical and biological oxygen demand present in the faeces introduced into the pit latrine. The proportion of proteins and carbohydrates in each individual's diet might result in different degradation rates and thus affect the accumulation of sludge in a pit (WHO, 2004). The findings on the determination of sludge accumulation rates in pit latrines from local and international experience is presented in **Table 2.3.**

Table 2.3: Pit latrine filling rates (Still, 2002).

Location	**Age of Latrines**	**Number of Sites**	**Number of Visits**	**Avg. Pit Volume m^3**	**Range of Filling Rates ℓ/ca/annum**	**Mean Filling Rate ℓ/ca/annum**
Soshanguve	3 years	11	14 over 28 months	1.96	13.1 to 34.0	24.1
Bester's Camp	4 years	159	2 or 3 over 25 months	3.16	18.3 to 120.5	69.4
Mbila	5 years	11	1	2.83	10.0 to 33.2	18.5
Gabarone, Dar es Salaam	not stated	not stated	not stated	not stated	25 to 30	27.5 (implied)

Franceys *et al*, (1992), recommended that it is necessary to determine pit latrine sludge accumulation rates for a particular location before designing new pit latrines and in situations where there is no available data for that location, the values presented in

Table 2.4 can be used as maximum values for designing a new pit latrine. These values were based on whether the pit sludge content was above or below the water table and the type of anal cleaning material used (either degradable or non degradable material).

Table 2.4: Proposed maximum sludge accumulation rates for VIP latrine design (Franceys *et al*, 1992)

Conditions in the pit	Sludge Accumulation Rate (ℓ/person·year)
Wastes retained in water where degradable anal cleaning materials are used	40
Wastes retained in water where non- degradable anal cleaning materials are used	60
Wastes retained in dry conditions where degradable anal cleaning materials are used	60
Wastes retained in dry conditions where non- degradable anal cleaning materials are used	90

According to Norris (2000), the design criteria used in the determination of sludge build up in various on-site sanitation systems in South Africa were generally inappropriate because they were based largely on experience in other countries. The main objective of the study conducted by Norris (2000) was to establish the rate at which sludge builds up in various on-site sanitation systems under South African conditions. In this study, sludge levels in VIP latrines was measured by lowering a steel measuring tape which was attached to a steel weight into the pit and the vertical distance between the pedestal and sludge surface was measured. The change in the vertical distance was taken to be the change in sludge volume for each pit investigated. The findings of this study recommended that sludge accumulation rate of 25 ℓ/person·year can be used for VIP latrine design purposes in South Africa.

Still *et al* (2010) further explains that the prediction of pit emptying interval needs to take into consideration estimated sludge accumulation rates in pits and this could only be achieved if adequate knowledge of pit latrine age and pit volumes are known. Two studies were conducted by these authors in different province (KwaZulu-Natal and Limpopo) in order to investigate sludge accumulation rate in pit latrines and the method of measurement was not presented. However it was found that sludge accumulation rates in pit latrines decreases with an increase in the number of users for the two studies. It was then concluded that householder might have exaggerated the number of people in the house thinking that they might be provided with a second pit latrine or numbers given by householders do/do not take into consideration regular visitors. **Figure 2.4** presents the results obtained from these two studies.

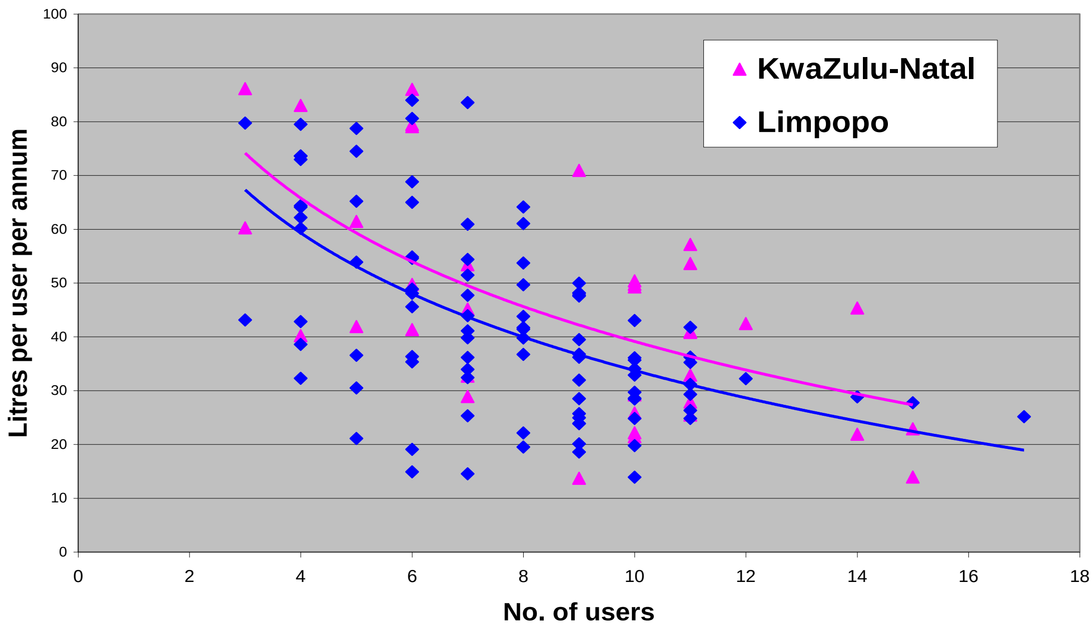


Figure 2.4: Observed sludge accumulation rates with reported number of users (Still *et al*, 2010).

The average sludge accumulation rate obtained for these two studies was 33 ℓ/person·year for KwaZulu-Natal study and 50 ℓ/person·year for the Limpopo study. It was proposed that, for pit emptying programme where the VIP latrine is to be emptied before the pit becomes unusable an accumulation rate of 60 ℓ/person·year should be considered for planning the emptying programme.

2.3.1.2 Hydraulic flow of liquid containing soluble components within the pit

The decomposition of faeces, urine, anal cleansing material, latrine floor/pan cleaning and sometimes sullage tipped into the latrine contribute significantly to the amount of moisture found in pit latrines (Cotton *et al*, 1995). According to Buckley et al. (2008), the only moisture expected to be present in sealed pit latrines is associated with urine and faeces. Buckley et al. (2008) also indicated that the addition of water by users of the pits or from rain caused as a result of damaged or poorly constructed superstructure may also contribute significantly to the moisture present in the pit. For unsealed pits, the permeability of the soil and the location of the water table beneath the pit contribute to the inflow and outflow of liquids in the pit. Therefore movement of liquids in and out of the pit through the walls and beneath the pit depend on the construction of the pit and the hydrogeology of the pit location (Cotton *et al*, 1995; Franceys *et al*, 1992).

2.3.2 Biological Processes in Pit latrines

A survey of the literature suggests that anaerobic digestion is the predominant biological process taking place in pit latrines (Buckley *et al*, 2008; Chaggu, 2004; Mara, 1984; Still, 2002). Although aerobic conditions might occur at the topmost layer of the heap in the pit latrine, however the extent of aerobic degradation within the pit is not understood.

2.3.2.1 Aerobic Digestion Process

Although the extent in which aerobic digestion occurs within the pit is not clearly understood, it is believed that at the air interface (top surface) of the pit, aerobic digestion and other processes might take place. Aerobic digestion processes involve the biochemical breakdown of biodegradable organic material by microbes in the presence of sufficient oxygen resulting in an increase in temperature and production of carbon dioxide, water and cellular protoplasm (Gray *et al,* 1971). This process is carried out by wide range of microorganisms that are naturally occurring and the digestion process is far more rapid than anaerobic digestion processes (Henze *et al,* 1997). Metcalf and Eddy (2003) describe the aerobic conversion of organic matter by microorganisms in accordance with the stoichiometric equations shown below;

Oxidation and Synthesis

$$aCOHNS \quad + bO_2 + Nutrients \xrightarrow{Bacteria} cCO_2 + dNH_3 + eC_5H_7NO_2 + End\ products$$

Organic matter ↓ new cells ↓ **[2.2]**

Endogenous Respiration

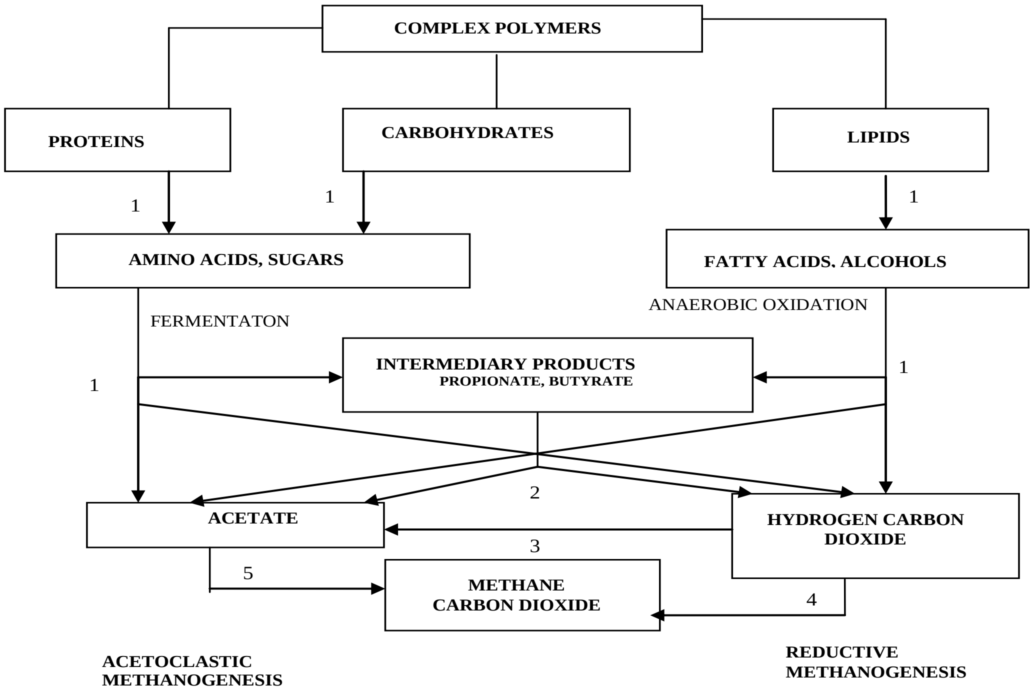
$$C_5H_7NO_2 \quad + 5O_2 \xrightarrow{Bacteria} 5CO_2 + 2H_2O + NH_3 + Energy$$ **[2.3]**

Cells ↓

2.3.2.2 Anaerobic Digestion Processes

Anaerobic digestion involves the conversion or breakdown of organic matter by microbes in a molecular oxygen free environment. In pit latrines, faecal sludge is converted under anaerobic condition to produce carbon dioxide, methane, hydrogen sulphide gases which are released through the ventilation pipe and soluble components which drain away with the moisture content of the pit latrine (Franceys *et al,* 1992; Mara, 1984). Anaerobic digestions of organic material are mediated by different groups of microbes which follow a series of stages. During anaerobic digestion process, available and readily biodegradable organic materials are converted to gases and only a small fraction (typically 10%) is converted to new cell mass as a result of microbial growth (Speece, 1996). **Figure 2.5** shows how complex substrates are converted into simpler substrates and the type of microorganisms that facilitate each process.

The series of stages involved for complete anaerobic digestion of organic material can be grouped into four main steps (Seghezzo *et al,* 1998). The first step in the anaerobic digestion process is hydrolysis which involves the conversion of complex particulate matter into soluble substrates (Adrianus *et al*, 1994). It is a combination of extracellular, enzymatic processes in which specific group of microorganisms produces enzymes used for hydrolysing complex particulate matter to produce smaller soluble substrates that can be further degraded (Batstone *et al*, 2002). The second step, Acidogenesis involves fermentation of the soluble compounds produced during the hydrolysis stage which results in the production of simple organic compounds such as volatile fatty acids, alcohols, lactic acid, carbon dioxide, hydrogen, ammonia, and hydrogen sulphide gas (Adrianus *et al*, 1994; Anderson and Uyanik, 2003, McCarty, 1991). During this stage, organic compounds produced dissociate releasing H^+ ions into the liquid phase which results to an increase in the acidity of the process (Anderson and Uyanik 2003). This fermentation process is carried out by a diverse group of bacteria most of which are obligate anaerobes (Min *et al* 2005; Adrianus *et al*, 1994). The third step, Acetogenesis is the conversion of volatile fatty acid produced from the Acidogenesis stage into the final products (acetate, carbon dioxide, and hydrogen) for methane production (Adrianus *et al*, 1994; McInerney and Bryant, 1981). In the final step, Methanogenesis, methane is produced from acetate or from the reduction of carbon dioxide by hydrogen using the acetotrophic and hydrogenotrophic microbes respectively (Vom, 2010; Anderson and Uyanik, 2003; Adrianus *et al*, 1994).



1: Fermentative Bacteria
2: Hydrogen- Producing Acetogenic Bacteria
3: Hydrogen- Consuming Acetogenic Bacteria
4: Carbon Dioxide- Reducing Methanogens
5: Acetoclastic Bacteria

Figure 2.5: Schematic Representation of Anaerobic processes indicating which Microorganism facilitates each conversion process (Speece, 1996).

2.4 FACTORS AFFECTING ANAEROBIC DIGESTION PROCESSES

There are various factors which can affect the growth and survival of microorganisms during the process of anaerobic digestion of organic materials. These factors can also slow down or speed up the rate at which anaerobic degradation take place. The main factors affecting anaerobic digestion processes are; Temperature, pH, presence of essential nutrients and absence of excessive concentrations of toxic compounds (O'Flaherty, 2006). **Section 2.4.1 to 2.4.4** describes these main factors.

2.4.1 Temperature

According to Adrianus *et al*, 1994 and Speece, 1996, anaerobic digestion of organic waste depends to a great extent on temperature. The major temperature ranges that are normally defined in anaerobic digestion processes are psychrophillic (0 to 25°C), mesophillic (20 to 40°C) and thermophillic (45 to 75°C). This temperature range relative to the growth rate of methanogens is as shown in **Figure 2.6.** Maximum growth rates for mesophillic microbes are between 35°C and 40°C while for thermophillic microbes they operate at about 55°C during anaerobic digestion processes.

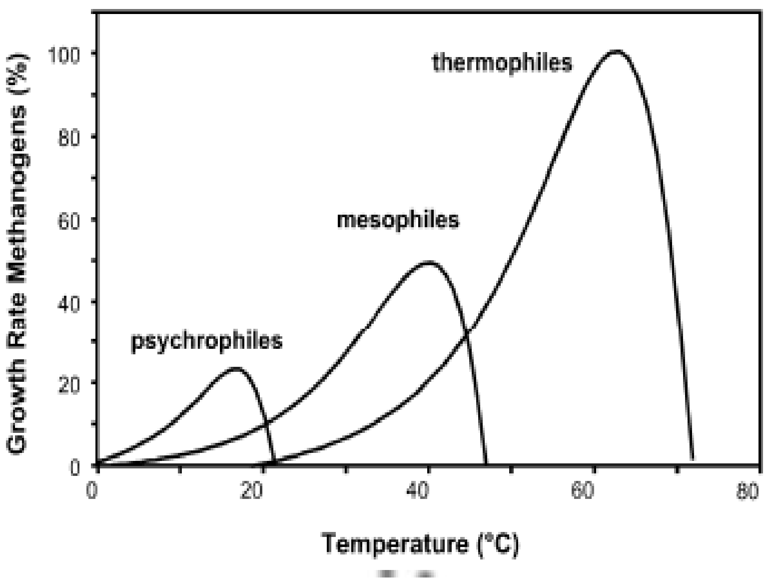


Figure 2.6: Growth rate of psychrophillic, mesophillic and thermophillic Methanogens (Van, 1997).

Henze *et al* (1997) stated that during anaerobic digestion processes, the conversion rate decreases by about 11% for every degree Celsius temperature decrease if anaerobic digestion processes takes place below 30°C. This change in conversion rates during anaerobic digestion processes with temperature is described by modified Arrhenius exponential equation expressed below:

$$\mu_{\max}(T) = \mu_{\max}(20°C)e^{\kappa(T-20)} \qquad \textbf{[2.4]}$$

Each sub-process will have different temperature coefficient (κ).

Temperatures in pit latrines will vary between 15 and 30°C in most cases in South Africa depending on the ambient temperatures resulting in considerable differences in the rate of stabilization (Foxon *et al*, 2006).

2.4.2 Moisture Content

The presence of moisture during anaerobic degradation processes influences microbial activity. According to Williams (1998) in landfill degradation process, moisture content below a minimum of 40% will reduce biological activity of microbes significantly. Methane production during anaerobic degradation process in landfill is said to increase with increasing moisture (Buivid, 1980; Rees, 1980). Active methane production requires moisture content of 50 to 100 % of the dry weight of the waste body or 30 to 50 % of the wet weight of the waste body (Ham, 1979). In a study conducted by Lay *et al*, 1997 to investigate the influence of moisture content on the methanogenic activity in the anaerobic digestion of wastewater treatment plant sludge cake, it was documented that methanogenic activity dropped from 100 % at a moisture content of 96 % to 53 % of the maximum activity when the moisture content was reduced to 90 %.

The main effect of moisture on anaerobic degradation process is that it facilitates the exchange of substrate nutrients, buffer, and dilution of the inhibitors, spreading of microorganisms in niche areas and also limiting oxygen transport from the atmosphere (Christensen *et al,* 1989). In pit latrines, increasing the moisture content has the potential to quicken the establishment of anaerobic conditions within the pit, thus the rate of sludge accumulation is slower (**Table 2.4).**

2.4.3 pH

During anaerobic digestion processes the value and stability of pH throughout the digestion process is an important factor to be considered especially during methanogenic activity, since methanogenic activity requires the pH to be maintained at neutral values in order for the digestion process to proceed at optimum rate (Adrianus *et al*, 1994). According to Batstone *et al*, 2002 and Henze *et al*, 1997 a pH value between 6.5 and 8 is generally considered suitable during the methanogenic stage of anaerobic digestion process.

2.4.4 Nutrients

Nitrogen, phosphorus, sulphur, iron and other micro-nutrients which are required for microbial growth are the essential nutrients for anaerobic digestion processes. If the required nutrients are not sufficient or are not available during anaerobic digestion processes, this could inhibit the production of methane during the methanogenic stage (Schanbacher *et al*, 2005). These nutrients should be readily available in sufficient quantity in faecal material in order to supply the anaerobic microbial requirements for complete digestion of the faecal material (Buckley *et al*, 2008).

2.4.5 Toxic Compounds

Several compounds apart from hydrogen ion concentration affect the rate of anaerobic digestion processes even at very low concentrations such as heavy metals and chloro-organic compounds (Adrianus *et al*, 1994). The methane producing microbes are very sensitive to their environments. High concentrations of some compounds such nitrogen, sodium potassium may have inhibitory effect on the production of methane during the digestion process (Fricke *et al*, 2007). Any inhibitory effect during anaerobic digestion process in conventional anaerobic digesters for the methanogens results to the accumulation of acid and failure of the digestion process (Henze *et al*, 1997).

2.5 PROBLEMS ASSOCIATED WITH VIP LATRINES

There are several problems encountered during the construction and operation of pit latrines. Depending on the location of the pit, difficulties may be encountered during the construction of the pit latrines. In rocky ground, construction of pit latrines becomes extremely difficult and expensive and digging deep pits is often not feasible (Cairncross & Feachem, 1996). Conversely, pit latrines constructed in loose and unconsolidated soils such as running sand or alluvium are liable to collapse (Cairncross & Feachem, 1996). Thus, during excavation there is need for support and the pit must be lined down to bottom without preventing the seepage of faecal liquors out of the pit onto the surrounding soils (Cairncross & Feachem, 1996). In areas of high water table, construction of pits also becomes very difficult and excavation is best carried out during the dry season because pits tend to collapse in the wet season (Cairncross & Feachem, 1996).

The main problems encountered during the operation of pit latrines are often related to the number of users and their habits. The type of maintenance routine practiced by householders and the type of materials deposited in the pit apart from human wastes (faeces and urine) could have a significant effect on the sludge contents and processes occurring within the pit. Householders may have different cleaning practices but the more common are the use of water, detergent or disinfectants. The use of water could significantly influence the total moisture present in the pit, which may results in the solubilisation of soluble substrates allowing for the movement of soluble components relative to stationary solid components within the pit (Buckley *et al* 2008). Disinfectants are prone to have detrimental effects on the biological processes occurring within the pit because of their chemical biocidal components which might have inhibitory effect on the microbial activity.

The disposal of kitchen refuse or addition of soil to the pit by householders will significantly contribute to the load and diversity of microorganisms in the pit (Still, 2002). This would assist in the establishment of natural microbial population provided that conditions within the pit are favourable (Buckley *et al,* 2008). The disposal of non-biodegradable materials such as glass, plastic, metals etc into the pit will result in an accelerated filling up of the pit.

Apart from all the problems associated with the construction and maintenance of VIP latrines during the operational life, the South African government is faced with a situation where considerable numbers of existing VIP latrines and conventional pit latrines are full and overflowing. When pit latrines become full, it is often necessary to empty the pit or the pit is covered up and a new one has to be dug. This leads to questions such as: what available techniques can be used to empty the pit, what is the health risk associated with handling pit latrine sludge content and what are the available disposal options?

2.5.1 Pit emptying techniques.

Although this study has not investigated aspects of pit emptying techniques it is necessary to present previous work done on available pit emptying techniques because pit emptying forms part of the management strategies required when pit latrines become full. The use of VIP latrine systems eventually results in the accumulation of sludge in the pit and the removal of accumulated sludge will be required once the pit becomes full unless the full pit can be covered and a new VIP latrine built to replace the full pit. Building a new pit will depend on the availability of space and also this might be a costly option. It is always necessary to empty ventilated improved pit latrines if they fill to within 0.5 ℓ of the cover slab. Ventilated improved pit latrines and conventional pit latrines can be emptied either manually or mechanically.

2.5.1.1 Manual methods

Only lined pit latrines can be emptied manually (EWS, 2004 and Sugden, 2005). Liquid that enters a pit latrine includes urine, washing water, the ingress of groundwater and storm water overflow. In a pit where there is no ingress of groundwater and storm water, the sludge is usually dry and solidified at the base while being fairly moist at the surface where the faecal matter is still fresh (Buckley et al, 2008). The most basic approach to the removal of pit latrine sludge is manual emptying. In 2004, the eThekwini Water and Sanitation service conducted an exhaustive study on the available pit emptying techniques and concluded that manual pit emptying is the most viable and cost effective techniques for the excavation of pit latrine sludge content (EWS, 2004). According to the study conducted manual pit emptying was found to be the preferred option based on the following reason:

- Virtually any type of pit latrine can be emptied using this method.
- This method, among other methods of pit emptying has the least risk of mechanical failure.
- The method maximizes the use of labour thereby offering significant job creation in a context of high unemployment rate.
- The method was found to be the most cost effective method for evacuating sludge content in pit latrines.

Manual pit emptying involves people digging out the content in a pit latrine by making use of long shovels, spades, forks, buckets, skips and other hand tools. **Figure 2.7** shows the way in which manual pit emptying is carried out. Manual pit emptying has many disadvantages with health and safety of workers and excessive time requirement to empty a pit being the most important.

Figure 2.7: Manual pit emptying.

Apart from lengthy time required to manually empty a pit latrine, the workers (i.e. pit emptier) are exposed to a number of health-related issues if not properly managed, particularly infection by various helminths species, and the work might be unpleasant. In Uganda the application of a certain substance named 'Verpona' is usually added to the pit twenty minutes before the pit is emptied (Kiggundu, 1995). This is said to destroy any viable pathogens present in the sludge. According to Scott and Reed (2006), making use of a safety harness and rope when the emptier enters the pit is necessary to provide adequate safety from fumes and also when the pit collapse. In South Africa, it is recommended that pit emptier wear protective clothing and have access to adequate supply of water for washing (DWAF, 2005).

2.5.1.2 MAPET: Manual Pit Emptying Technology

The MAPET system is a fully hand operated machine which requires manpower to build up the vacuum. The system was first developed by the Dutch NGO WASTE to solve the problems associated with the pure manual exhaustion of pit latrine sludge contents in Dar es Salaam, Tanzania (Muller and Rijnsburger, 1994). According to Muller and Rijnsburger (1994), the MAPET system is comprised of a 200 litre vacuum tank and a hand pump mounted on a push cart. A 20 mm air hose is use to connect the pump to the 200 litre vacuum tank and a 100 mm pipe is used to drain the sludge from the pit. The MAPET system for pit latrine emptying is shown in **Figure 2.8**. The sludge drained from the pit is usually buried on site, it normally takes up to twenty minutes to fill up the 200 litre vacuum tank and a team of three operators empties one pit per day on average (Kirango and Muller, 1997).

Figure 2.8: The MAPET system (Source: Sugden, 2005).

The MAPET develops a maximum pumping head of 3 m of liquid sludge and the width of the equipment which is usually 800 mm allows the equipment to be manoeuvred between houses (Muller and Rijnsburger, 1994). The major challenge with the use of this system is that with the amount of extraneous material that can be found in pit latrines and the thickness of the sludge in pit latrines, it will be necessary to add significant amounts of water into the pit. Adequate mixing of the sludge in the pit with the added water may be required and probably removal of debris from the pit before the equipment could be used.

2.5.1.3 The Gulper

The Gulper is a device developed to bridge the technology gap between manual exhaustion of pit latrine sludge content and the MAPET system by the London School of Hygiene and Tropical Medicine in the course of a research study conducted in Dar es Salaam, Tanzania (Sugden, 2005). **Figure 2.9** shows the use of the Gulper for pit emptying. Sludge from pit latrines is usually drained out by the action of a flap valve which is fitted to a 200 mm drainpipe and the sludge is emptied into a 20 litre drum for disposal. The Gulper is locally manufactured and can be operated by one person; it empties to a depth of 1 m below the top of the pit (Sugden, 2005).

Figure 2.9: The Gulper (Source: Sugden, 2005)

2.5.1.4 The Vacutug

The Vacutug was developed for United Nation Habitat and tested in Kibera, Kenya in 1996/1997 by Manus Coffey & associates (Wegelin-Schuringa and Coffey, 1998). The Vacutug is a pedestrian controlled pit emptying machine and consists of 500 litre vacuum tank and a motor which serves a dual purpose of propelling the unit at a speed of 5 km/h as well as creating the required vacuum in the tank so as to drain the pit latrine contents. The Vacutug is capable of developing a 9 m suction head and is capable of evacuating dense sludge (BPD, 2001). The Vacutug was developed to be low technology equipment which should be easy and cheap to maintain. The width of the equipment which is usually 1 350 mm allows the equipment to be manoeuvred between houses. The Vacutug is as shown in **Figure 2.10.**

Figure 2.10: The Vacutug (Source: Sugden, 2005)

2.5.1.5 Vacuum Tankers

The Micravac is a small type of vacuum tanker which is able to reach pit latrines which larger tankers are not able to reach (EWS, 2004). The Micravac has a capacity of 2000 litre and able to dispose and transport the sludge to about 8 km from pit latrine site.

Figure 2.11: The Micravac (Source: Coffey, 2006)

Larger vacuum tankers have capacities of between 5 000 to 10 000 litres and could be used for either direct evacuation of sludge from pit latrine or serve as transfer vehicles where smaller or slower vehicles have been used to empty the pit latrine (Strauss and Montangero, 2002). Vacuum tankers are characterised by high capital and maintenance cost and are vulnerable to failure (pipe blockage, pump failure etc).

Figure 2.12: Vacuum Tankers (Source: Sugden, 2005)

2.5.2 Factors influencing the choice of pit emptying techniques.

The nature of the pit contents, costs of emptying as well as the accessibility to the pit determine which emptying techniques would be used.

2.5.2.1 The nature of pit latrine sludge content

Extraneous material added to pit latrines (rags, clothes, broken bottles, plastics, papers, glass etc) makes pit emptying a very difficult task to perform. Sludge contents in pit latrines usually tend to be partially compacted and in solid form. The most viable pit emptying technique in conditions like this is to dig out the content manually because the use of mechanical equipment described in **section 2.5.1.2 to 2.5.1.5** may be vulnerable to failure. The major causes of failure are blockages in the suction pipe and valve as a result of the nature of sludge content.

2.5.2.2 Accessibility

Figure 2.13: Typical scene in Durban South Africa

According to EWS (2004), accessibility to the pit latrine is a major factor that influences the choice of technique to be used in emptying a pit. The use of vacuum tankers usually make pit emptying easy and fast but are usually faced with problems relating to access to the pit. Accessibility to pit location using vacuum tankers are often restricted and regularly impossible because of bad roads, steep terrain and densely settled areas (EWS, 2004) as shown in **Figure 2.13**.

2.5.2.3 Pit emptying cost

Manual pit emptying has been shown to be the most cost effective option when compared to the use of mechanical techniques to evacuate sludge content in pit latrines Eales (2005). The cost of emptying a pit, depending on removal method, content disposal location, accessibility of pit, and terrain, ranges between R 600 and R 1 000 per pit (WIN-SA 2006 values). Manual pit emptying does not require initial capital cost for acquiring machinery and also maintenance cost for the machinery. Although manual pit emptying might be labour intensive, in a situation where local community members are employed, it improves the standard of living and helps in the creation of job opportunities within the local community. On the other hand capital costs and maintenance requirements are very high when making use of mechanical techniques to empty pit latrines Eales (2005).

2.5.3 Health Risks Associated with Pit latrine Sludge content.

When there is no proper operation and management of the provided toilet especially in the case of onsite sanitation like the VIP latrines, household are prone to health risks. Faecal sludge can contain high concentration of excreted pathogens which include viruses, bacteria protozoa and helminths (Jiménez 2009). In a study conducted by the Pollution Research Group University of KwaZulu-Natal in 2008 which investigated Prevalence of helminths and protozoan in VIP latrine sludge, sludge samples from VIP latrines were collected from 120 households. It was found that out of the 120 households investigated:

- 10 % of samples had neither type of parasite
- 60% had Ascaris
- 55% had Giardia
- 50% had Trichuris
- 21% had Cryptosporidium
- 11% had Taenia; and
- 60% had either Cryptosporidium or Giardia

According to IWMI and SANDEC (2002), the rates at which various pathogens die off are influenced by the ambient temperature, with more rapid die off in warmer climates. The rate for pathogen die off in faecal sludge was also calculated, this is presented in **Table 2.5**.

Table 2.5: Pathogen survival periods in faecal sludge (according to IWMI & SANDEC, 2002)

Organism	Average survival time in wet faecal sludge at ambient temperature (days)	
	Temperate climate (10-15°C)	Tropical climate (20-30°C)
VIRUSES	<100 days	<20 days
BACTERIA:		
salmonellae	<100 days	<30 days
cholera	<30 days	<5 days
faecal coliforms	<150 days	<50 days
PROTOZOA:		
Amoebic cysts	<30 days	<15 days
HELMINTHS:		
Ascaris eggs	2-3 years	10-12 months
Tapeworm eggs	12 months	6 months

2.5.4 Sludge Disposal

In terms of the National Water Act (Act 36 of 1998) (DWAF, 1999) and the Environment Conservation Act (Act 73 of 1989), the Department of Water Affairs and forestry (DWAF, from 2010, Department of Water Affairs, DWA) is responsible for the regulation and control of the disposal of sludge from pit latrines. These acts and other acts or legislation as presented in the Guidelines for the Utilisation and Disposal of Wastewater Sludge Vol. 1, 2006 by Snyman and Herselman**,** is as shown in the box.

The Department of Water Affairs and Forestry has previously classified sewage sludge based on its potential to cause odour nuisances, fly breeding and also the potential to transmit pathogenic organisms to man and his environment (Murphy, 1997). Sewage sludge was classified into Type A,B, C and D. Sewage sludge which is unstable with high odour, fly nuisance potential as well as high content of pathogenic organisms was classified as Type A sludge and was followed in increasing order of stability by Type B, C, and D sludge. In this classification, sludge content from pit latrines was not specified but based on the unstable nature, high odour and fly nuisance as well as high content of pathogenic organisms, pit latrine sludge content would have been classified as Type A sludge. This would have subjected sludge from pit latrine to very high restrictions in terms of use and disposal.

The use and disposal of sludge are influenced by, amongst others, the following Acts and guidelines: • The National Water Act (Act 36 of 1998) (NWA) • The Water Act (Act 54 of 1956) (WA) • The Environment Conservation Act (Act 73 of 1989) (ECA) • The Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act 36 of 1947) • The Conservation of Agricultural Resources Act (Act 43 of 1983) (CARA) • The National Health Act (Act 61 of 2003) (HA) • The Water Services Act (Act 108 of 1997) (WSA) • The National Environmental Management Act (Act 107 of 1998) (NEMA) • Minimum Requirements: (Second Edition) 1998 This refers to the Waste Management Series published by Department of Water Affairs and Forestry, which establishes a reference framework of standards for waste management in South Africa in terms of Section 20 of the ECA. This trilogy consists of: - Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste - Minimum Requirements for Waste Disposal by Landfill - Minimum Requirements for Water Monitoring at Waste Management Facilities • Water Use Authorisation and Registration Management System (WARMS). This is a registration system used by DWAF for water uses Source: Guidelines for the Utilisation and Disposal of Wastewater Sludge Vol. 1, 2006

The new classification system of sludge has taken into account three aspects of the sludge; these are:

- Physical characteristics – pH, total solids, volatile solids.

- Chemical quality – nutrients, metals, organic pollutants.

- Microbiological quality – faecal coliforms, helminths ova.

This new system of classification of sludge is aligned to international trends and has resulted in a classification system with three classes for each of the three aspects of the sludge as presented in **Table 2.4.**

Table 2.4: Classification System for Sludge in South Africa (Snyman and Herselman, 2006)

Microbiological class	**A:Unrestricted use**	**B:General use**	**C:Limited use**
Stability class	**1:Stable**	**2:Partially stable**	**3:Unstable**
Pollutant class	**a:Minimal restriction**	**b:Moderate restriction**	**c:High restriction**

If a particular sludge is classified as A1a, this means that the sludge has low content of pathogenic organisms, is relatively stable and has low pollutant contamination and therefore has the least restrictions applied to its usage. A sludge which is heavily contaminated with pathogens, unstable, and heavily contaminated with pollutants would be classified as C3c.

The utilization/ disposal option available for pit latrine sludge content is limited because of the fact that the sludge is highly contaminated with faecal coliforms and helminths ova as well as the unstable nature of the sludge. The existing options that are being considered by the eThekwini Water and Sanitation Services (EWS) for sludge disposal (DWAF, 2007) include:

- The discharge of sludge into main sewers
- The discharge of sludge into sea outfall

- Transport to waste water treatment works
- Burial on site
- Transport to landfill site
- Deep row entrenchment of sludge for agroforestry
- Further dewatering and treatment/ processing to produce agricultural fertilizers

The next sections endeavour to review literature regarding all these options.

2.5.4.1 Deep row entrenchment of sludge for Agroforestry

Although no specific work has been carried out previously to investigate the benefit of direct deep row entrenchment of pit latrine sludge content, researchers at the University of Maryland pioneered the deep row entrenchment of wastewater treatment plant secondary sludge in the early 1980s as a result of an increase in the production of sludge estimated to exceed 1.2 million wet tons per annum, increasing cost of sludge disposal and reduced option for the disposal of sludge (Sikora *et al* 1982).

The deep row entrenchment technique for sludge disposal involves manual or Tractor Loader Backhoe (TLB) excavation of a trench. According to Kays *et al* (1999) trenches are dug 200 m long, 600 mm wide and 1.2 to 1.5 m deep with row spacing of 2.4 to 3 m between centres. The depth of the trench varies depending on the sludge application rate proposed and filled with sludge to within 300 mm of the surface and then backfilled with the overburden heaped after which trees or other vegetation are usually planted in rows parallel to or on top of the trench. Variables to be considered include trench dimensions, spacing, and method of filling (layered with soil or co-composted with vegetable matter), plant species, composition and density of vegetation and end purpose (Kays *et al*, 2007). There is usually no adverse effect on the surrounding groundwater and nutrients are usually recycled as a result of entrenching wastewater treatment plant sludge and planting trees for commercial harvest. Additional benefits include erosion control and creation of wildlife habitat (Buswell, 2006). In 1995, 72 000 m^3 of composted wastewater treatment sludge was used to landscape the Sydney airport (Kelly, 2006).

This technique has also been used in North America and Australia the application of wastewater treatment plant sludge in the plantation forest industries is a well known practice. Surface application of sludge in a study conducted in Australia contributed to 30 % increase in the growth rates of existing pine plantations, while incorporating into the soil prior to planting improved the height of the trees by almost 50 % after 5 years and also the diameter of the tree increased by 85 % without affecting the density of the wood produced (Kelly, 2006). Surface application of sludge is usually associated with unpleasant odours, potential run off into streams and sudden increase in the amount of human and animal pathogens in surface water but studies have shown that deep row entrenchment of wastewater treatment plant sludge for agroforestry prevents the issues related to surface application of sludge (Sikora et al, 1982; Toffey *et al*, 2005).

2.5.4.2 Sludge Burial onsite

Also among the options proposed by eThekwini Municipality for dealing with pit latrine sludge is the burial of sludge evacuated from pit latrines on site. This option seems to be the most economical disposal option. When pit contents are buried, there is a concern that pathogens present in the sludge might have direct contact with the earth and could eventually find their way into surrounding water sources (EWS, 2004). The eThekwini municipality's Health Unit was not in full support of this option because there could be associated risks of this option to public health (DWAF, 2007).

2.5.4.3 Transport to landfill sites

Another option proposed by the eThekwini water and sanitation is the transportation of pit latrines sludge to landfill site. However, there are issues related to transportation of sludge to landfill sites, this issues includes: cost, health risks and also the willingness of landfill operators to accept sludge evacuated from pit latrines (EWS, 2004). There is also a need to stabilize the sludge with lime according to the sludge disposal guidelines before disposal to landfill. For these issues, this option has not considered for the disposal of pit latrine sludge content in eThekwini Municipality.

2.6 Pit Latrine Additives

Manufacturers of various additives indicated that the use of additives has the ability to reduce the volume of pit contents, flies and odour but fail to adequately describe the mechanisms in which these additives accomplish this said function.

A study conducted for WRC by Taljaard *et al* (2003) attempted to evaluate the ability of different commercial microbial or microbial derived products to treat organic waste in pit latrines. The study involved both laboratory scale experiment and field trials. The laboratory scale trial involved comparing the different microbial or microbial derived products by their ability to digest organic material in small scale laboratory trials. The results obtained indicated that some of the products are able to significantly increase the rate of COD removal and TSS removal over those which naturally occur at the applied dosage.

Two of the products that showed effective COD and TSS removal in the laboratory scale experiment were used for the field trials which involved the treatment of pit latrine sludge content. The selected pits were treated with the products over 3 months and also the control pits were treated with same amount of water but without addition of the product. It was noted that there was a significant reduction odour and flies especially from the treated pits.

The study concluded that the use of these microbial derived products for the degradation of organic waste in pit latrine is feasible (Taljaard *et al,* 2003). However Foxon *et al* 2009 proposed that the Taljaard study used application rates many times higher than prescribed application rates and therefore challenged the interpretation of the results.

In another study conducted by Sugden (2006) "*Investigating the potential of bio-additives to prolong the life of pit latrines and septic tanks in emergency situations*", the study involved investigating the efficacy of five bio-additives designed to reduce sludge volumes in pit latrines and septic tanks by enhancing the anaerobic digestion process taking place. Fresh pig faeces were used as a test material. Twenty five litre buckets where used to simulate pit latrine condition and also to facilitate measurement during the study. Holes were drill at the base of the buckets and the bottom of each bucket was filled with 3 litres of alpine grit, to allow liquid to exit the buckets simulating the natural percolation of water through the soil. Each bucket was then placed in 60 litre bucket to collect effluent and protect the inner buckets. Each 60 litre bucket was covered with a lid to minimise intrusion. Each of the 25 litre buckets was then filled with 10 litres of fresh pig faeces. Bio-additives where added according to manufacturers instruction with quantity adjusted to correspond with the small size experimental pits compared to the real pits.

Temperature, pH, sludge and effluent volume were monitored over 31 days subsequent to dosing with bio-additives. The volume of gas produced was estimated from the difference between volume decrease and effluent. Gas production was used as a proxy-indicator for the occurrence of methanogenesis, the final stage of anaerobic digestion.

The study concluded that all the four stages of anaerobic digestion took place in all the buckets but there was no evidence to show that the use of any of the bio-additive either enhanced or inhibited the anaerobic digestion process.

Buckley *et al* (2008) conducted a study to investigate the efficacy of commercial pit latrine additives on VIP latrine sludge content. The study undertook to perform reproducible laboratory scale experiments that would quantify the effect of commercial pit latrine additive products. The laboratory scale experiment involved collecting samples from the surface of the pit just beneath the pedestal. The dosing rates was scaled to the mass (or volume) additive per surface area of the pit. The test was performed in 3 or 5 replicates. Two sets of controls were included; one to which there was no water or additive addition and the other to which only water was added.

The mass of samples were measured, immediately after filling and at intervals of approximately 3 days for between 27 and 46 days after the commencement of the trials. The COD, moisture content and total solids were determined of each sample at beginning and at the end of the experiment. The rate of mass loss, extent of moisture loss extent of COD reduction was calculated.

The study found that:

- Pit latrine additive products when used to treat the sludge contents in pits had no statistically significant effect on the rate of mass loss of pit sludge contents under either aerobic or anaerobic conditions.

- There was no obvious difference in the final moisture content and final COD in the surface of test units between treatments and controls in either of the trials although differences were recorded between the test units.

The study concluded that the use of commercial pit latrine additives to treat pit latrine sludge content was unable to accelerate biodegradation rate and mass loss in the test units.

In the field trial to test efficacy of pit latrine additives presented in Buckley *et al*, (2008) it was also concluded that the use of simple height measurement does not provide accuracy in the measure of the volume reduction in a pit latrine. It was proposed that photographs of the shape of the pile could be used to determine the shape and depth of the pit surface using image analysis software.

2.7 SUMMARY

The provision of adequate sanitation facilities still remains a major challenge in many parts of the world, including South Africa. In the current drive to provide adequate sanitation to all in South Africa, the ventilated improved pit latrine has been identified as the minimum acceptable level of sanitation service. The major challenge faced with the use of ventilated improved pit latrine as described in the literatures reviewed, is finding an appropriate disposal route for the sludge that would be evacuated when the pit becomes full and what could be done, if any, to reduce the rate at which sludge build up within the pit. It was also stated in the literature reviewed that sludge contents from VIP latrines poses significant health and environmental risks because of the organic pollutant compounds and pathogenic microorganisms contained in the sludge. There is also no clear understanding as to what happens to the sludge in the pit over the life span of the pit. Hence, there is an urgent need to put in place necessary strategies for the management of VIP latrines throughout their life cycle of filling and identifying an appropriate disposal route for accumulated sludge when the pit becomes full.

Thus, based on the review conducted, this research work aims to provide better understanding on the strategies and plans that should be in place to adequately maintain VIP latrines in their current basic sanitation program. This would be addressed by:

- Investigating as accurately as possible how fast pits will fill up and how often they will need to be serviced in terms of emptying.
- Providing better understanding of what happen to pit sludge content and composition of pit contents in order to facilitate better management of pit contents during their life span and better handling of pit contents when emptying.
- The information provided based on the composition of pit contents will be used as a background to assess the feasibility of entrenchment of VIP latrine sludge for agroforestry as an option for the disposal of pit contents. This will depend on the inherent ability of the entrenchment process to handle the load of solids and organic material in the sludge, the residual biodegradability of the VIP sludge, and the health risks associated with this disposal option.
- Finally, an investigation would be conducted into the efficacy of pit additives on sludge content in pit latrines through laboratory and field trial. This trial is conducted to justify the discrepancy of the findings presented in the literature.

3 INVESTIGATION INTO SLUDGE ACCUMULATION RATE IN VIP LATRINES

The knowledge of sludge accumulation rates in pit latrines is an important criterion in sizing the pit and could be use to estimate the time frame a pit would be in use before it reaches its capacity. Several factors affecting the rate at which sludge accumulates in a pit latrines have been identified in **chapter 2 (Section 2.3.1.1)**.

There are also several difficulties associated with the determination of sludge accumulation rate in pit latrines as these depend on accurate measurements of changes in pit latrine content and number of users with time. It is very important that the measuring techniques adopted are able to accurately quantify the sludge content in the pit latrine. This is because the sludge surface in pit latrines often has an irregular shape, not level and does not maintain the same shape over time. Thus, reliable measurement of pit latrines content may be difficult to obtain. Various methods which have been used in previous studies to quantify the contents of pit latrines have been discussed in **Chapter 2**.

In instances where the accumulation rate is determined during an emptying exercise, it is very difficult to accurately determine the volume of sludge removed from the pit by counting the number of bins of sludge removed because they are not generally filled to the same degree. If the pit had been previously emptied, there is no way of determining whether some sludge remained and therefore how much of the sludge removed at a subsequent pit emptying had accumulated in the intervening period. Also from a hygiene perspective, the measuring techniques adopted might be potentially hazardous. It is also necessary to have reliable information on the number of pit users. This number cannot be easily defined because this information depends on the numbers provided by the household which may not give a true picture of the people using the pit latrine. However, the number of people using a pit latrine is a major factor that affects the rate at which sludge accumulates in a pit as stated in **Chapter 2**. This also contributes to the type of biological process **(Section 2.3.2)** that would predominate in the pit because if there are a large number of people using a particular pit latrine compared to a pit where fewer number of people make use of the pit, materials at the surface of the pit would be covered much quicker. Thus the residence time in which fresh materials deposited in the pit comes in contact with atmospheric air is reduced. Apart from this, the amount of moisture present or ingress of ground water into the pit could also influence the type of biological process taking place and thus influence the rate in which sludge accumulate in pit latrines (**Table 2.4**). Adequate knowledge of how long the pit has been in use since it was built or previously emptied also affects accurate measurement of sludge accumulation rate in pit latrines. Despite all these difficulties, it is still very important to propose an estimated value of sludge accumulation rate in pit latrines that can be use for sizing the pit and making future plans for maintenance purpose of the sludge that would accumulate over the lifespan of the pit.

This chapter is aimed at interrogating new data on sludge accumulation rates to propose a sludge accumulation rate value that could be used by municipalities and sanitation practitioners when sizing a pit and to give an indication of the extent of degradation of pit sludge content. It was then hypothesised that through the determination of sludge accumulation rate in pit latrines, the extent of biological degradation of materials added to the pit could be estimated. Thus in order to achieve this, the following investigations was conducted:

- Sludge accumulation rate in VIP latrines from low cost housing developments around Durban were determine using two different methods.
- The extent of biological stabilization of sludge within a pit was estimated based on knowledge of the volume of material added to the pit from literature and the overall average sludge accumulation rate obtained from this investigation.
- The role of anaerobic and aerobic digestion process on sludge accumulation rate in pit larine was also investigated.

3.1 DETERMINATION OF SLUDGE ACCUMULATION RATES

This section of the chapter presents the methodological approach used in this study to determine sludge accumulation rates in VIP latrines. In this study, sludge accumulation rates in VIP latrines in low cost housing developments around Durban were investigated. Four different communities were identified; Savana Park, eFolweni, eZimangweni Area 1 and eZimangweni Area 3. These communities were selected to represent a geographic spread of low cost housing within the eThekwini municipality. Well structured questionnaires were administered to each household that owns the VIP latrines and also necessary information was gathered from the pit emptying teams. The questionnaire used is presented in **Appendix A.**

The first method used to determine the rate of sludge accumulation in VIP latrines involved measuring the volume of sludge removed from the pit during the emptying process by estimating the volume of sludge removed in bins. This method was used because VIP latrines that were investigated within these communities (eZimangweni area 1 and 3) were in the process of being emptied. Pit latrines in these two communities were emptied manually and the sludge removed was loaded into bins. It was then assumed that the volume of sludge removed per bin load was constant, hence estimates of the volume of sludge in a filled bin and the number of bins of sludge removed from each pit were used to calculate the volume of sludge removed from each VIP latrines. The volume of sludge removed from each pit was thus calculated as the number of bins multiplied by the estimated volume of sludge in the bin.

In order to determine the volume of sludge removed from each pit within these two communities, the number of bins of sludge removed from the pit during the emptying process was noted and the dimension of the bin was measured when full and also when empty. It was found that the volume of sludge removed per bin was approximately 0.085 m^3 (85 ℓ). The accumulation rate of sludge was then calculated from **Equation 2.1** presented in **Chapter 2** which is given as:

$$R = \frac{V_S}{n \cdot t} \qquad \textbf{[3.1]}$$

Where,

R = the sludge accumulation rate,

n = the number of people in the household and

t = the time from when the pit was last emptied or time when the pit was built.

The second method used involved estimating the sludge volume as the difference between pit design volume and the remaining empty volume of a pit. This method was because VIP latrines in these communities (Savana park and eFolweni community) were still in use and were not due for emptying. In order to determine the sludge volume (V_S) in the pit at each time of measurement, the dimensions of the most common type of VIP latrine in these communities were obtained and were used to determine the volume of a full pit. The height of sludge in the pit was therefore the difference between the total pit depth h_f and the vertical distance h_s measured from the pedestal to the sludge surface using an infrared laser distance measure. Three different measurements were taken from the pedestal to the sludge surface in the pit at different point, namely; left, right and midpoint on the sludge surface. This was done because of the uneven nature of the sludge surface in pit latrines. The three points were averaged and used as the vertical distance h_s. The volume of sludge in the VIP latrine at the time in which measurement was taken was calculated using **Equation 3.2:**

$$V_S = (h_f - h_s) \cdot A \qquad \textbf{[3.2]}$$

Where,

h_f = the estimated total pit depth

h_s = the vertical distance measured from the pedestal to the sludge surface in the pit at the time of measurement and

A = the cross sectional (surface) area of the pit.

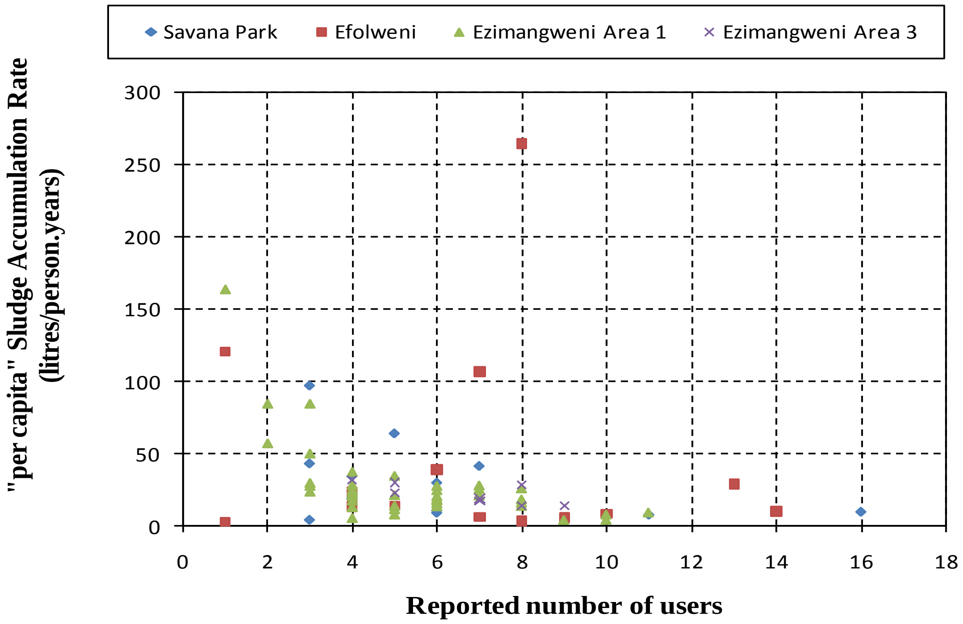
Thus the sludge accumulation rate was also calculated using **Equation 3.1.**

3.2 OBSERVED SLUDGE ACCUMULATION RATE

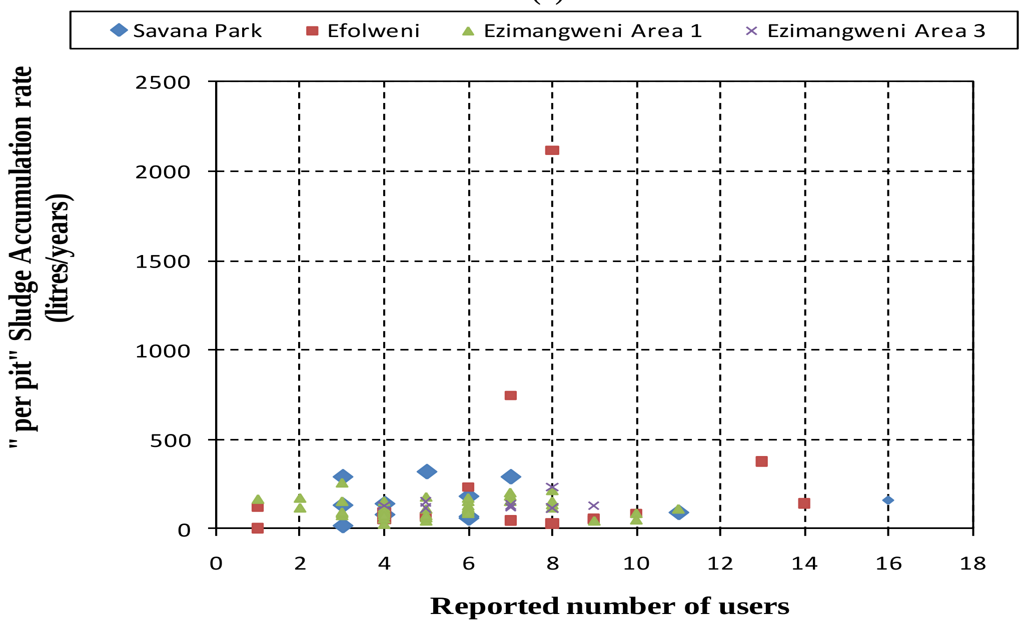
The sludge accumulation rates in the VIP latrines investigated were calculated on two bases:

- As volume of sludge accumulated in the VIP latrine per person per year, and
- As volume of sludge accumulated in the VIP latrine per year.

Figure 3.1 presents the scatter plot of the results obtained from the determination of sludge accumulation rates within the four communities where this study was conducted. The results are plotted as sludge accumulation rate/person·year as a function of number of users and sludge accumulation rate/year as a function of number of users. This is done to present the apparent effect the number of pit latrine users as on sludge accumulation rate in pit latrines.



(a)



(b)

Figure 3.1: Scatter plot for observed sludge accumulation rate with number of users for the four communities.

The result obtained in this study supports the findings of Still *et al* (2010). It was found that for all the communities investigated in this study, the sludge accumulation rate (on a per person per year basis) was negatively correlated to the number of users as shown **Figure 3.1(a).** This suggests that there is statistically significant relationship between sludge accumulation rates in pit latrines and number of users i.e. sludge accumulation rate in pits investigated decreases with an increase in the number of users.

A summary of the sludge accumulation rate results obtained from the four communities is presented in **Table 3.1**. The sludge accumulation rate is calculated as litres per person per year ± 95 % confidence interval on the mean.

Table 3.1: **Pit sludge accumulation rates from four communities located near Durban, sludge accumulation rates are calculated as ℓ/ person.year ± 95% confidence interval on the mean**

Location	No of pits	Average No of Users	Accumulation Rate (ℓ/ person.year)
Savana Park	12	6.2	31 ± 21
eFolweni	15	7	44 ± 46
eZimangweni 1	40	6.6	28 ± 10
eZimangweni 3	8	5.4	22 ± 7

Clearly there is a significant amount of variation between sludge accumulation rates as evidenced by the large confidence intervals. There is also a significant amount of uncertainty in the measurements, particularly those taken in Savana Park and eFolweni, where pit volumes had to be determined using an estimate of pit depth. Sludge accumulation rate data obtained from eFolweni was considered to be the most unreliable due to uncertainties in the pit volume estimates. The sludge accumulation rate data obtained from eFolweni followed the same general trend as the other areas, but gave extreme values (e.g. 7 and 260 ℓ/person·year) which were considered unlikely. There were no statistically significant differences between results obtained from the remaining three areas.

The average accumulation rate for pit latrine sludge in communities served with VIP latrines were between 22 and 44 ℓ/person·year. An overall average sludge accumulation rate of 31 ± 10 ℓ/person·year was obtained for all the four communities in which a total number of 76 pit were investigated. The values obtained in this study are within the range of values presented in literature (**Table 2.3**).

The significance of this findings from the investigation conducted to determine sludge accumulation rate in pit latrines from the selected communities are as follows:

- The sludge accumulation rate data obtain in this study without considering the data obtained from the eFolweni community suggests that 40 ℓ/person·year could be a good figure for sizing new pit latrines, however sludge accumulation rate values of up to 60 ℓ/person·year could be considered and when planning for large scale pit emptying programmes higher sludge accumulation rate value could be taken into consideration.

- As presented in **Section 2.3.1.1**, an individual produces approximately 110 ℓ/person·year of faeces and 440 ℓ/person·year of urine. Added to this volume is anal cleansing material and if municipalities do not provide reliable solid waste collection, the pit is seldom used for disposal of household refuse. if it is assumed that the estimated volume of material added to the pit latrines investigated is 600 ℓ/person·year, then the sludge accumulation rate value (31 ℓ/person·year) obtained in this study suggests that only approximately 5 % of the materials added to the pit per person per year accumulates while the remaining 95 % of the material added either decomposes or leached out as liquid from the pit. It is only the liquid that is expected to leach out from the pit and the solid material is expected to decompose. Thus, out of the 600 ℓ/person·year of material added to the pit, approximately 160 ℓ/person·year is said to be solid materials and the remaining 440 ℓ/person·year is liquid. Therefore, only 1 % of the 5 % accumulated material is solid. Hence, without even investigating the processes in the pit and sludge characteristics in the pit it is clearly shown that significant stabilization of materials added to the pit must have occurred. This supports the motivating hypothesis of this research work presented in Chapter 1.

- The findings of this investigation conducted also suggest that treatment of pit latrine sludge as though the sludge were fresh sanitation waste is not appropriate because significant stabilization of the waste must have occurred within the pit.

3.3 Role of Anaerobic/Aerobic Digestion on Sludge Accumulation Rate

If sludge accumulation in pit latrine does decrease with increasing number of users as presented in **Figure 3.1(a)**, it could be hypothesized that at higher user rates, the more rapidly the material within the pit is covered with fresh faeces, the earlier the establishment of anaerobic conditions and thus sludge accumulation rate within the pit latrine becomes slightly slower. The hypothesis is based on the theory of aerobic and anaerobic digestion biomass yield. A brief description of these two digestion processes has been presented in **Chapter 2** of this thesis. Buckley *et al* (2008) indicated that about 80 % of organic material in faeces that is deposited in a pit latrine is biodegradable and that 30 % of the dry mass of faeces is made up of bacteria while between 75 % and 80 % of the mass of faeces is moisture. The biodegradable organics in the pit degrade with time; certain dissolved components are leached out of the pit while non biodegradable components such as rubbish deposited in the pit remain unchanged. Pit latrine sludge degrades mainly in the absence of oxygen (anaerobic degradation), however near the surface of the pit there is a small layer were aerobic activity occurs.

During aerobic digestion which is in the presence of oxygen the biomass yield is relatively higher as compared to anaerobic digestion that occurs in the absence of oxygen. About 50 to 70 % of the organics consumed during aerobic digestion is converted to biomass whereas in anaerobic digestion only a small portion of the organics which is about 5 to 10 % of the organic is converted to biomass (Speece, 1996; Henze *et al,* 1997 and Buckley *et a*l 2008). **Figure 3.2** presents a visualization of how the different biological process occurring within the pit might influence sludge accumulation rate.

In order to illustrate the concept presented in **Figure 3.2,** it was assumed that the composition of the material added to the pit is comprised mainly of organic biodegradable material, organic unbiodegradable material, inorganic material and naturally occurring faecal micro-organisms. Thus, during aerobic digestion of the material in the pit latrine, the available organic biodegradable material is consumed by bacteria and other micro-organism present in the pit resulting in the production of more biomass and carbon dioxide.

However during anaerobic digestion available organic biodegradable material is also consumed by bacterial in the pits resulting also in the production of biomass but methane gas instead of carbon dioxide. Therefore, if it is assumed that there is no loss of inorganic material and organic unbiodegradable material out of the pit by leaching, then as shown in **Figure 3.2**, the amount of solid material that would remain in the pit (water free basis) when all biodegradable material is broken down is about 26 % for aerobic digestion and about 21 % for anaerobic degradation (using the assumed feed and degradation ratios).

Although aerobic digestion is a much faster process, it results into more biomass yield and as such accumulation of sludge may be greater compared to anaerobic digestion. However, only a portion of the pit sludge will undergo aerobic digestion. Therefore a pit latrine must be described by a combination of these two effects with a net accumulation value somewhere between the two values presented. This suggests that different ratios of aerobic and/or anaerobic process will result in accumulation values that are indistinguishable from one another.

Also the amount of non-degradable material (e.g. household refuse) would influence greatly on the biological activity taking place within the pit as well as the amount of solid material that would remain in the pit and the rate at which sludge would build up within the pit.

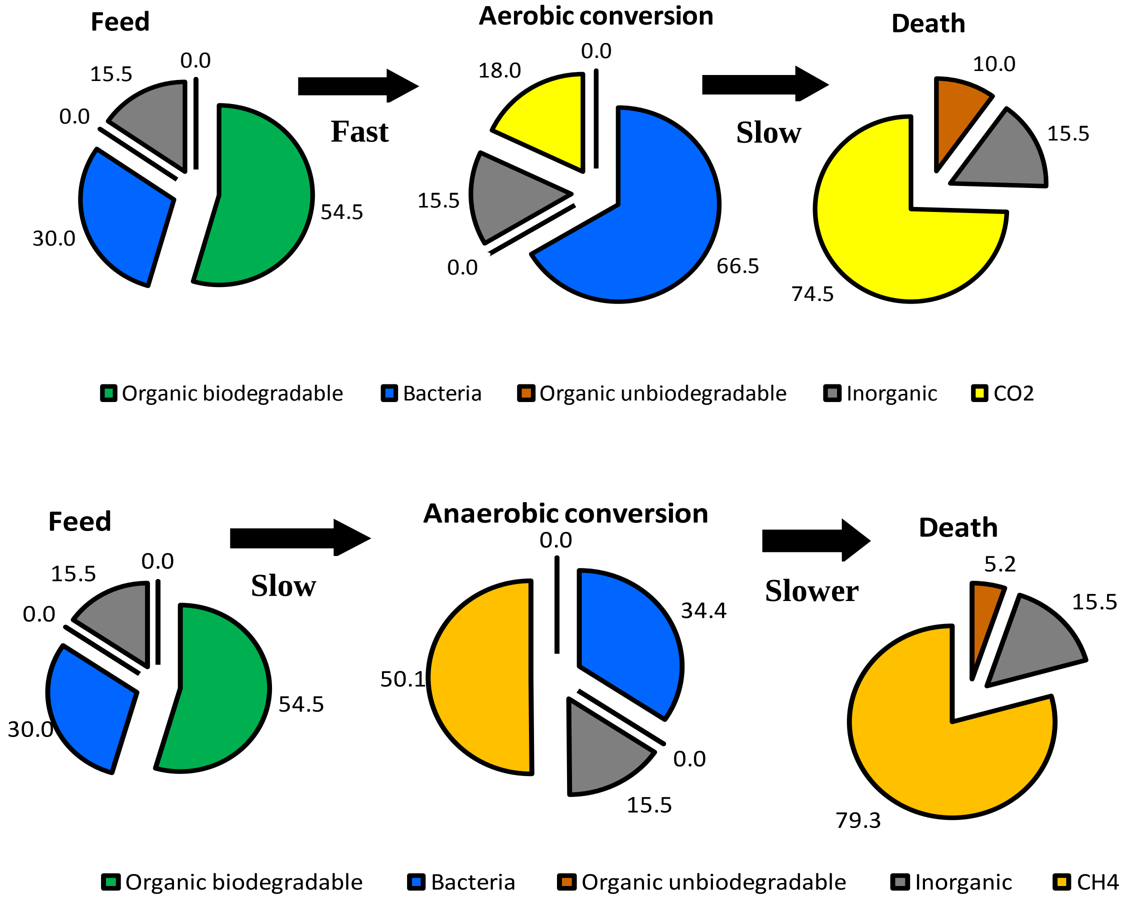


Figure 3.2: Degradation of pit latrine sludge content with time showing aerobic conversion and anaerobic conversion process.

Thus in order to test the hypothesis presented earlier that at higher user rates, the more rapidly the material within the pit is covered with fresh faeces, the earlier the establishment of anaerobic conditions and thus sludge accumulation rate within the pit latrine slightly becomes slower, a laboratory scale experiment that will assess the long term effect of aerobic and anaerobic conditions on sludge degradation is required. Since it has been documented (Franceys *et al*, 1992) that in pit latrines with extreme wet conditions, greater degree of anaerobic digestion occurs and as such a lower net sludge accumulation rate is observed.

The reason could be that the sludge content in the pit will possibly settle with a layer of liquid above it, lowering and/or hindering oxygen contact with the sludge thereby creating anaerobic conditions. Thus the laboratory experiment was designed to quantify the cumulative mass loss for a series of pit sludge jar tests at different moisture content over a long time. Sludge sample from the surface layer of a pit latrine were collected and the moisture content was determined. A representative aliquot sample of known mass from the collected pit latrine sludge sample was placed in twenty different jars. These jars were separated into four groups which had the moisture content raised from 78 % to 91 % by adding a calculated amount of water using **Equation 3.4**. The sludge samples were collected from the surface layer of the pit latrine.

$$\% = \frac{gH_2O_{initial} + mH_2O_{added}}{gSample + mH_2O_{added}} \qquad \textbf{[3.4]}$$

$$gH_2O_{initial} = Initial\ moisture\ content\ of\ \ pit\ sludge \times g\ Sample$$

For each moisture level, five replicates were prepared and the twenty jars were kept in a slightly humidified fume cupboard and incubated for 230 days. The initial mass of all jars containing the sludge samples at different moisture level was recorded after which the mass of each jar was measured on a weekly basis throughout the duration of the experiment. It was expected that the rate of mass loss would decrease with increasing moisture content because in sludge samples with higher moisture content a free liquid surface existed and therefore the predominant digestion taking place was anaerobic digestion which is a slower process compared to aerobic digestion process. However if the hypothesis of lower accumulation rate with anaerobic digestion is valid, then the final mass loss from high moisture level samples should be greater than for lower moisture level samples. The plot of the cumulative mass loss for the pit sludge jar test at different moisture content is presented in **Figure 3.3**.

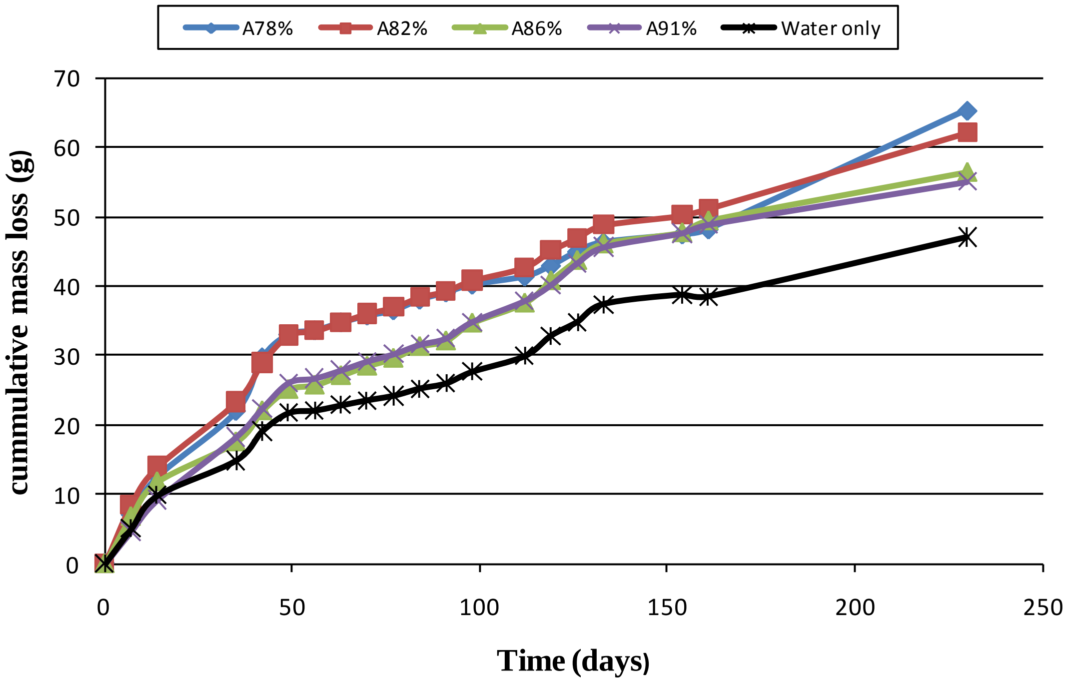


Figure 3.3: Cumulative mass loss of pit latrine sludge jar test at different moisture content over the entire duration of the experiment.

As presented in **Figure 3.3,** the hypothesis presented is not supported because at this stage the final mass loss from lower moisture level samples is found to be greater compared to higher moisture level samples. This suggests is that it will take a significant period of time before we could make any conclusions since anaerobic digestion occurs at a very slow rate. Thus for comparison of the effect of each moisture level on mass loss rate it is important to normalize the cumulative mass loss for the mass of sludge and water added to each honey jars. Therefore if assumed that water loss from all jars due to evaporation is the same, Then the normalized cumulative mass loss per day for the entire duration of the experiment is calculated using **Equation 3.5** for each honey jar (five for each moisture level) and the average is calculated and plotted with respect to the different moisture level.

$$Normalized\ Cum.mass\,loss\ rate = \frac{\left(final\ cum.mass\,loss - average\,moisture\,loss\right)}{starting\ mass\,of\ sludge} \quad \textbf{[3.5]}$$

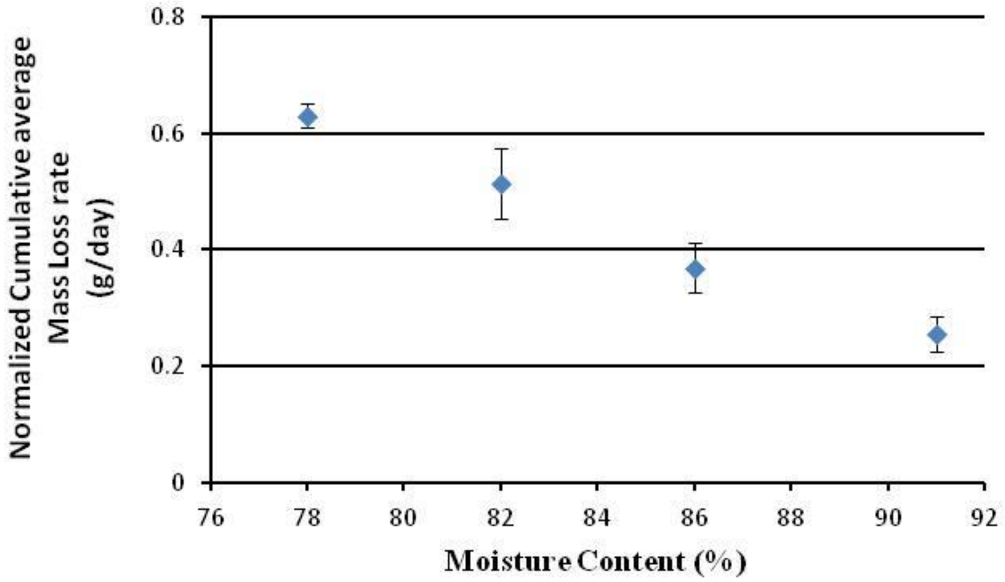


Figure 3.4: Normalized cumulative mass loss rate to show the significant effect of increasing moisture content on mass loss rate of pit latrine sludge content. Error bars represent standard deviation on the mean.

Thus, the plot presented in **Figure 3.4** indicates that by increasing the moisture content the rate of degradation of sludge samples decreases. This suggests that sludge samples with high moisture content might have undergone a greater degree of anaerobic digestion when compared to sludge samples with lower moisture content because during anaerobic condition the rate of degradation is usually slower. Thus, if the experiment were to have continued until the mass stops changing, the end mass of the sludge samples with high moisture content may be lower because the residual amount of non-degradable solids produced during anaerobic digestion is usually smaller.

The outcome of this experiment could suggest the possibility of a decrease in sludge accumulation rate with increasing number of user if the condition within the pit is predominantly anaerobic.

3.4 SUMMARY

In this chapter, sludge accumulation rate in Ventilated Improved Pit latrines in low cost housing developments within Durban were investigated. The overall average sludge accumulation rate obtained for all the communities investigated was found to be 31 ± 10 ℓ/person·year. A total number of 76 pit latrines was investigated. The findings of this investigation suggests that:

- Sludge accumulation rate of 40 ℓ/person·year is a could figure to work with when sizing new pit latrines in conditions similar to Durban South Africa and figures of up to 60 ℓ/person·year are not unusual however, when planning for large scale pit emptying programmes higher figures could be considered in order to prevent the pit from becoming unusable before emptying.

- Based on the estimated volumes of material added to a pit as presented **Section 2.3.1.1,** only approximately 5 % of the materials added to the pit per annum eventually accumulates as sludge and out of this 5 % only 1 % is solid material. This suggests that significant stabilization of added solid materials within the a pit do occur over time. This confirms the motivating hypothesis of this research work presented in Chapter 1

- Since significant stabilization do occur within the pit, treatment of pit latrine sludge content as though they were fresh sanitation waste is not appropriate.

- A combination of both aerobic and anaerobic digestion process do occur in pit latrines, however if the predominant process is anaerobic, the rate at which sludge would accumulate within the pit might be slower compare to aerobic conditions.

4 CHARACTERIZATION OF SLUDGE CONTENTS IN A VIP LATRINE

It is very important to have an understanding of the physical, biological and chemical characteristics of the sludge content in a pit because this will provide relevant information as to which disposal option is applicable and the health and environmental risks associated with handling and disposal of VIP latrine sludge.

Ventilated improved pit latrine sludge content is heterogeneous in nature because of the wide range of material that could be found in a pit as described in **Chapter 2 (section 2.2)**. Thus obtaining a representative sample to describe the sludge content in a pit is usually very difficult. The type of material found in a pit depends largely on what is added by the householders and therefore the characteristics of the sludge in one pit cannot be taken to be the same as in another pit.

The findings from **Chapter 3** have clearly shown that significant stabilization of pit latrine sludge content do occur within the pit, however this **Chapter** aim to investigate the processes within pit latrines through laboratory characterization of pit sludge content at specific location within the pit in order to understand the nature of the material that is in a pit and thus be able to propose suitable disposal options for accumulated sludge when the pit becomes full.

According to the theory proposed by Buckley *et al* (2008) in **Chapter 2(section 2.2)**, it is expected that the material (mainly faeces and urine) added to pit latrines should undergo rapid degradation under aerobic conditions until it is covered over. Thereafter anaerobic degradation occurs until all biodegradable material in the pit is stabilized. The implication of the proposed theory by Buckley *et al* (2008) is that when sludge samples are collected from these four different layers within any pit latrine, the residual biodegradable solid as a fraction of total solids should decrease for samples collected from the surface layer (i) through to layer (iii) and should remain fairly constant in layer (iv). This would result in decreases in chemical oxygen demand (COD), volatile solids (VS) and biodegradability of pit latrine sludge content as a function of total solids as one digs from the surface layer down to the bottom layer of the pit. The general expected trend for the decrease of the residual biodegradable solid as a fraction of total solids is as shown in **Figure 4.1.** It should also be noted that depending on the household habits and local environmental conditions, and the history of these factors, the sludge content within a pit will vary considerably in its moisture content, organic content, non-biodegradable content and microbial population with time within a pit and when compared with another pit. This theory applies when there is relatively little movement of material in the pit after original addition, such that the age of the material in the pit (amount of time since it was deposited) increases with increasing depth and is therefore probably limited to relatively dry pits (no free liquid surface).

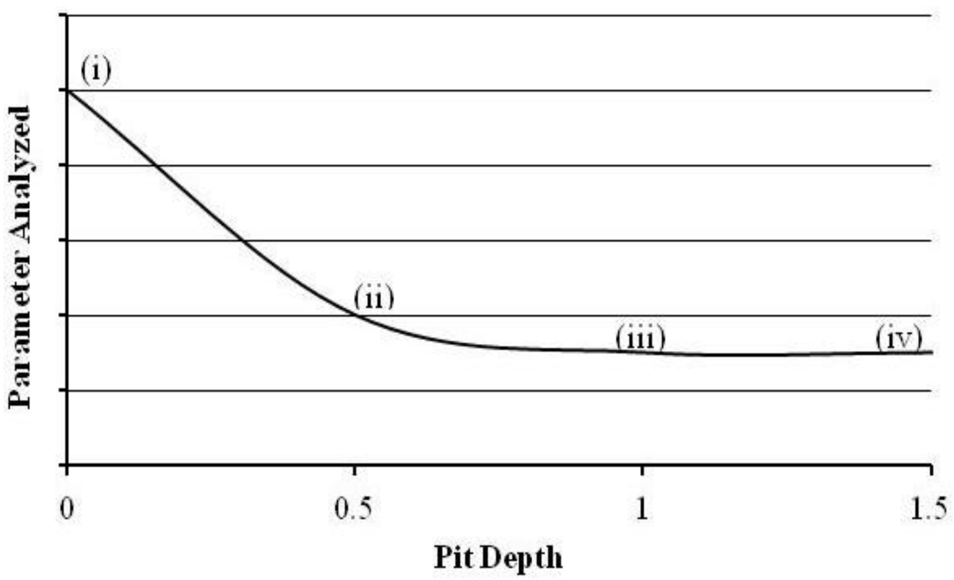


Figure 4.1: Expected trend for the decrease of the residual biodegradable solid as a fraction of total solids from the surface layer of the pit down to the bottom of the pit.

Pit latrine sludge from randomly selected twenty VIP latrines within the eThekwini Municipality was collected and analyzed for moisture content, total and volatile solids, chemical oxygen demand, and aerobic biodegradability. Sludge samples were collected from four specific locations within each pit investigated. The aim was to investigate the variation in the characteristics of VIP latrine sludge from one pit to another and also the degree of stabilization or variation of sludge content with increasing depth in the pits. Two different approaches were used in order to achieve these set aims; these are:

- A well structured questionnaire was distributed to each household during the sampling process. This was a primary method used in the course of this investigation to gain information about the users of each pit and the state or condition of the pits investigated.
- Laboratory characterization of samples collected.

4.1 PIT INVESTIGATIONS AND SAMPLING TECHNIQUES

A questionnaire was administered to 20 households, the household-owned pit latrines. All respondents were informed of the objective of the study in both English and isiZulu. The survey was conducted anonymously and all participants were allowed to check the completed questionnaire answer sheet for anonymity. The questionnaire is presented in **Appendix A.**

Sludge samples were collected from all the pit latrines at different depths and the samples subjected to a series of analyses. The pit latrines sampled all qualified as ventilated improved pit latrines with concrete slab, enclosed superstructure, and a tall vent pipe equipped with a fly screen. The pit latrines were all located within eThekwini municipality in the east coast of KwaZulu-Natal, and samples were obtained during a routine pit latrine emptying programme undertaken by the municipality. All pits were between 75% and 100% full. Before the pits were emptied, the distance between the pedestal and the top of the pit contents was measured using an infra-red laser meter and at the end of the emptying process, the distance between the pedestal and the bottom of the pit and cross-sectional area were measured in the same way.

All the pits investigated were emptied manually using a shovel, long handle forks, buckets and skips by professional pit emptier contracted to the pit emptying team. In most instances, this required that workers climbed into the pit to access the lower reaches of the pit. Pit contents were collected in 200ℓ refuse bins equipped with wheels, which were eventually removed by a utility vehicle. For the purposes of this study, samples were taken at different levels of the sludge pile while the pit was being emptied, collected in plastic bags, which were individually packed into sealed plastic containers, which were then placed in a large refuse bag to maintain three levels of containment of the sample and to limit sample exposure to air. The location from which samples were collected within each pits are specified as follows:

- Top level sample: the sludge was collected from the surface of the pit beneath the pedestal
- 0.5 m depth sample: the sludge was collected after the top 0.5 m of the pit content had been emptied by the pit emptying contractors.
- 1 m depth sample: the sludge was collected after of 1 m of the pit sludge had been emptied.
- Bottom level sample: the sludge was collected at the very bottom of the pit from the last bucket removed from the pit.

The samples was transported to the laboratory and stored in the cold room at 4°C before laboratory characterization was undertaken. The time between sampling and analysis was less than 2 days.

4.2 LABORATORY CHARACTERIZATION TECHNIQUES

The laboratory characterization performed on the collected samples involved a number of chemical and biological analyses which included:

- Moisture content
- Solids characterization (Total and Volatile)
- Chemical oxygen demand (COD) and
- Aerobic biodegradability tests.

Standard methods (APHA, 1998) were used to analyse the sludge samples where applicable and where no appropriate method was published, adaptations of existing methods were used or entirely new methods were developed. Only 16 of the 20 pits were analyzed because the labels on samples from 4 pit latrines were moistened and could not be identified which layer the samples were taken from. A brief description of each method presenting the significance of each method is given in the following sections. A detailed description of each method is presented in **Appendix B.**

4.2.1 Moisture Content Analysis

The moisture content of all the samples collected was determined by drying to constant weight at 105°C in an oven according to the Standard methods (APHA, 1998). The analysis for the moisture content in each of the samples was carried out for comparison with the sample biodegradability. Each sample was analyzed in triplicate.

4.2.2 Solids Characterizations

Total solids and Volatile solids measurements were carried out on each sample collected from the pit latrines by drying to constant weight at 105°C and then igniting at 550°C according to the Standard methods (APHA, 1998).

The total solid analysis was carried out as an intermediate step in determining the amount of organic solids (volatile solids). A total solid is the amount of dry solid per mass of wet sample. It is often useful to present the results of other analyses (e.g. COD) on a dry basis in order to eliminate variation in the COD of the samples caused by the dilution effect of different sample moisture contents. The volatile solids serves as a measure of the organic solids present in each sample analyzed.

4.2.3 Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is the amount of oxygen required to oxidize the organic matter in a sample. It is measured by the oxidation of the representative sample by potassium dichromate in an acid solution producing carbon dioxide, water and ammonia. The value of chemical oxygen demand is always higher than biochemical oxygen demand because many organic substances can be oxidized chemically but are recalcitrant to biological oxidation. Since COD is a conserved species and the analysis for COD is fairly quick and is reproducible, COD was preferred for the measurement of the oxidizable organic matter present in the sludge sample. The open reflux method for particulate samples was used to carry out the COD analysis according to standard methods (APHA, 1998).

4.2.4 Aerobic Biodegradability

Aerobic biodegradability test were carried out in order to obtain estimates of the relative biodegradability (g biodegradable COD/gCOD) of each sample. The method used was developed within the project and was based on an adaptation from existing methods. The principle of the method is that vigorous aeration of sludge samples for an extended period (8 days) will result in biological oxidation of all the organic material in the sludge sample that is inherently biologically oxidizable. Thus the difference in COD content before and after aeration is the biodegradable COD of the sample. The detail of this method is given in **Appendix B**.

4.3 RESULTS OF CHARACTERIZATION OF PIT SLUDGE CONTENT

This section presents responses to the questionnaire distributed and the results from the laboratory characterization.

4.3.1 Results based on questionnaire distributed

The questionnaire distributed to each household provided valuable information on user habits and the condition of the pits. A total of twenty questionnaires were distributed, one for each pit in which samples were collected. The reported number of people in each household ranged from 7 to 30 and the pit depth after emptying ranges from 1.5 to 2 m. All pits had been in operation for more than 10 years and only 3 of the pits investigated had been previously emptied. Pit 1 was emptied 5 years earlier and pit 6 was emptied 9 years earlier while pit 11 was partially emptied 9 years earlier. All households except for pit 6 had been making use of the pit without the addition of additives or other substances to control pit filling rate, while the users of pit 6 had added a dilute solution of Jeyes Fluid (a low cost disinfectant, containing a substance named carbolic acid) to control odour and macro-invertebrates. All pits investigated except for pit 7 were full but all pits were still in use (pit contents had reached the level of the bottom of the pedestal). A general observation during the emptying exercise was that a wide range of materials other than faecal and anal cleansing material were found in the pit. This confirms that households make use of the pit for the disposal of solid material. When owners of the pit were questioned as to why they dispose solid waste into the pit, the general response was that the pit serves as the only practical and safe place to dispose hazardous materials such as disposable nappies, broken glass or sharp metals, sanitary pads, or materials which could not be easily burned. **Figure 4.2** presents the rubbish removed from a pit during emptying after the rest of the sludge content had been washed through a screen into the sewer.

Figure 4.2: Material found in a pit during emptying.

4.3.2 Laboratory characterization results

This section presents the result obtained from the laboratory characterization of pit latrine sludge content collected at different depth for 16 pit latrines. The overall averages are presented in **Table 4.1.**

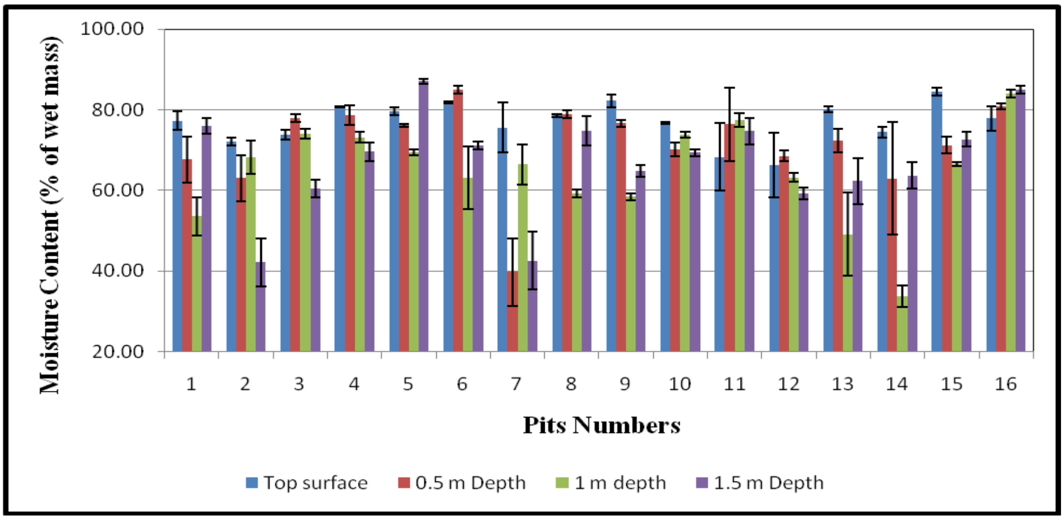
Moisture content characterization results

The moisture content characterization results are presented in **Figure 4.3**. In most of the pit latrines, the moisture content showed a general decrease with increasing depth

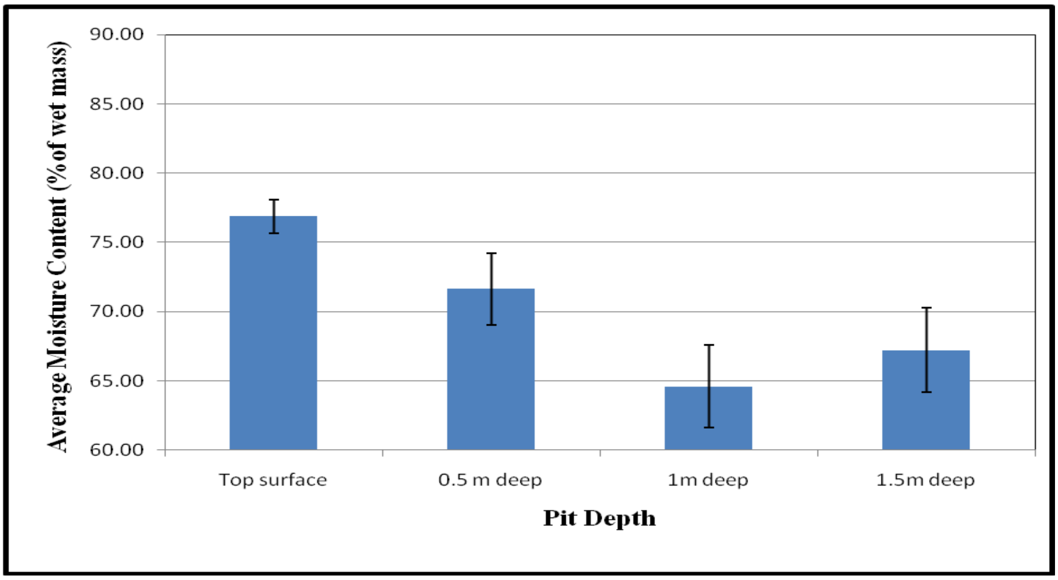
Figure 4.3(a). This suggests that most of the pit latrines investigated were located in areas where most of the pit volume was above the level where free ground water can be found at the time that the pit were sampled. This implies that there was a net movement of water out of the pit.

A Pearson correlation test was performed which confirms that there was a significant decrease in moisture content with increasing depth (P= 0.05). The average total moisture content within each pit analyzed was about 60%, this falls within the range reported in literatures (50 – 60 % of the total weight) to be adequate for microbial activity (Peavy *et al*, 1985; EPA, 1995). Hence, biological activity in most of the pits would not have ceased due to low moisture content.

The general trend in the moisture content results for all pits was a decrease from the surface to 1m depth and little to no further change from 1 m to 1.5 m. An atypical result was observed for pit 16 were there was a gradual increase in the moisture content of the material in the pit from the surface of the pit to the bottom of the pit. This suggests that there might be water ingress from somewhere else, which may be from ground water or a leaking tap nearby. On average the mean moisture content at the surface layer of the pit was found to be 77 % and at the bottom layer it was found to be 67 % as shown in **Figure 4.3(b)**. In eight of the pit latrines investigated, the moisture content at the bottom layer was substantially higher than the moisture content of the 1 m depth sludge samples. These pit latrines may have been located such that the water table was higher than the bottom of the pit.



(a)

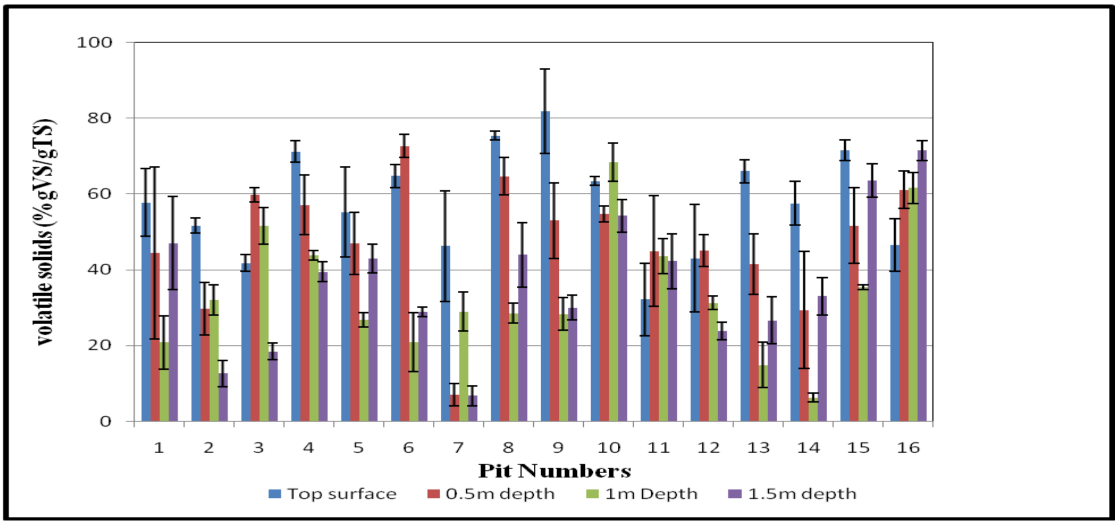


(b)

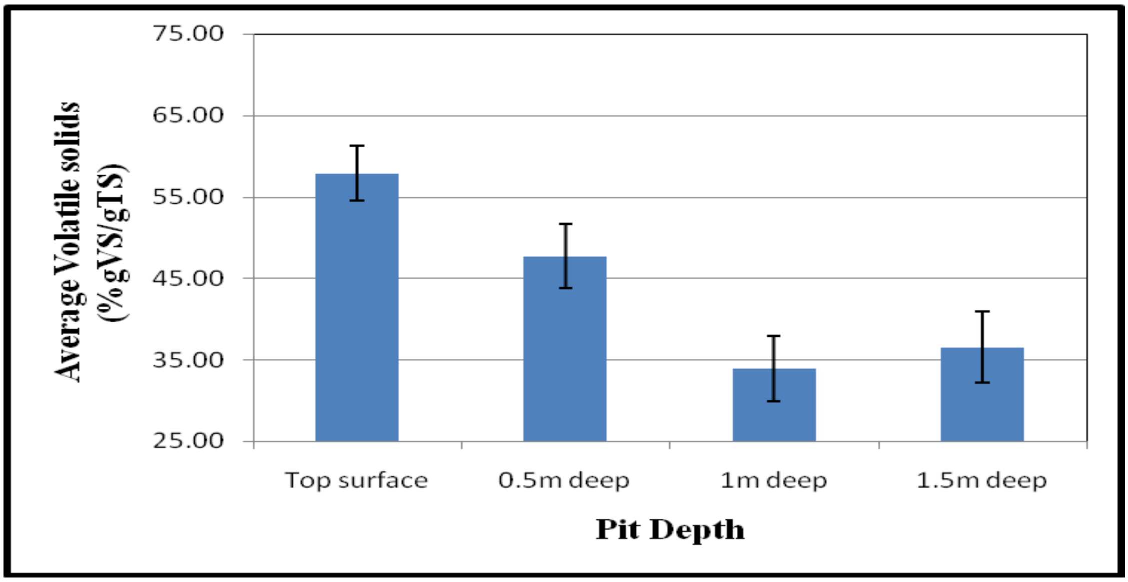
Figure 4.3: Moisture content characterization results (a) for each of the 16 pits from different layers within each pit (b) average moisture content at each layer for the 16 pits. Error bars represent 95 % confidence on the mean value of each layer.

Volatile solid characterization results

The results obtained for the volatile solid characterization is presented in **Figure 4.4.**



(a)



(b)

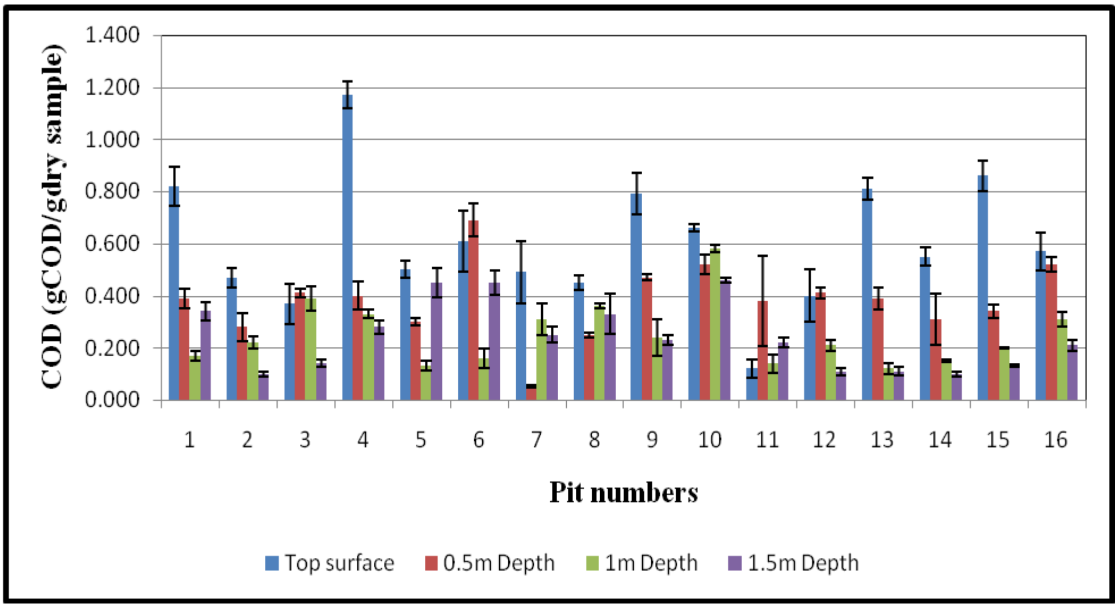
Figure 4.4: **Volatile solid characterization results (a) for each of the 16 pits from different layers within each pit (b) average volatile solids at each layer for the 16 pits. Error bars represent 95% confidence interval on the mean value of each layer.**

The most important feature observed from the results obtained from the volatile solid characterization as shown in **Figure 4.4(a)** is that, for each of the 16 pits investigated the volatile solid as proportion of total solids decreases although not in a regular manner with increasing depth down the pit. This trend is reversed in pit 16, although this apparent upward trend in volatile solid fraction is not statistically significant. **Figure 4.4 (b)** shows a decreasing trend in the average volatile solid as proportion of total solids of the 16 pits top surface to the bottom layer of the pit. These suggest that the degree of stabilization in the pit increases from the top surface to the bottom layer of the pit leaving mostly non- volatile (ash-like) components. Also none of the 16 pit analyzed had the same volatile solids composition.

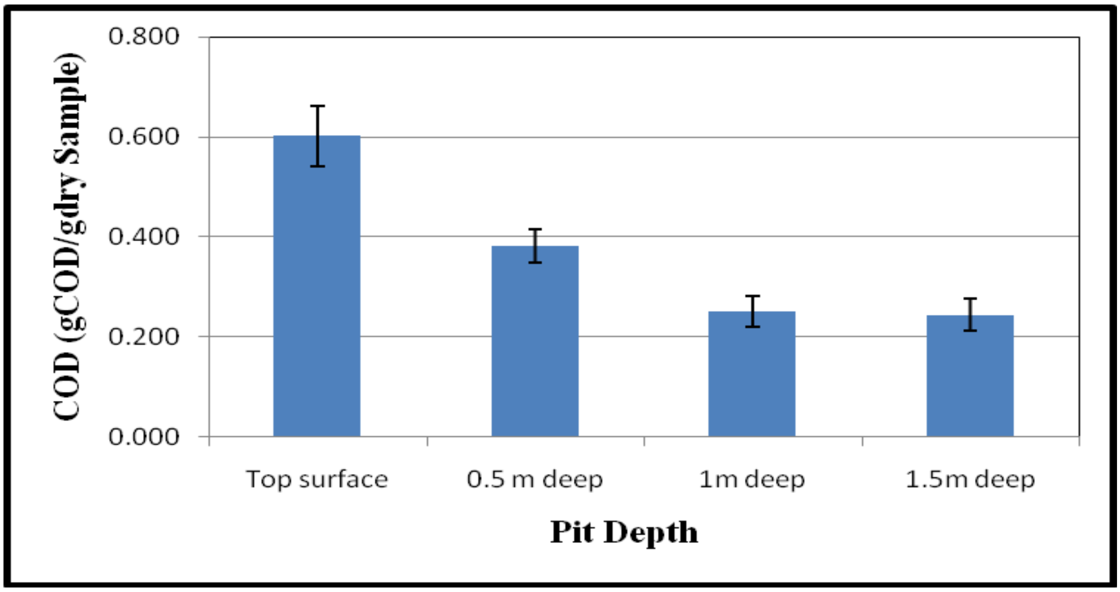
A Pearson correlation test was performed to quantify the relationship between volatile solids as a proportion of total solids and different layer from which samples were collected within the pit. The test confirms that there was a significant decrease in the volatile solids with increasing depth (P= 0.05). Univariate analysis of variance was also performed using SPSS15 with a post-hoc Scheffe test to compare mean values of volatile solids of the different samples collected at different depth. It was found that there was significant difference between the top layer, 0.5 m depth and 1 m depth in volatile solids between all samples collected from this different depth, but for 1m depth and the bottom layer (1.5m depth) there was no significant difference. The Volatile solid result obtained in this study supports the Buckley *et al* (2008) proposed theory as the trend observed in **Figure 4.4(b)** is very similar to that presented in **Figure 4.2.**

Chemical oxygen demand characterization results

Chemical Oxygen Demand is a measure of the oxidizable organic matter present in samples. Comparatively, COD analyses can be used as an indication of the degree of degradation which materials present in the pit have undergone. **Figure 4.5** presents the chemical oxygen demand characterization result obtained for the sixteen VIP latrines sludge collected.



(a)



(b)

Figure 4.5: **Total COD characterization results (a) for each of the 16 pits from different layers within each pit (b) average COD at each layer for the 16 pits. Error bars represent 95% confidence interval on the mean value of each layer.**

As shown in **Figure 4.5(a)**, it is observed that the COD concentration (on a dry basis) at the surface of all the pits analyzed is significantly higher when compared to the bottom layer of the pits (except for pit 5 and 11 which have almost the same bottom sample value for pit 5 and greater value for pit 11). **Figure 4.5(b)** presents average COD value per layer for the 16 pits. It is observed that the COD concentration on a dry basis (gCOD/g dry sample) follows a decreasing trend from the surface layer of the pit down to the bottom layer of the pit. This implies that below the surface layer in a pit some additional degradation/stabilization does occur.

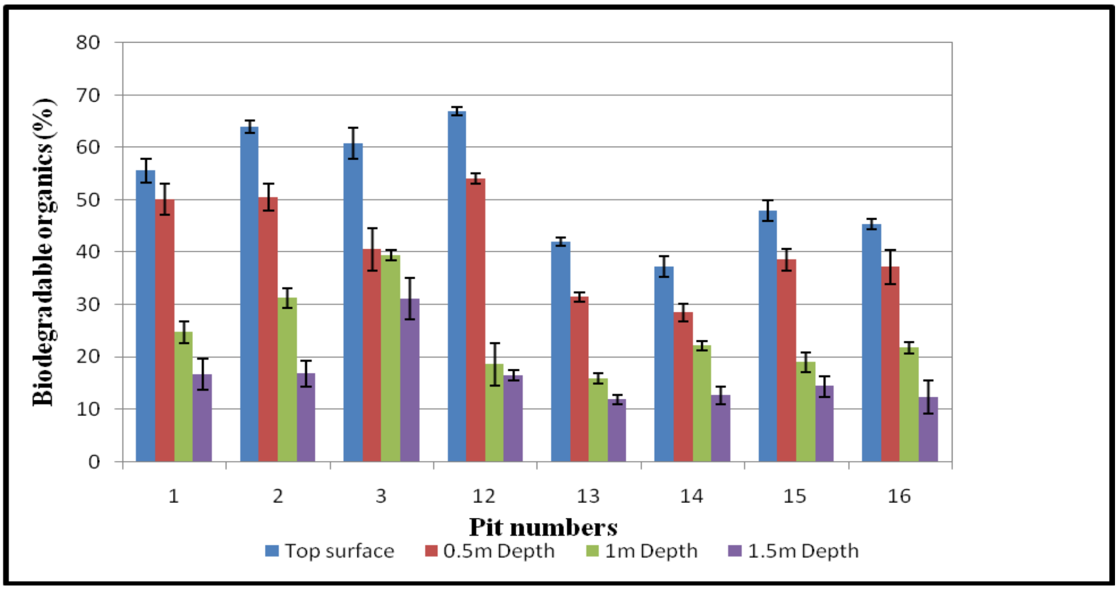
A Pearson correlation test was performed to quantify the relationship between COD concentrations of samples and the different depth from which samples were collected within the pit. It was confirmed by the test that the COD concentrations decreases significantly with increasing depth within each of the pit latrines investigated ($P = 0.05$). Also, Univariate analysis of variance was also performed using SPSS15 with a post-hoc Scheffe test to compare mean values of COD of the different samples collected at different depths. It was found that there was a significant difference ($p<0.05$) in COD between all samples collected from different depths but for 1m depth and the bottom layer (1.5m depth) there was no significant difference. These COD results are exactly what the Buckley *et al* (2008) theory proposed.

Aerobic biodegradability characterization results

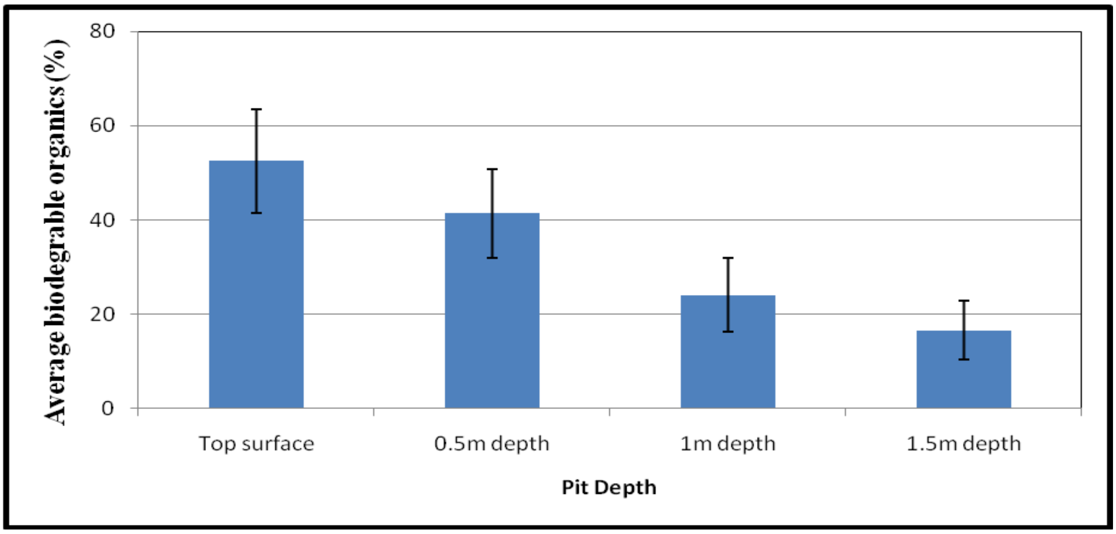
The Aerobic biodegradability test gives an estimate of the amount of biodegradable material present in each sample collected. **Figure 4.6** presents the aerobic biodegradability characterization results obtained. A low value indicates that the samples contain little biodegradable material and therefore have undergone a significant degree of stabilization. Only half of the total sample collected could be analysed since analysis of a sample takes approximately eight days to complete. Thus only 8 of the 16 pits were analyzed because the delay between sampling and analysis would have been too great for the results to be valid especially since samples are exposed to air during sampling and storage and the effect of this on samples is not known.

The biodegradability results for all the 8 pits follow the same trend. In **Figure 4.6(a)**, the biodegradability (in %) at different depths for each of the 8 pits analyzed is presented. The results showed a decreasing trend from surface layer to the bottom layer of each pit. This suggests that for each of the pits analyzed the degree of stabilization increases from the surface layer to the bottom layer of the pit. The average biodegradability for each layer for the 8 pits analyzed as shown in **Figure 4.4(b)** also shows a decreasing trend from surface layer to the bottom layer. This supports the motivating hypothesis that the degree of stabilization within the pit increases with increasing depth within the pit.

A Pearson correlation was performed to quantify the relationship that exists between the biodegradability of samples and the different depth from which samples were collected within the pit. The test indicated that biodegradability of sludge samples collected decreases significantly with increasing depth within a pit ($P = 0.05$). Univariate analysis of variance was also performed using SPSS15 with a post-hoc Scheffe test to compare mean values of biodegradability of the different samples collected at different depth. It was found that there was significant difference ($p < 0.05$) in biodegradability between all samples collected from different depth but for 1 m depth and the bottom layer (1.5 m depth) there was no significant difference. This also confirms the theory proposed by Buckley *et al* (2008).



(a)



(b)

Figure 4.6 Aerobic Biodegradability results (a) for each of the 16 pits from different layers within each pit (b) average Biodegradability at each layer for the 16 pit Error bars represent 95% confidence on the mean value of each layer.

4.4 SUMMARY OF CHARACTERIZATION OF SLUDGE CONTENT IN VIP LATRINES

The purpose of this chapter was to investigate the variations in the characteristics of sludge from different ventilated improved pit latrines and the variation in these characteristics at specific depth within each VIP latrines. Samples were collected, analyzed and tested to investigate whether the data support the theory proposed by Buckley *et al* (2008) in **chapter 2** of this thesis. The investigation was conducted in eThekwini Municipality where pit conditions are predominantly fairly dry, i.e. there is usually no free liquid surface on the top of pit latrine contents. Thus, the degree of stratification in the pit (and therefore limited mixing between layers) may not necessarily be found under different conditions, especially under wet conditions. With that stipulation in mind, it was found that all analytes correlated with biodegradable material, i.e. COD, volatile solids fraction and biodegradable COD decreased significantly between the surface sample and the third sample, taken from approximately 1 m below the surface. However, the difference between the 1m sample and the bottom sample was not statistically significant. These results support the Buckley *et al* (2008) theory that biological stabilisation, otherwise described as the degradation of biodegradable components, occurs in a section of the pit contents that extends from the surface down to a point corresponding with material deposited some years previously, but below this section, the material has reached a composition that does not degrade further to any substantial degree with time. This result challenges the common assumption that pit latrines act as storage vessels in which little biodegradation occurs.

From these results, a picture of the life cycle of the pit can be developed: when a pit is first commissioned, or emptied, the material added to the pit is fairly fresh, and to begin with, the pit material has undergone little stabilisation. It is all similar to layer 2 of the Buckley theory. After a period of time, as material undergoes degradation and gets covered over with fresh material, the bottom layers become anaerobic and partially degraded (layer 3 of the Buckley theory) while the new top layer is the Buckley layer 2. After a considerable amount of time (years) the bottom layers have undergone degradation to an extent that they cannot degrade further under pit conditions, and may be said to be fully stabilised (layer 4). Once layer 4 has established, assuming that the material entering the pit is added at a fairly constant rate and composition, the rate at which the pit latrine contents accumulate is the rate at which layer 4 increases since the layers above will move upward in a steady fashion. Thus the rate at which the pit fills is approximately equal to the rate at which material that will ultimately end up as unbiodegradable residue is added to the pit. This is of course a much lower rate than the volume addition rate of fresh pit contents.

The important corollary of these findings is that the only sustainable way to reduce pit accumulation rate is to reduce the amount of material that will ultimately end up as unbiodegradable residue. Increasing the rate of degradation will only result in the thickness of the combined Buckley layers 2 and 3 being smaller, which would extend the life of the pit slightly by reducing the average accumulation rate. Alternatively, if it were possible to degrade layer 4 contents further than occurs naturally (i.e. changing the yield of non-degradable residue from pit feed material), the amount of material that will ultimately end up as unbiodegradable residue will be a smaller proportion of what is originally added and will have the same net affect. To date, there is no documented method of achieving either of these options.

Table 4.1 presents a summary of all the characteristics of VIP samples measured. The measurement did not take into consideration general household waste found in the pit latrines sampled, it only considered the faecal sludge component of the pit since this is the fraction that is expected to degrade in predictable way. The measurement of sludge samples collected at different layers for all the pits were averaged for each of the layers. The characterization results have provided information on the variability of VIP latrine sludge content from one pit to another and at different layers within a pit. A significant variation within a pit and between pits was observed despite the fact that all VIPs used in this study were located within similar geological/ environmental conditions. Changes in sludge characteristics at different depths within the same pit suggest that biodegradable material presents in faecal sludge found in pit latrines changes with time.

The average COD obtained for faecal material at the surface of the pit was found to be 0.603 gCOD/gdrysample which is significantly lower than the value of 1.13 gCOD/g drysample obtained for fresh faeces by Nwaneri (2009) and other literature value presented in **Table 2.1.** Also there was a significant difference in the amount of volatile solid (58 %gVS/gTS) at the surface of the pit compared to that of fresh faeces (84 % gVS/gTS) and the average biodegradability obtained for the surface layer (52 %) of the pit was also found to be significantly lower (80 %) than that of fresh faeces presented in **Table 2.1.** It should be noted that the values of COD, VS and biodegradability reported in **Table 2.1** may not be the same as in the fresh faeces of users of the pit latrines investigated. However, these values provide a basis for comparing the expected characteristics of fresh faeces added to the pit.

The findings of the characterization of sludge from VIP latrines implies that materials present at the surface layer in the pits when the samples were collected had undergone a degree of stabilization when compared to the fresh faeces and also that, immediately after faeces had been deposited in the pit degradation of readily biodegradable components of the faeces takes place rapidly.

Table 4.1: Summary of VIP Sludge contents at different layer within the pit. Data are presented as mean value ± 95% conf. Interval, [min, max]

Parameters	Units	Surface Layer	0.5 m depth	1m depth	1.5m depth
Moisture	%	76.84±1.68 [57.58, 85.71]	71.63±3.32 [30.06, 86.06]	64.94±3.59 [30.72, 84.83]	67.08±3.72 [34.71, 87.48]
COD	g/gdrysample	0.60±0.07 [0.10, 1.23]	0.38±0.04 [0.05,0.76]	0.25±0.036 [0.10, 0.59]	0.24±0.039 [0.09,0.49]
VS	%gVS/gTS	57.68±4.41 [23.60,94.64]	47.26±5.10 [3.67,75.62]	34.37±4.83 [4.89, 73.57]	36.54±5.29 [3.94, 74.46]
Biodegrad.	%	52.46±10.92 [35, 68]	41.35±9.38 [27, 56]	24.08±7.73 [7, 44]	16.55±6.25 [8, 35]

5 ENTRENCHMENT OF VIP LATRINES SLUDGE FOR AGROFORESTRY

Safe disposal of VIP latrine sludge is essential for public health protection. The unsafe disposal of VIP latrine sludge is not only a menace to public health but could also be a roadblock to sustainable development and a huge strain on financial resources. Thus, any chosen disposal option should be appropriately designed, sited and adequately managed to avoid both public health and environmental risk.

eThekwini Municipality has proposed various options to handle sludge content from full pits which were discussed in **Chapter 2**. However, according to the new sludge guidelines (Snyman and Herselman, 2006), sustainable sludge management options include recovering energy, recycling the nutrients or synthesizing commercial products from the sludge. Based on the sludge classification system presented in the new sludge guidelines and the findings from the two previous Chapters (which clearly showed that significant stabilization of sludge content within the pit takes place and that treatment of pit sludge as though it were fresh sanitation waste is not appropriate), the only permissible options which seem appropriate for the utilization of sludge from VIP latrine are composting the sludge with other organic materials or mixing or covering the sludge with soil in natural veld or tree plantations.

According to Cofie and Kone (2008), compositing of VIP latrine sludge may require the addition of material with a high carbon content such as municipal organic solid waste since raw material for compositing should have a carbon: nitrogen ratio of approximately 30:1 and faecal sludge has a ratio of approximately 6:1 which could be an expensive process. Mixing or covering of sludge with soil in natural veld or tree plantations have focused exclusively on the utilization of treated sludge from wastewater treatment works. In South Africa where VIP latrine is the standard for basic sanitation provision and many of the pits provided have reached their capacity which requires emptying and disposal of the accumulated sludge, an investigation into the applicability of deep row entrenchment of pit latrine sludge might be a feasible option for the disposal and beneficial reuse use of VIP latrine sludge.

This chapter presents part of a broader study conducted on the applicability of deep row entrenchment of VIP latrine sludge content in eThekwini municipality. The broader study considers the effect of sludge entrenchment on growth characteristics of trees, on soil characteristics, changes in the characteristics of sludge buried in trenches and on the surrounding groundwater. The primary aim of this chapter was to investigate entrenchment of VIP latrine sludge in association with agroforestry has the potential to turn the sludge from a problematic waste to a beneficial resource without causing any environmental impacts. It is expected that the residual nutrients present in the sludge (especially nitrogen, phosphorus and potassium) may be a source of fertilizing nutrients which would be released slowly and become available at the same slow rate at which the sludge is degraded. Changes in the characteristics of VIP latrine sludge buried in trenches were investigated to determine the effect of entrenchment on the sludge buried in trenches and the effect of VIP sludge burial sludge on the surrounding groundwater was also investigated.

According to Jönsson *et al* (2004), burial of sludge increases the organic content of the soil, which enhances the moisture retention characteristics, ion-buffering capacity and generally increasing the fertility of the soil. It has been documented that in plantations the trees planted draw the available water within the surroundings into the plantation area to supply the water requirements of the trees (Don, 1987 and Duncan, 1993), therefore planting of trees near the entrenched VIP latrine sludge may have an added advantage, in that the presence of the trees will result in a net movement of water into the burial site to supply the water requirements of the trees. Thus planting trees next to the buried sludge should result in a lower risk of contamination of ground and surface water in the vicinity caused by nutrient and pathogen release from the buried sludge.

In addition, entrenchment of VIP latrine sludge in soil might result in a greater degree of stabilization than can be achieved in the pit latrine. The logic behind this proposition was that field studies of pit latrines indicated that stabilization of sludge in pit latrines that are no longer in use apparently occurs from the soil/sludge interface inwards

(Morgan, 2004). It was hypothesized that this observation was due to the action of soil fungi.

The major processes involved in organic matter cycling in an aquatic environment are dominated by bacteria and eukaryotes (in particular algae) with bacteria found to be the dominant decomposers of organic matter in water and sediments (de Boer *et al* 2005; Del Giorgio and Cole 1998). However, in soils, soil fungi contribute significantly to the biodegradation of organic material. Various studies have demonstrated that the presence of organic matter in soils or organic fertilization of soil has a positive influence on the soil fungi population (Abbott and Murphy, 2003). This is because the soil contains air-filled voids which are essentially different to sediments; bacterial motility in soils is restricted due to the inability of the unicellular body form of bacteria to bridge these air-filled voids (de Boer *et al*, 2005). The hyphal/mycelial growth form of soil fungi makes it possible for soil fungi to bridge these air-filled voids and as such motility of fungi in soils are not restricted (Griffin, 1985). Fungi hyphae also have a greater ability than bacteria to translocate nutrients within the soil (Jennings, 1987). Interestingly, the hyphal growth form has also been developed by certain soil bacteria known as the actinomycetes however heterotrophic processes and the degradation of recalcitrant organic compounds taking place in the soil are dominated by fungi (de Boer *et al*, 2005; Griffin, 1985; Taylor and Osborne, 1996). According to de Boer *et al* (2005), the two important processes which are the formation of mycorrhiza and the decomposition of lignocelluloses within the terrestrial ecosystem are dominated by fungi and therefore, the functioning of the terrestrial ecosystem relies significantly on fungi.

Soil fungi are microscopic plant-like cells which are the most important and diverse class of soil organisms (Abbott and Murphy, 2003). Soil fungi have the ability to decompose virtually all organic matter, recycle nutrients, make use of the hyphal mantle spread over the surface of the roots to provide protection against the pathogenic entry into plant roots, and the hyphal network in soil surroundings roots enhances water uptake from the soil (Abbott and Murphy, 2003; Smith and Read, 1997). Soil fungi grow best in moist but well aerated soil conditions with pH near neutral (Abbott, 2003); conditions within the pit (mostly anaerobic with fluctuations in pit latrine sludge pH, significant moisture, little or no air and possibly the presence of biocidal chemicals and other materials added to the pit) makes it possible for fungi to survive in the soil and not in the pit latrine. Thus cellulosic cell components that can only be broken down by certain species of fungi cannot be degraded in a pit latrine, but might be biodegradable in the presence of soil fungi.

When a pit latrine is full, the sludge consists of oldest and most stabilized material at the bottom of the pit and newest, least stabilized material at the top of the pit as found in **Chapter 4**. Thus during pit emptying, the mixed pit contents have a mixture of well-degraded and poorly degraded material. When this material is disposed of into entrenchments, it will be mixed to a certain extent during the processes of being dug out of the pit and reburied in the entrenchment, and thereafter undergo similar bio-degradative processes as occur in pit latrines, as well as some different, possibly aerobic and possibly fungal mediated processes in the trenches.

5.1 SITE DESCRIPTION

The site selected for the entrenchment trials was in Umlazi E-Section on land owned by eThekwini Municipality that was formerly used as wastewater stabilization ponds. **Figure 5.1** presents the aerial view of the Umlazi VIP sludge burial site. The former Umlazi oxidation pond treatment works was comprised of three oxidation ponds and was operated until 1999 when it was decommissioned after a heavy flood which resulted in the damage of the oxidation ponds. The Umlazi sludge burial site has several advantages;

- The site is close to a number of VIP latrines which were being emptied at the time of this study.
- The site was previously used for sewage processing; hence there is precedent in terms of land usage.
- The site is situated below the 1:50 year flood line, therefore the land has no value for other purposes.

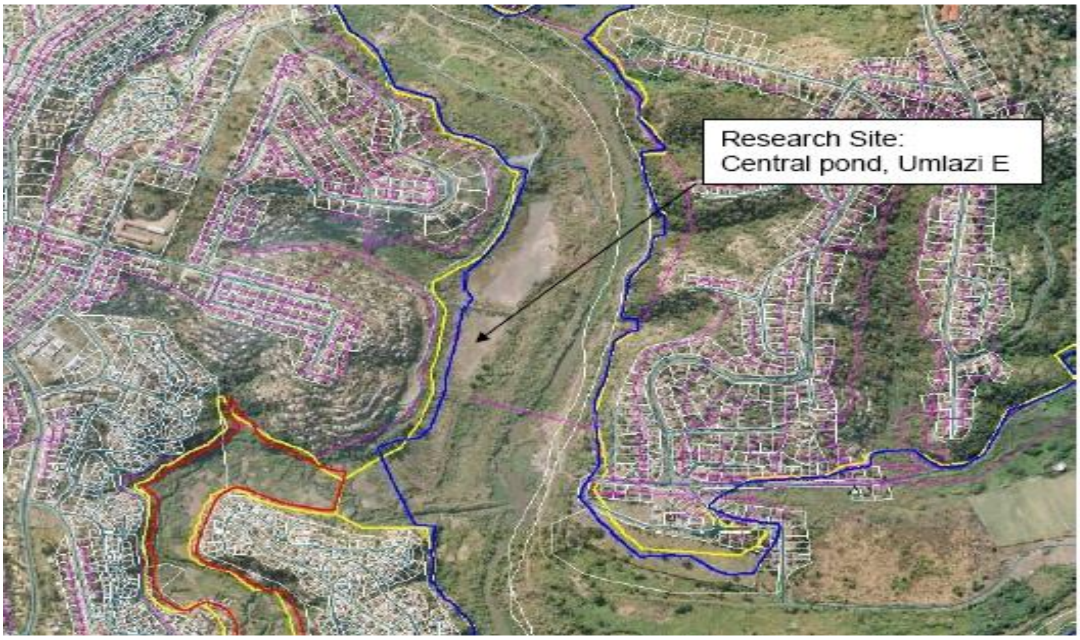


Figure 5.1: Aerial View of Umlazi sludge burial site with 1:50 flood line in blue

The results of a soil characterization performed by the School of Bioresource Engineering and Environmental Hydrology University of KwaZulu- Natal, is presented in **Table 5.1**. The data indicates that the soil at the burial site appears to be of poor quality, predominantly composed of sand. This suggests that the soil has almost no agricultural value. Therefore it was proposed that the burial of VIP latrine sludge on this site could improve the condition of the soil by increasing the organic materials and nutrients. The layout and details of the Umlazi VIP latrine sludge entrenchment site are shown in **Figure 5.2**.

Table 5.1: Soil Analysis from Umlazi E-Pond

Sample ID	Particle Size Analysis				pH	EC (electrical conductivity) dS/m
	%Sand	%Silt	%Clay	Textural class		
South East (1.3 m)	93.2	2.9	3.8	Sand	5.1	0.079
South West (2 m)	94.3	2.6	3.1	Sand	5.9	0.061
North East (1.5 m)	97.1	0.7	2.1	Sand	5.3	0.033
North West (2 m)	97.2	0.7	2.1	Sand	5.0	0.06

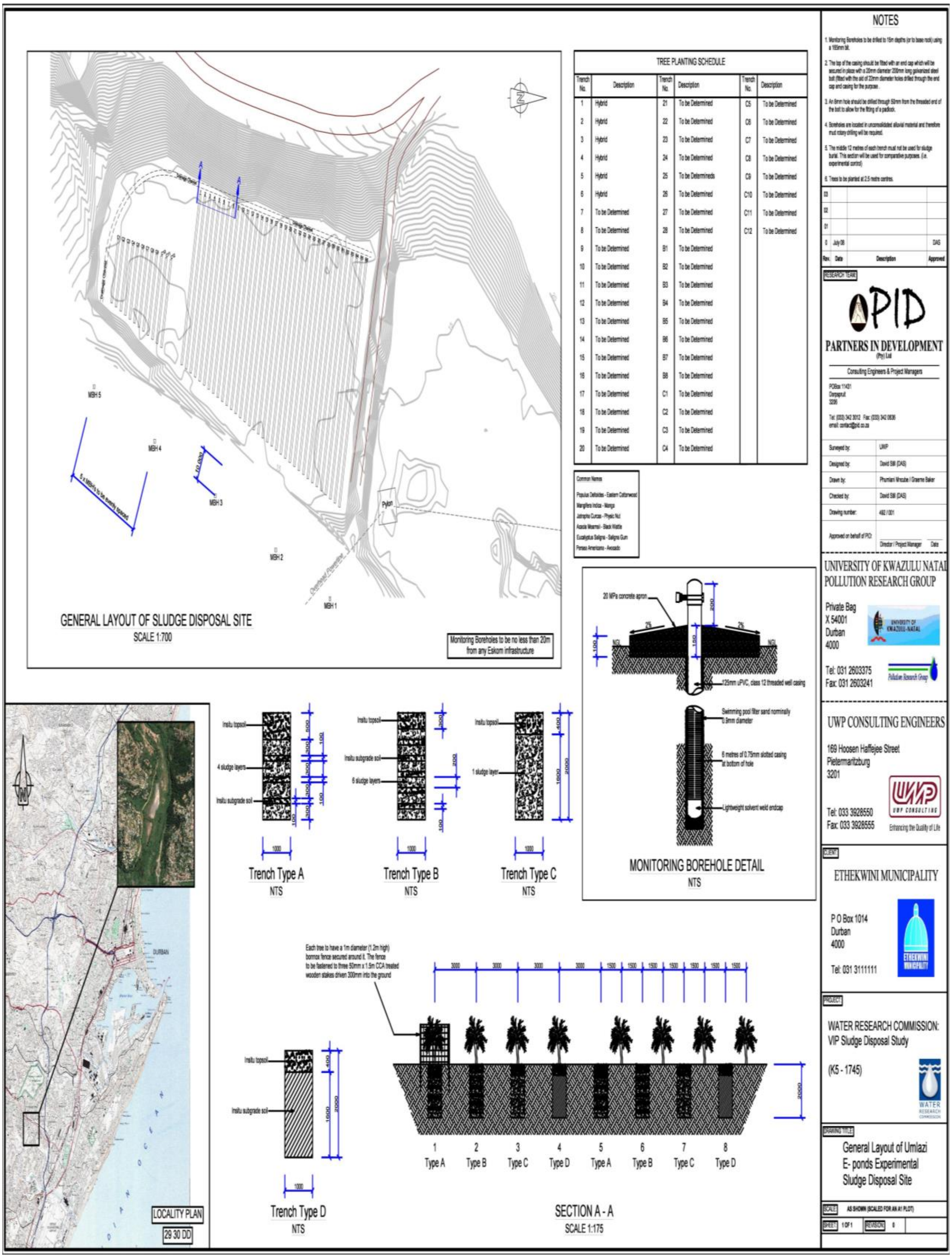


Figure 5.2: General layout and details of the Umlazi VIP latrine sludge entrenchment site.

5.2 METHODOLOGICAL APPROACH

This section presents the methodological approach used for monitoring the changes in the characteristics of VIP latrine sludge buried in trenches and groundwater monitoring procedure at the Umlazi burial site.

5.2.1 Monitoring of VIP latrine Sludge buried in trenches

Sludge exhumed from pit latrines as part of the eThekwini Water and Sanitation Services (EWS) pit emptying programme was delivered to the disposal site in bins and buried in trenches. The procedure for the entrenchment VIP latrine sludge involved both manual and TLB (Tractor-Loader-Backhoe) excavation of trenches 200 m long, 600 mm wide and 1.2 to 1.5 m deep, with rows spaced 3 m between centres. The trenches were filled with VIP latrine sludge to within 300 mm of the surface and then backfilled with the overburden heaped on top of the trench. Trees were then planted in rows parallel to the trenches. Excavation of trenches and burial of sludge in trenches commenced in October 2008 until January 2010, **Figure 5.3** shows images taken during excavation and sludge burial in trenches.

Monitoring of VIP latrine sludge buried in trenches has two components. Firstly, fresh VIP latrine sludge samples were collected during the delivery of sludge to the burial site so as to give initial characteristics of the sludge before entrenchment. During the emptying of sludge content from the VIP latrines, it is expected that there would be substantial mixing of pit contents, both from different locations in the pit and from different pits and thus the material that arrives at the entrenchment site is expected to exhibit characteristics that are similar to the global averages for pit sludge, and with a lower variance than at source because of this mixing. Thirty samples were collected over a period of six weeks in order to assess the variability in the VIP latrine sludge that arrived at the entrenchment site.

The second component involved exhuming sludge from the trenches and performing laboratory characterization of the exhumed sludge in order to determine the sludge characteristics. Sampling and analysis was performed at specified intervals of time (1 year and 1.5 years) after the entrenchment of the VIP latrine sludge. Sludge samples from the trenches were exhumed using a soil auger. For each of the time intervals, twenty five sludge samples were collected at identified point across the trenches. This was done in order to ascertain that the sludge samples collected at different time intervals were approximately from the same point across the trenches. The purpose of this part of the study was therefore to identify whether there was a significant change in average sludge characteristics of exhumed sludge from the trenches with time and also if further stabilization of the sludge occurs in the trenches than at the bottom layer of a pit latrine. By monitoring changes in the characteristics of sludge buried in trenches with time and changes in environmental conditions (tree growth/ groundwater monitoring), this part of the study sought to investigate the possible benefits of entrenchment and beneficial reuse of pit latrine sludge for agroforestry. It is proposed that this technique is appropriate it can utilize a range of degree of sludge stabilization and the economic and operational benefits are not dependent on sludge being essentially undigested.

The techniques used for the characterization of samples obtained from the two components involved a number of biological/physical/chemical analyses which include; moisture content, solids (total and volatile solids), chemical oxygen demand (COD), aerobic biodegradability, Total Kjeldahl Nitrogen (TKN) and phosphorus. Standard Methods (APHA, 1998) were used to analyse the collected sludge samples where applicable and where no appropriate method was published, adaptations of existing methods was used or entirely new methods were developed. A brief description of each method presenting the significance of each method has been presented in **Chapter 4** and the detailed description of each method is presented in the **Appendix B and C.**

Figure 5.3: Excavation and Sludge burial in Trenches at the Umlazi Site

5.2.2 Groundwater monitoring procedure

The groundwater study was done in conjunction with the School of Bioresource Engineering and Environmental Hydrology University of KwaZulu- Natal and aspect presented in this thesis is part of a broader study. The research work presented in this thesis only involved monitoring of groundwater at the umlazi sludge entrenchment site involved sampling of groundwater from each of the monitoring boreholes on a regular basis and performing laboratory analysis on water samples collected in order to identify and quantify any migration of pollutant or changes in the surrounding groundwater as a result of the sludge entrenchment activities. Five evenly spaced groundwater monitoring boreholes were dug at the entrenchment site in the direction of the hydraulic gradient to monitor any potential migration of pollutant and pathogens into the groundwater. Their respective location is as shown in **Figure 5.4.**

Figure 5.4: Location of boreholes at the umlazi E-pond entrenchment site

The boreholes are dug between the trench where VIP latrine sludge was buried and a river. The distance from the trenches to the boreholes was 55 metres while the distance from the trenches to river flowing behind the boreholes was 129 metres. The monitoring boreholes were drilled to 15 metre depth using a 165 mm bit. The cross section of the monitoring borehole design is presented in **Figure 5.5**.

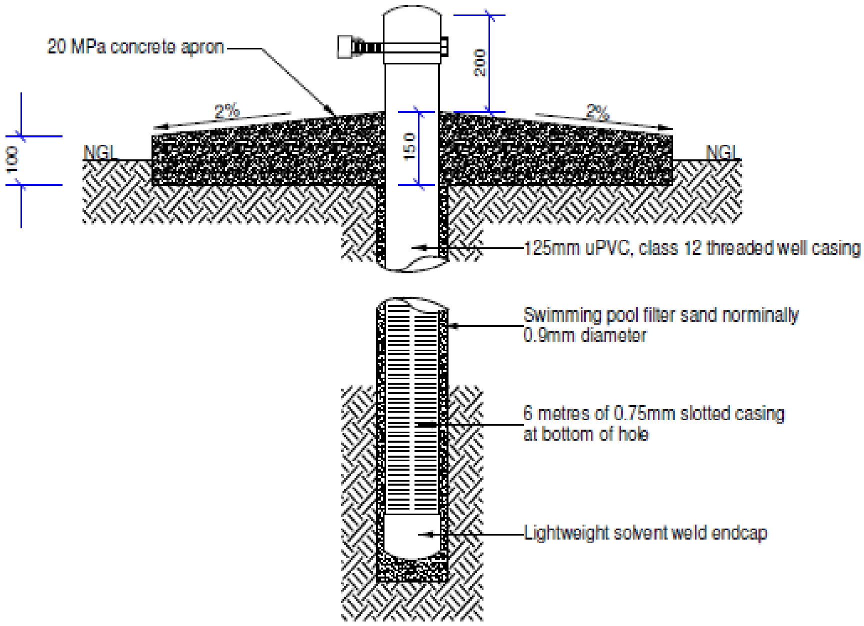


Figure 5.5: Groundwater monitoring borehole detail (extracted from Figure 5.2)

The collection of groundwater samples from the monitoring boreholes at the Umlazi sludge entrenchment site followed four steps; field sampling equipment preparation, measuring of water level in boreholes, purging the boreholes and collecting and delivering the water samples to the laboratory for analysis. These four steps follow the Standard Groundwater sampling procedures described by Weaver *et al*, 2007 and are explained as follows;

Field Sampling Equipment Preparations

Water samples were collected from the monitoring boreholes at the Umlazi sludge entrenchment site on a monthly basis where possible. Before the collection of water samples, it was always necessary to clean the field sampling equipment to eliminate contamination of the water samples. The sampling equipments were also calibrated before use. The field sampling equipment included; pumping equipment, water level meter, probes and instruments used for measuring temperature, pH, conductivity, dissolved oxygen; sampling bottles/containers/buckets, preserving containers (this includes cooler box and ice).

Measurement of Water Level in Boreholes

The measurement of water level in each of the five boreholes is the first exercise performed on getting to the site on each visit. This is an important exercise because it provides an estimate of the volume of water that should be purged and can be used in calculating groundwater flow directions and seasonal changes of the aquifer layer (Weaver *et al*, 2007). A dip meter is used in measuring the water level in each of the five boreholes. The dip meter is made up of a twin core cable and an ohm meter. The end of each cable is bared to avoid contact of the two ends. When the two bared end of the cable are immersed in the water, a signal is recorded by the ohm-meter. Therefore the bare cable ends are lowered into the borehole and when a deflection is observed on the ohm meter, it is concluded that the water level has been reached. The depth of the water level can be calculated from the length of the cable lowered into the borehole. This gives the static depth to water level in the borehole. The standing/stagnant volume of water in the borehole can then be calculated using the following equation;

$$V = \frac{\Pi \times d^2 \times h}{4000} \qquad \textbf{[5.1]}$$

Where;

V = Volume of standing/stagnant water in Litres

d = Diameter of borehole in millimetres

h = Height of water column in meters

The height of water column is calculated as;

Borehole depth – static depth to water level **[5.2]**

Purging the Boreholes

Purging of boreholes is an important exercise that must be carried out before groundwater sample can be collected. This is done in order to remove any stagnant water in the borehole casings and ensure that groundwater samples collected originated from the aquifer layer. In practice, borehole purging generally involves pumping out sufficient amount of water from a borehole until field parameters such as pH, electrical conductivity, dissolved oxygen, temperature and turbidity stabilize. pH, temperature and electrical conductivity are the three field parameters considered for the purging of the five boreholes at the Umlazi sludge burial site. The readings of the field parameters during the purging exercise are taken and logged at different time interval and are noted, together with the volume of water pumped and all other field measurement.

Sample Collection

It is necessary that water sample from boreholes be collected within six hours after purging of boreholes has been performed (Weaver *et al,* 2007). Samples from boreholes at the Umlazi sludge burial site were collected immediately after purging. The valve on the pump is usually lowered after purging before samples are taken so that water will flow slowly without aeration. Sample bottles were properly labelled and samples were normally collected directly from the valve on the pump. Samples were then placed in the cooler box containing ice blocks and then transported to eThekwini water and sanitation laboratory for analysis.

The parameters of concern in groundwater as a result of VIP latrine sludge burial in trenches are pathogens, nitrates, sodium, chloride and phosphate. Analysis of water samples from the monitoring boreholes were performed from November 2008 to February 2011 and samples were analysed for chloride, COD, conductivity, sodium, ammonia, nitrate and nitrite, dissolved oxygen, pH and orthophosphate as well as T. coli, *E. coli* and total organisms on a monthly basis. The details on why these parameters were chosen are presented in **Appendix C** of this thesis. All analysis on the groundwater samples were performed at the eThekwini Water and Sanitation service laboratory according to standard methods (APHA, 1998).

5.2.3 Challenges

Sampling of groundwater from the five monitoring boreholes commenced from November 2008 to February 2011 when the writing up of this thesis started. Initially sampling of groundwater from the five monitoring boreholes was meant to be on monthly basis, however due to the hostile community where the entrenchment site was located, it was impossible for consistent sampling on a monthly basis. In April 2009 sampling of groundwater from the five monitoring boreholes was not performed as a result of various protests that sprung up within the community because this was the month in which the South African Presidential election was conducted. However, it was possible to conduct the sampling run from all boreholes in May 2009 but between the months of June 2009 up until May 2010 it was not possible to carryout sampling from borehole 1. This was because the lock on borehole 1 was damaged. Three nails were hammered into the key opening of the lock by someone in the community. These locks were special locks supplied by the eThekwini Municipality and the lock had to be blasted to open the locks.

Also in the month of July 2010 the sampling could not be performed on all five boreholes, as this was the month in which the local community were hijacking and attacking workers at the entrenchment site and as such it was decided to stay away from the entrenchment site until issues have been resolved. Sampling from all boreholes was only possible in the month of August 2010 but there was a major fire disaster in the month of September 2010 at the eThekwini Water and Sanitation Laboratory where analysis of collected water samples were conducted. The laboratory sustained significant fire damage; rebuilding and refurbishment of the laboratory took several months and was only completed in February 2011. Thus, all these issues had resulted in the gaps in the analytical groundwater data presented.

5.3 RESULTS OF THE VIP LATRINE ENTRENCHMENT STUDIES

This section presents the results obtained from the characterization of VIP latrine sludge that arrived at the entrenchment site before being buried and the characterization of the sludge exhumed from the trenches at different time after burial. The results obtained from the analysis conducted on groundwater samples collected from the five boreholes are also presented.

5.3.1 Sludge Characterization Results

Figure 5.6 to Figure 5.9 presents the results obtained from the characterization of VIP latrine sludge that arrived at the entrenchment site before burial and sludge exhumed from the trenches at different time intervals. In this section fresh VIP sludge refers to the material that arrives at the entrenchment i.e. just before burial.

Figure 5.6 presents the moisture content characterization results obtained for both the fresh VIP latrine samples and the sludge exhumed from the trenches at different time intervals.

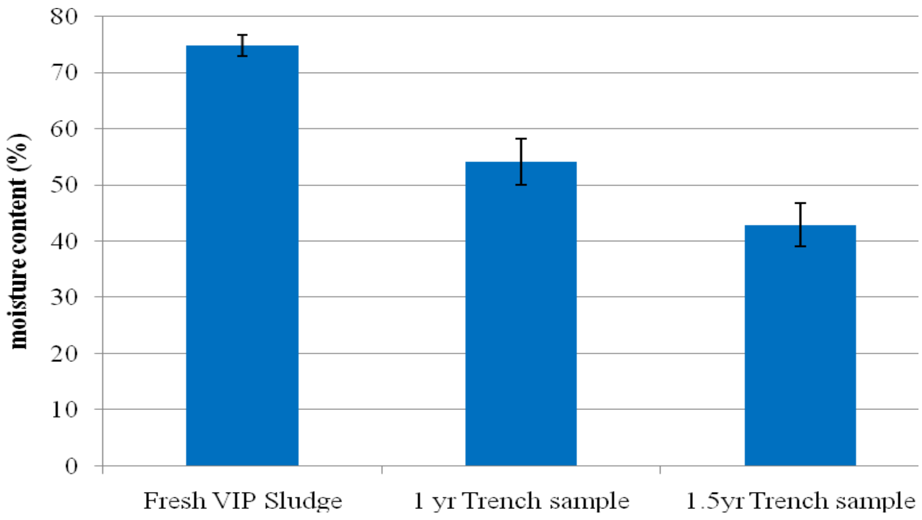


Figure 5.6: **Moisture content results for both fresh VIP latrine and trench samples. Error bars represent 95% confidence interval on the mean of the replicate measurements.**

The average moisture content obtained for the fresh VIP latrine samples was approximately 75%. This corresponds to the average value obtained for pit latrine sludge presented in **Chapter 4** of this thesis (78 %) and the value of 76% obtained from a previous study conducted by Buckley *et al* 2008. The average moisture content obtained from the sludge samples exhumed across the trenches at the Umlazi entrenchment site after a year was 58% and after 1.5 years was 43%. Univariate analysis of variance conducted using SPSS 15 with a post-hoc Scheffe test to values of the moisture content for both the fresh VIP samples and trench samples showed that there was significant difference ($p<0.05$) between the moisture content of fresh VIP sample and trench samples (1 and 1.5 year old trench sample). This implies that the moisture content of the fresh VIP sludge samples reduces with time when buried in trenches. Comparing these moisture results with the values measured in the pit latrines at different depths in **Chapter 4** suggests that further reduction in the moisture content of VIP latrine sludge does occur over time when the sludge is buried in trenches with trees planted alongside.

It has been documented (Cotton *et al*, 1995; Franceys *et al*, 1992), that liquid can leach into or out of pit latrine contents as a result of rain or groundwater ingress; thus it is conceivable that the moisture content in the entrenched sludge could show significant fluctuations due to seasonal changes. The soil at the burial site had good drainage properties, and the water table was found to be below the level at which sludge was buried. Thus, it is proposed that moisture loss may have accompanied biological degradation and that the rate of reduction in moisture content is a function of biodegradation rate (contrary to the situation within pit latrines).

Figure 5.7 presents the Volatile Solid results for both the fresh VIP latrine samples and sludge samples exhumed from the trenches at different time interval.

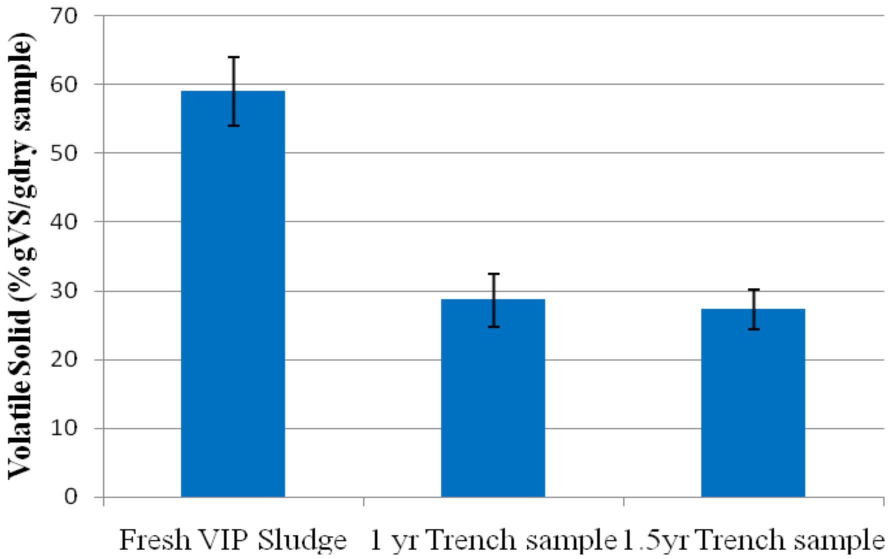


Figure 5.7: Volatile solid results for both fresh VIP latrine and trench samples. Error bars represent 95% confidence interval on the mean of the replicate measurements.

The average volatile solid (%gVS/g dry sample) result obtained for the fresh VIP samples analyzed was approximately 59% gVS/g dry sample while that of the trench samples exhumed after 1 year was approximately 29% g VS/ g dry sample and that of the exhumed trench sample after 1.5 years was approximately 27% gVS/g dry sample. Univariate analysis of variance carried out using SPSS 15 with a post-hoc Scheffe test to compare the volatile solid content for both the fresh VIP samples and trench samples showed that there was significant difference ($p<0.05$) between the fresh and trench samples but there was no significant difference ($p>0.05$) between the 1 year and 1.5 year exhumed sludge samples from the trenches.

The most important feature observed from the results presented in **Figure 5.7**, is that the average volatile solid measurement decreases between the fresh VIP sample and the buried sludge samples in trenches indicating a reduction in organic matter during entrenchment. This reduction in volatile solids indicates that significant stabilization of the sludge has taken place when sludge is buried in trenches. The results also indicate that rapid stabilization of the sludge takes place within one year of burial but after one year little or no further stabilization takes place.

Thus, by comparing the volatile solid value of approximately 27 % gVS/gTS obtained after 1.5 years of entrenchment of VIP latrine sludge with the average value of approximately 37 % gVS/gTS obtained for VIP latrine sludge collected from the bottom layer of the pit which is said to have undergone significant degree of stabilization (**Figure 4.4** in **Chapter 4)** suggests that further degradation of sludge may occur in trenches compared to pit latrines.

Figure 5.8 presents the COD results for both the fresh VIP latrine samples and sludge samples exhumed from the trenches at different time interval.

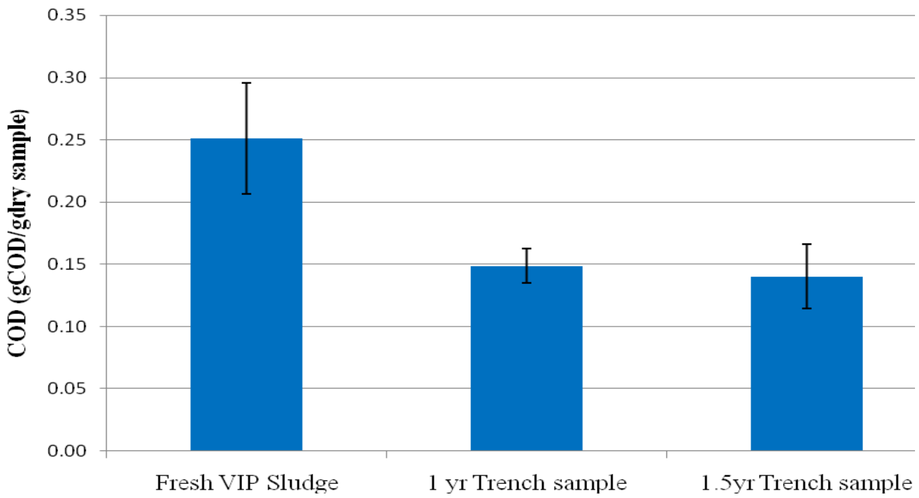


Figure 5.8: COD results for fresh VIP latrine and trench samples. Error bars represent 95% confidence interval on the mean of replicate measurements

COD is a measure of the oxidizable matter present in samples and is used as an indication of the amount of chemically oxidizable material in a sample. While the measurement does not directly indicate the amount of biologically oxidizable material, the advantage of the measurement over direct measures of biodegradable matter is that it is relatively quick to perform and the results are reproducible. Furthermore, if samples are exposed to conditions in which biological activity will dominate changes, then changes in COD can be equated to changes in organic matter. In this case, changes in COD can be used as an indication of the degree of degradation that materials present in the trenches have undergone.

The average COD value obtained for the fresh VIP samples analyzed was approximately 0.25 g COD /g dry sample while that of the trench samples exhumed after one year of burial was approximately 0.15 g COD/ g dry sample and the trench sample exhumed after 1.5 years was approximately 0.14 g COD/g dry sample. Univariate analysis of variance carried out using SPSS 15 with a post-hoc Scheffe test to compare mean values of the COD for both the fresh VIP samples and trench samples showed that there was significant difference between ($p<0.05$) the fresh VIP samples and trench samples but there was no significant difference ($p>0.05$) between the trench sample exhumed after one year and that exhumed after 1.5 years. The COD result has the same implications as the volatile solid data presented in **Figure 5.7** and as such supports those conclusions made.

It was observed that the average value of 0.25 g COD /g dry sample obtained from the characterization of VIP latrine sludge samples that arrived at the entrenchment site was lower than the global average value of 0.37 g COD /g dry sample obtained from the characterization of pit latrine sludge presented in **Chapter 4**. However, by comparing the COD value of approximately 0.14 g COD/g dry sample obtained after 1.5 years of entrenchment of VIP latrine sludge with the average value of approximately 0.24 g COD/g dry sample obtained for VIP latrine sludge collected from the bottom layer of the pit as presented in **Figure 4.5.** It appears that further degradation of sludge may occur in trenches than observed in a pit latrine.

Figure 5.9 below presents the Biodegradability results for both the fresh VIP latrine samples and sludge samples exhumed from the trenches at different time interval.

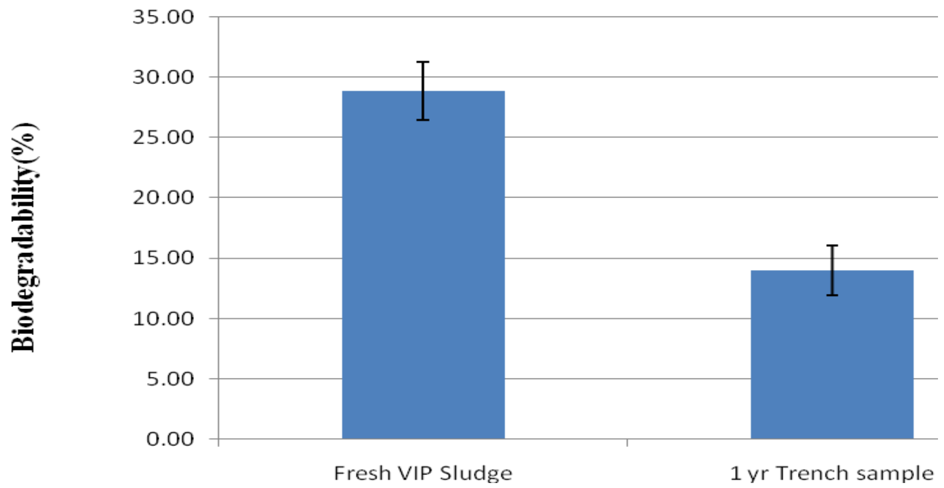


Figure 5.9: Biodegradability results for fresh VIP latrine and trench samples. Error bars represent 95% confidence interval on the mean of the replicate measurements.

The aerobic biodegradability test gives an estimate of the amount of biodegradable material present in the sample collected. The average Biodegradability result obtained for the fresh VIP samples analyzed was approximately 29% while that of the trench samples analyzed was approximately 15%. Univariate analysis of variance carried out using SPSS 15 with a post-hoc Scheffe test to compare mean values of the COD for both the fresh VIP samples and trench samples showed that there was significant difference between the fresh and trench sample. As shown in **Figure 5.9** the relative biodegradability of the fresh VIP samples is higher than that of the trench sample indicating that the fresh sample that was buried has further been stabilized in the trenches. Comparing these results with that obtained from the characterization of sludge at bottom layer of the pit as presented in **Chapter 4** indicated that biodegradability of sludge from the trench is slightly lower than that of the bottom layer of the pit but not significantly different.

Thus, one interpretation of the result obtained is that biological stabilization of the sludge occurs in the trenches resulting in a net decrease in COD, VS and biodegradability values with a corresponding reduction in sludge moisture content. Three possible explanations can be given for the reduction in the measured characteristics of the trench samples as compared to the fresh VIP latrine sludge:

- Freshly exhumed sludge from the pit latrine can be said to have much of its organic material as well as its moisture content contained in dead or inactive bacteria and yeast cells. Cell walls and cell membrane are known to be difficult to degrade but certain fungal species found in soils are often capable of degrading these cell walls and cell membranes (Boer *et al,* 2004). Thus, when sludge from VIP latrine is buried in trenches, the sludge might be exposed to conditions which accelerate the breakdown of the recalcitrant cell material due to contact with soil, thereby releasing moisture and biodegradable cell component which may then be easily degraded. Hence, an increase in the degree of stabilization of the sludge is observed with time which results in reduction of the measured characteristics of trench samples as compared to the freshly exhumed VIP latrine sludge.
- A further explanation of the reduction of the characteristics of the trench samples as compared to the freshly exhumed VIP latrine sludge could be related to the fact that when a pit latrine is emptied, a portion of the sludge originates from the surface material of the pit, which is relatively poorly degraded since the residence time of this portion of sludge is less than that of the rest of the pit contents. This

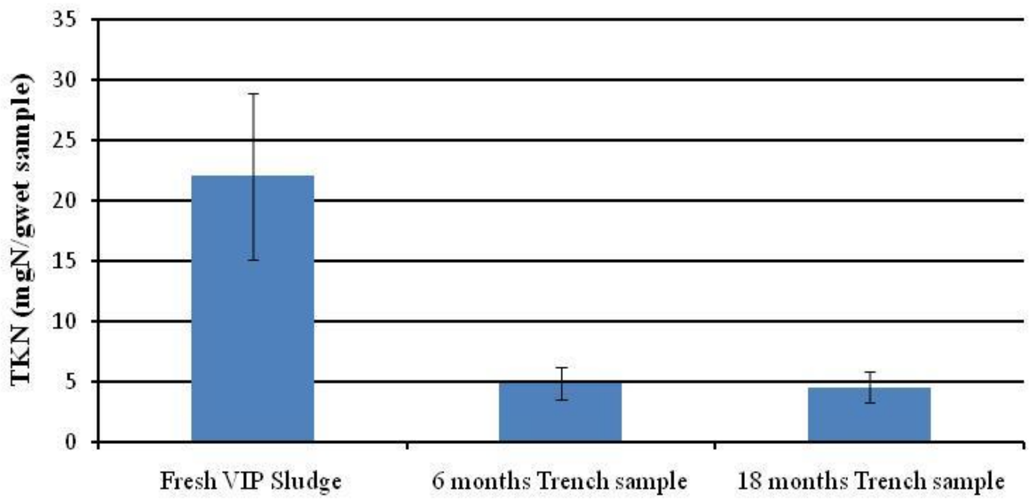
portion is mixed with the bulk of the pit sludge, thus despite the long residence time of much of the sludge in the VIP latrine before exhumation, there will be a portion of relatively fresh faecal sludge in the exhumed material which will then have to be degraded. Thus the reduction in organic content and moisture during entrenchment may be partially attributed to the degradation of this portion of relatively fresh faecal sludge in the trenches.

- The amount of sand that is entrapped in samples taken from entrenchments dilutes the measured concentration of solids. The reduction in biodegradability relative to that measured in the bottom of a pit latrine could not be accounted for by dilution with sand, since addition of sand would dilute both total and biodegradable COD. However, the variance in the method for measurement of biodegradability in pit latrine samples is inherently large, and the measured value (16%) is not much larger than the corresponding value of entrenched sludge after 12 months (15%). Differences for COD, volatile solids fraction and moisture content are significantly lower than the equivalent bottom-of-pit samples but these may be influenced by mixing with sand. Therefore, these results indicate that it is possible that the action of soil fungi can break down pit latrine content further than is achievable in a pit latrine, but the data is not sufficiently precise to prove the action of soil fungi.

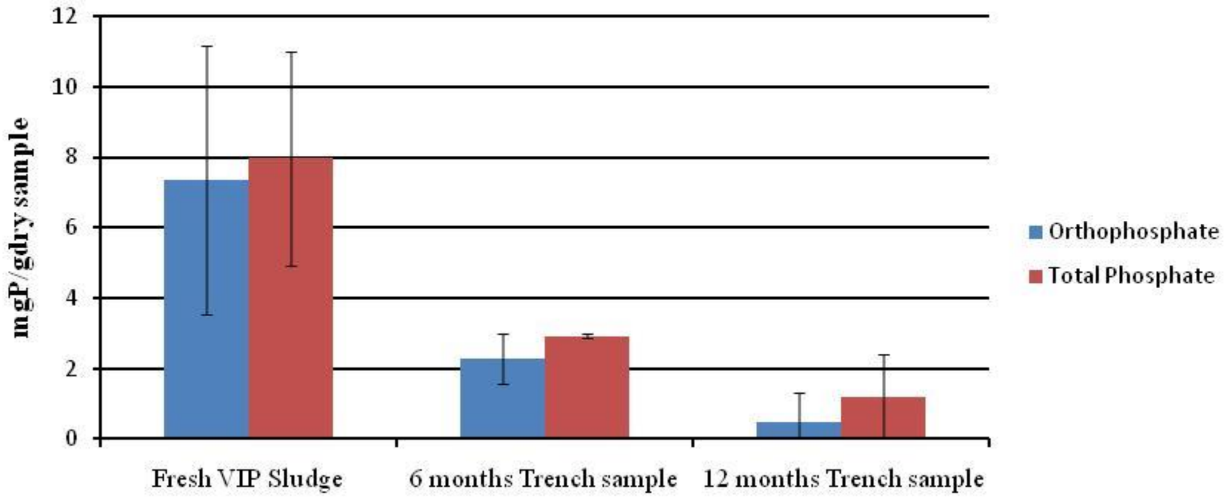
Nitrogen and phosphorus are essential nutrients for plant growth; the potential value of entrenching sludge for agroforestry is that nitrogen and possibly phosphorus present in the sludge may be a slow-release fertiliser for plant growth. Total kjeldahl nitrogen (TKN) has been used for many years to determine the concentration of nitrogen in various materials (Scarf, 1988). Thus, TKN analysis of the sludge before burial and after entrenchment was used as an approximation of the total nitrogen in the sludge.

Figure 5.10 presents the plot of the results obtained from the analysis of nitrogen and phosphorus content in VIP latrine sludge before the burial of the sludge and after significant periods of entrenchment of the sludge associated with tree planting. On each occasions, 15 sludge samples were exhumed from trenches at identified points very close to the root of the trees. It was found that the amount of nitrogen and phosphorus in the VIP latrine sludge before burial reduces when compared to that obtained from the exhumed sludge in the trenches. The amount of TKN released by the sludge is calculated from the difference in TKN on a wet basis between the initial TKN in sludge and the TKN remaining after 18 months. Thus, 17.5 mgN/gwetsample are lost over a period of 18 months

These results are consistent with the findings of Taylor (2012) that tree growth associated with buried sludge showed dramatically improved growth characteristics compared to a negative control, suggesting that the nitrogen and other nutrients released from the entrenched sludge may be biologically available as a fertiliser. A summary of the study conducted by Taylor (2012) is presented in **Appendix D**.



(a)



(b)

Figure 5.10: Results obtained from the analysis of nitrogen and phosphorus content in VIP latrine sludge before the burial of the sludge and after significant periods of entrenchment of the sludge associated with trees planting. Error bars represent 95% confidence interval on the mean on the replicate measurements.

5.3.2 Groundwater Quality Results at the entrenchment site

The suitability of a given groundwater quality for a particular purpose depends on the criteria or standards of acceptable quality for that use. Thus the results obtained from the laboratory analysis of the water samples collected from each of the monitoring boreholes has been compared with the South African Bureau of Standards No 241 specification where possible and DWAF (1999) discharge limits was also used. The result of the laboratory analysis of each determinant in the water samples collected from each of the monitoring boreholes is presented as follows;

<u>pH and Conductivity</u>

The pH value and the conductivity measurements for each of the monitoring boreholes were measured right at the borehole-head (Section 5.2.2). **Figure 5.11** presents the pH and conductivity results for each of the five monitoring boreholes. The pH of the water samples collected from each of the boreholes has remained consistent between slightly acidic pH (6.5) and neutral pH (7.5) since the commencement of the sampling process. This range of pH values obtained falls within the recommended maximum limit of pH value of 6 - 9 specified by the SABS specification for drinking water. The conductivity results obtained from the water samples from each of the boreholes has also been below the maximum allowable limit of 300 mS/m specified by the SABS specification for drinking water. Conductivity is a robust and sensitive measurement and thus changes with changes in nitrate, ammonia, chloride, sodium and phosphate. Therefore the conductivity measurement should be a reliable indicator of plumes in any ionic contaminants. From the data in **Figure 5.11a to 5.11e**, there are no sustained increases in conductivity suggesting that there has been no plume of ionic contaminants during the monitoring period.

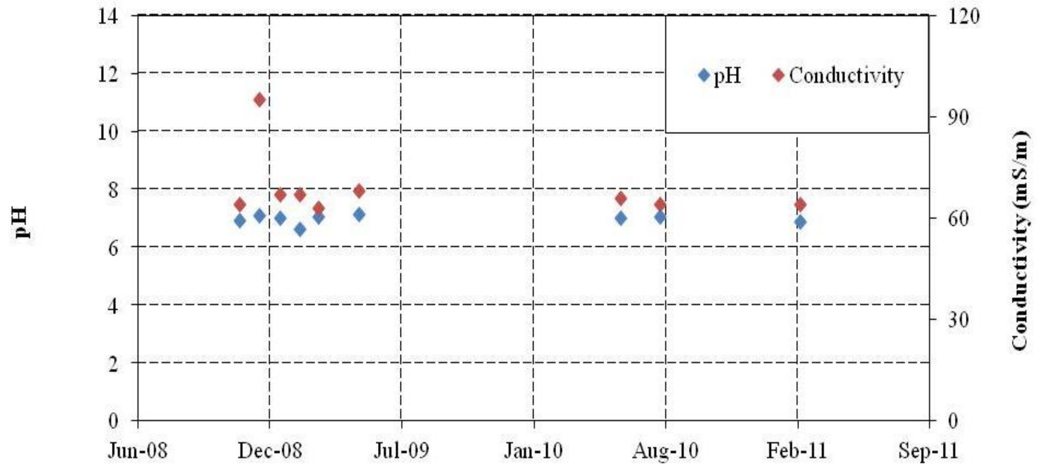


Figure 5.11a: pH and Conductivity Results for water samples from the monitoring Borehole 1 at the Umlazi VIP latrine sludge entrenchment site.

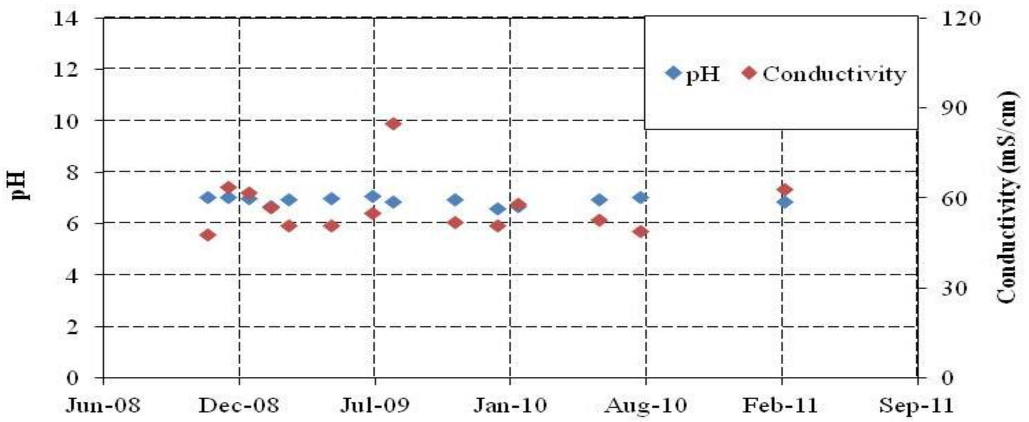


Figure 5.11b: pH and Conductivity Results for water samples from the monitoring Borehole 2 at the Umlazi VIP latrine sludge entrenchment site.

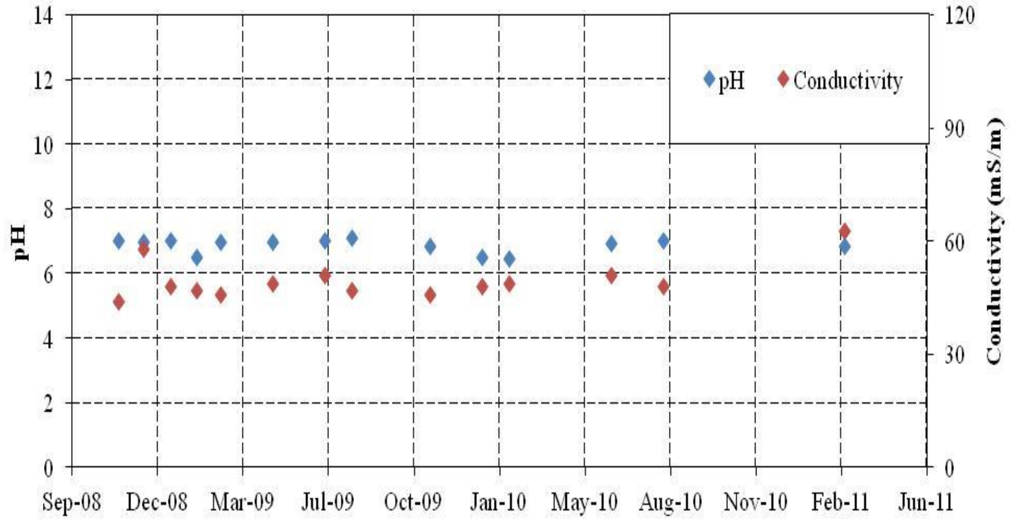


Figure 5.11c: pH and Conductivity Results for water samples from the monitoring Borehole 3 at the Umlazi VIP latrine sludge entrenchment site.

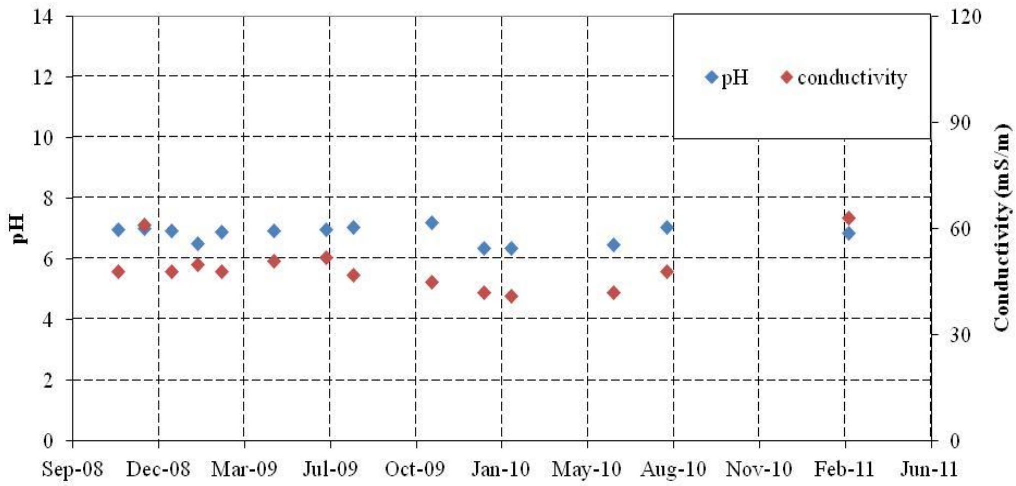


Figure 5.11d: pH and Conductivity Results for water samples from the monitoring Borehole 4 at the Umlazi VIP latrine sludge entrenchment site.

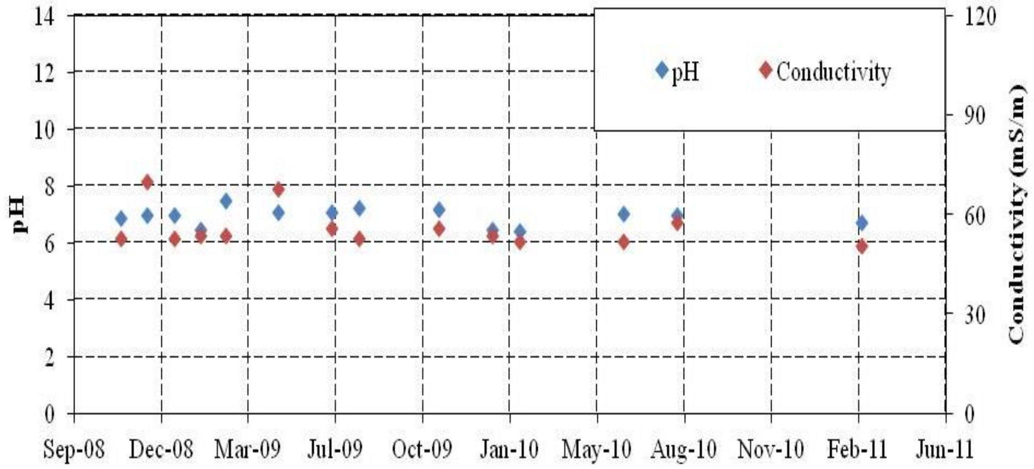


Figure 5.11e: pH and Conductivity Results for water samples from the monitoring Borehole 5 at the Umlazi VIP latrine sludge entrenchment site.

Sodium and Chloride concentrations

Figure 5.12 presents the sodium and chloride ion concentration obtained from the laboratory analysis of water samples collected from each of the five monitoring boreholes at the entrenchment site. It is observed that the concentration of sodium and chloride ions follow similar trends except for borehole number 2 in which there is a peak in the chloride and sodium ions measured as indicated by the red rings. It is believed that the peaks indicated in the figure by the red rings might be the result of analytical error or that these values were incorrectly recorded as these peaks do not correspond to the equivalent sodium or chloride measurements for the same sample. However, the values obtained for sodium concentration for each of the boreholes since the commencement of the sampling process were below the maximum allowable limits of 400 mg/l specified by the SABS specification for drinking water. The values obtained for the chloride concentration for all samples also fall below the maximum allowable limit of 600 mg/l specified by the SABS specification for drinking water. Overall there was no significant increasing trend observed in either the sodium or chloride concentrations for any of the boreholes.

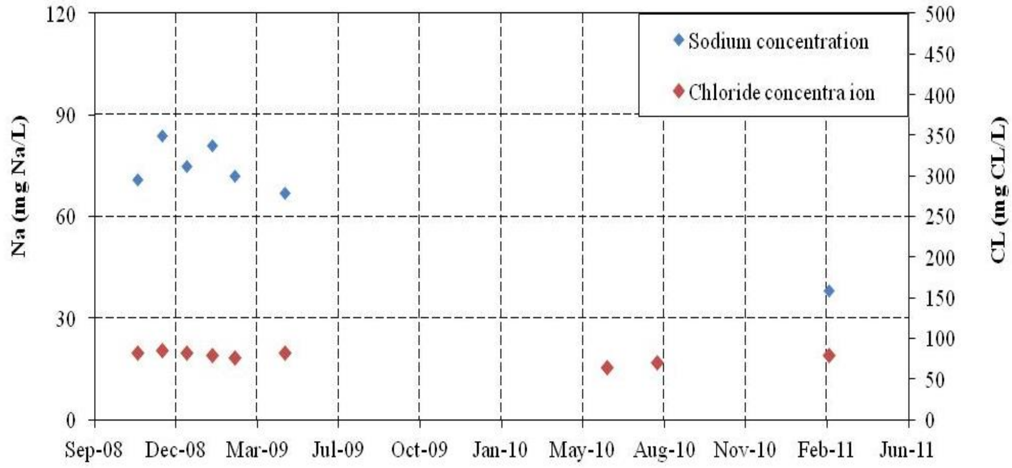


Figure 5.12a: Sodium (Na^+) and Chloride (Cl^-) concentration in water samples from the monitoring borehole 1 at the Umlazi VIP latrine sludge entrenchment site.

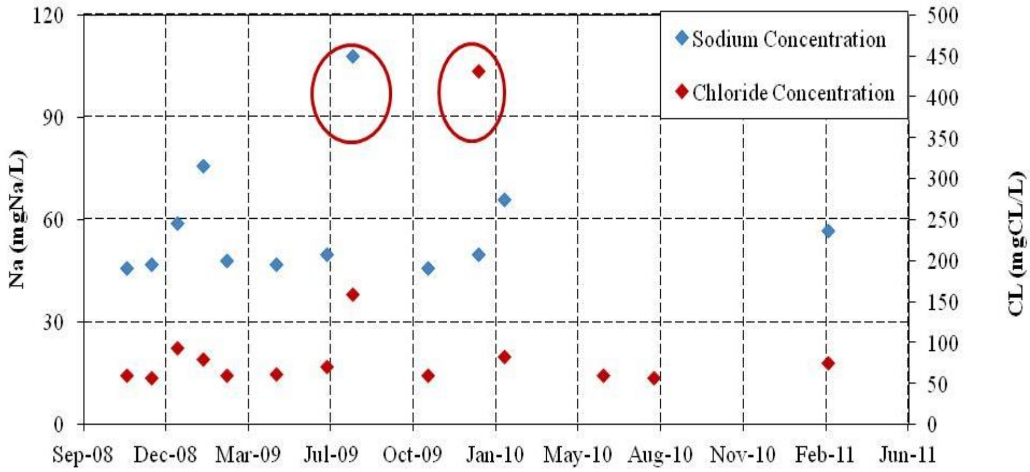


Figure 5.12b: Sodium (Na^+) and Chloride (Cl^-) concentration in water samples from the monitoring borehole 2 at the Umlazi VIP latrine sludge entrenchment site.

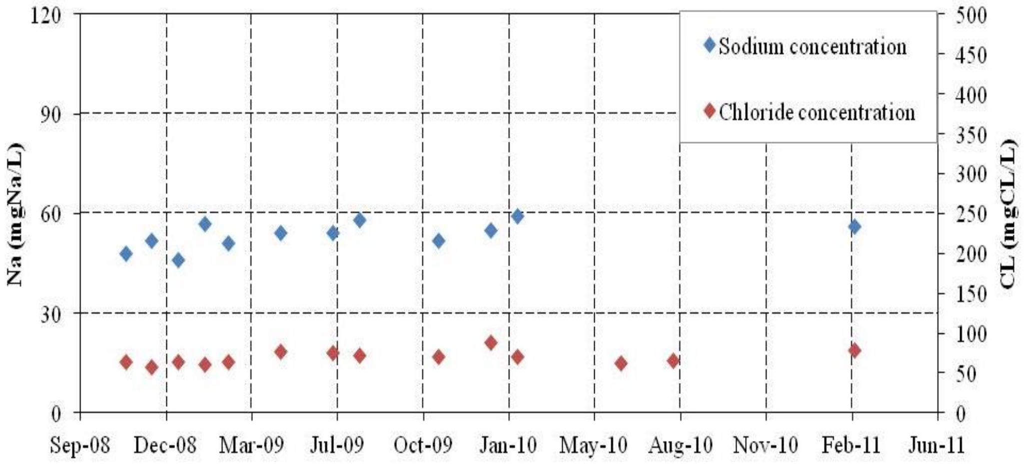


Figure 5.12c: Sodium (Na^+) and Chloride (Cl^-) concentration in water samples from the monitoring borehole 3 at the Umlazi VIP latrine sludge entrenchment site.

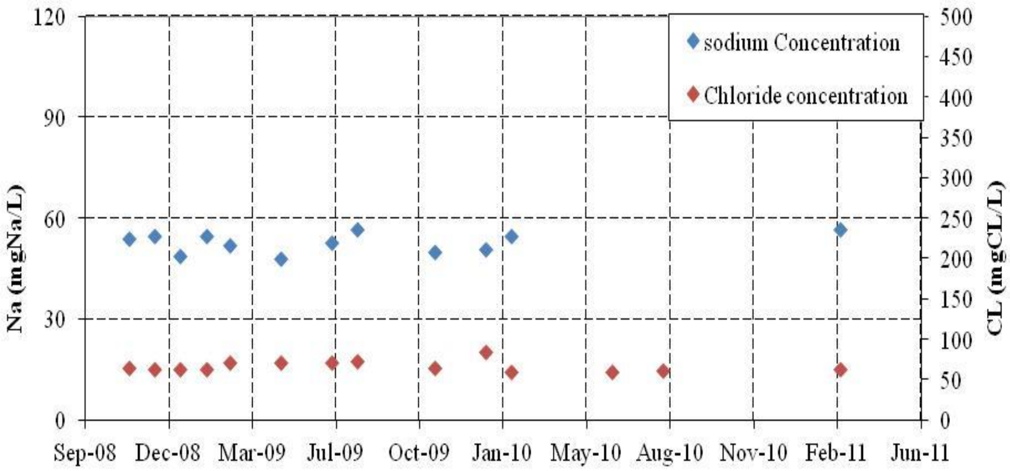


Figure 5.12d: Sodium (Na^+) and Chloride (Cl^-) concentration in water samples from the monitoring borehole 4 at the Umlazi VIP latrine sludge entrenchment site.

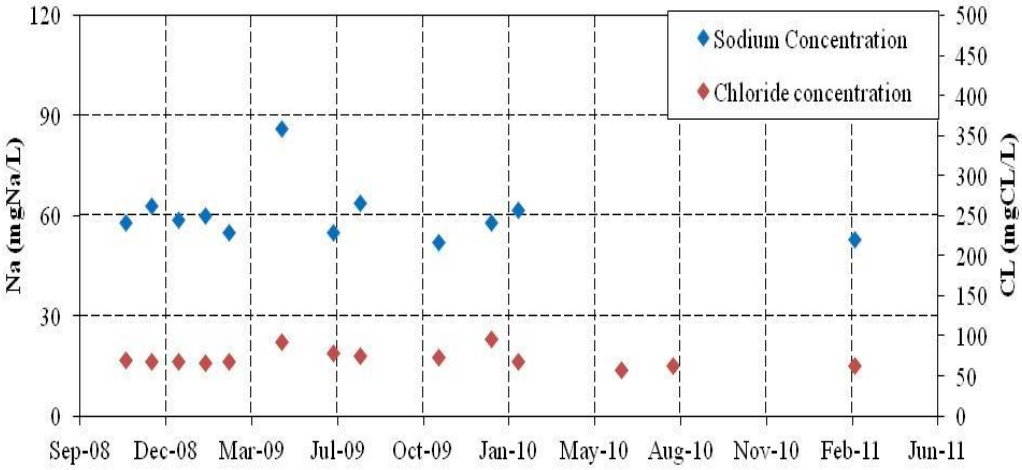


Figure 5.12e: Sodium (Na^+) and Chloride (Cl^-) concentration in water samples from the monitoring borehole 5 at the Umlazi VIP latrine sludge entrenchment site.

<u>Chemical Oxygen Demand</u>

The results obtained for the chemical oxygen demand performed on the water samples collected from the five monitoring boreholes is presented in **Figure 5.13**. COD results for the water samples collected from the five boreholes follow similar trends for all of the boreholes. Since the commencement of the sampling procedure the COD of the water samples has been within the maximum allowable effluent discharge target as presented in DWAF (1999). There is a spike in the measured COD between December 2008 and Febuary 2009 (4 to 6 months after trenching of sludge commenced) which might indicate a plume of organic pollutants. However no corresponding increase in ionic components was observed in this period.

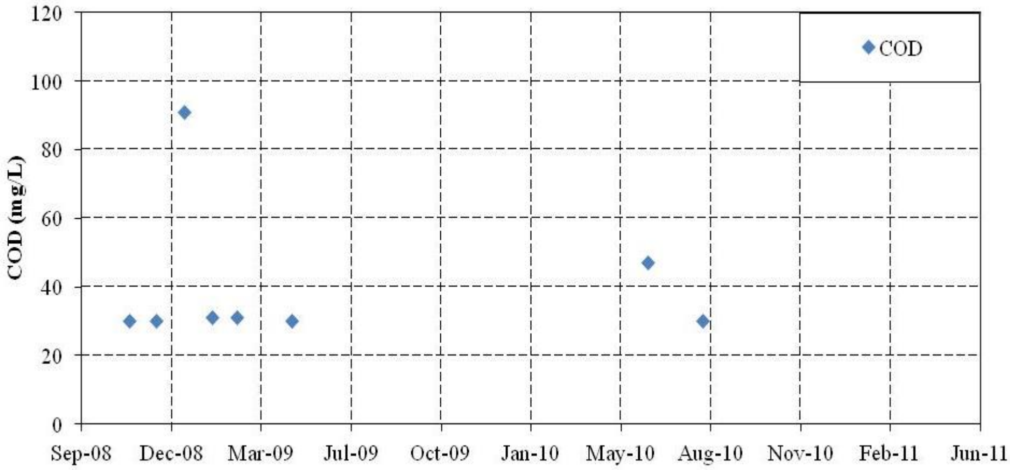


Figure 5.13a: Chemical Oxygen Demand in water samples from the monitoring borehole 1 at the Umlazi VIP latrine sludge entrenchment site.

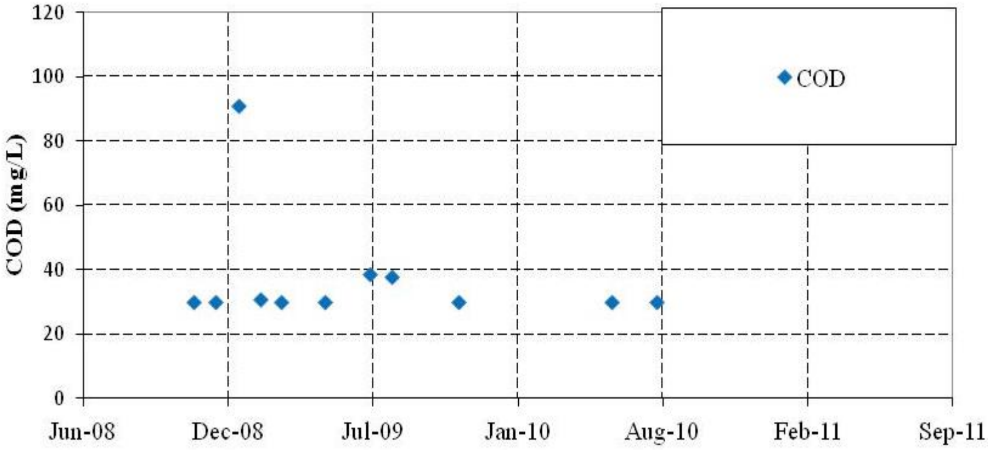


Figure 5.13b: Chemical Oxygen Demand in water samples from the monitoring borehole 2 at the Umlazi VIP latrine sludge entrenchment site.

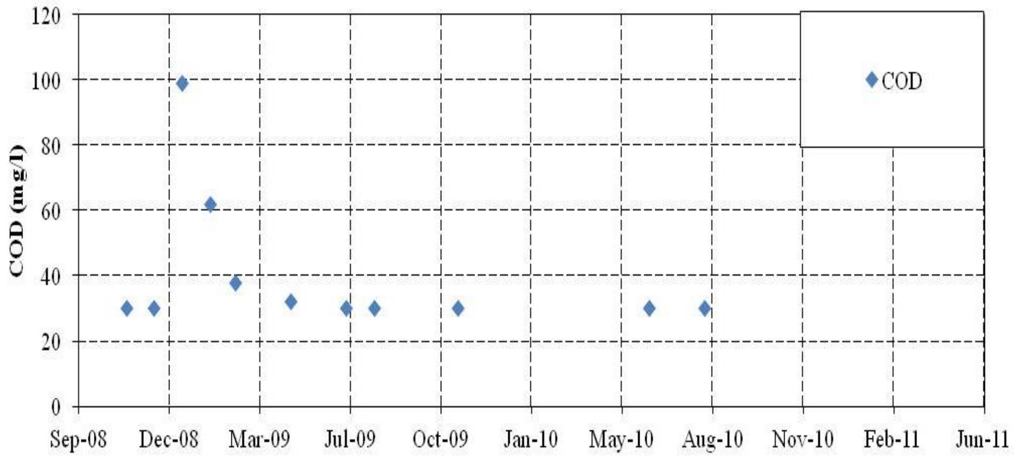


Figure 5.13c: Chemical Oxygen Demand in water samples from the monitoring borehole 3 at the Umlazi VIP latrine sludge entrenchment site.

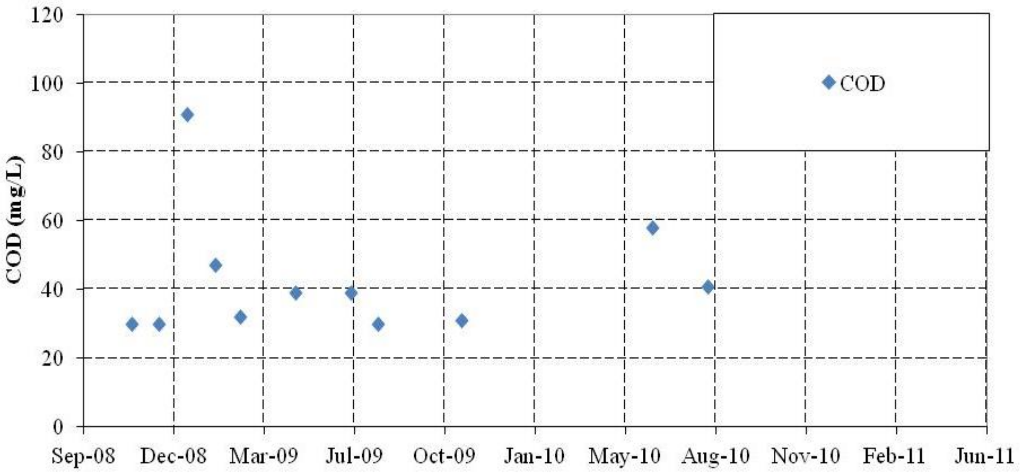


Figure 5.13d: Chemical Oxygen Demand in water samples from the monitoring borehole 4 at the Umlazi VIP latrine sludge entrenchment site.

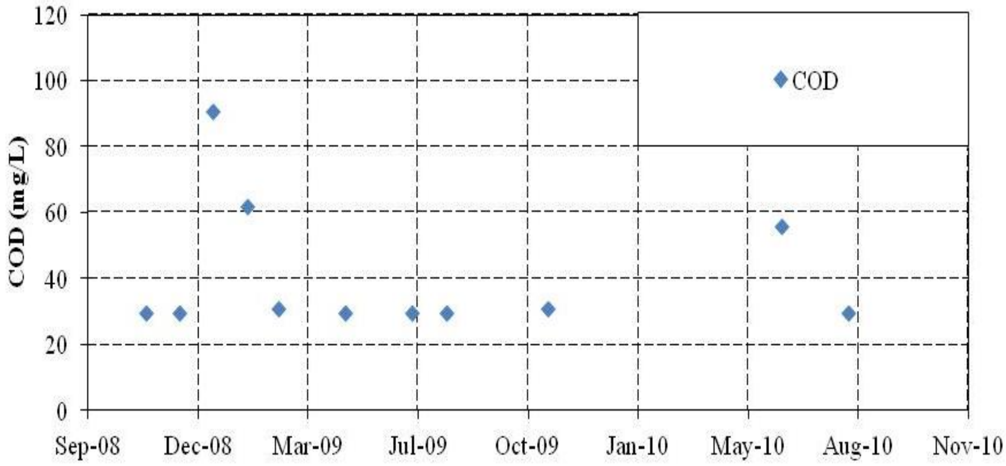


Figure 5.13e: Chemical Oxygen Demand in water samples from the monitoring borehole 5 at the Umlazi VIP latrine sludge entrenchment site.

<u>Nitrate and Ammonium concentration</u>

Figure 5.14 presents the nitrate and ammonium concentration of the water samples collected from the five boreholes at the Umlazi entrenchment site on a monthly basis. Nitrate and ammonium concentration usually serve as the determinant of pollutant in most groundwater monitoring programmes. A slight elevation in nitrate is observed in all boreholes between December 2008 and March 2009 but the increase was not significant after, however the nitrate concentrations returned to the base line. Two outlier measurements were observed in borehole 3 and borehole 5 at different times. There is no precedent for such a big change. The results obtained from the analysis of water samples collected from each of the five boreholes at the VIP latrine entrenchment site were consistently low and within the maximum allowable limits of 10 mgN/L for nitrate and 15 mgN/L for ammonium as specified by the SABS specification for drinking water.

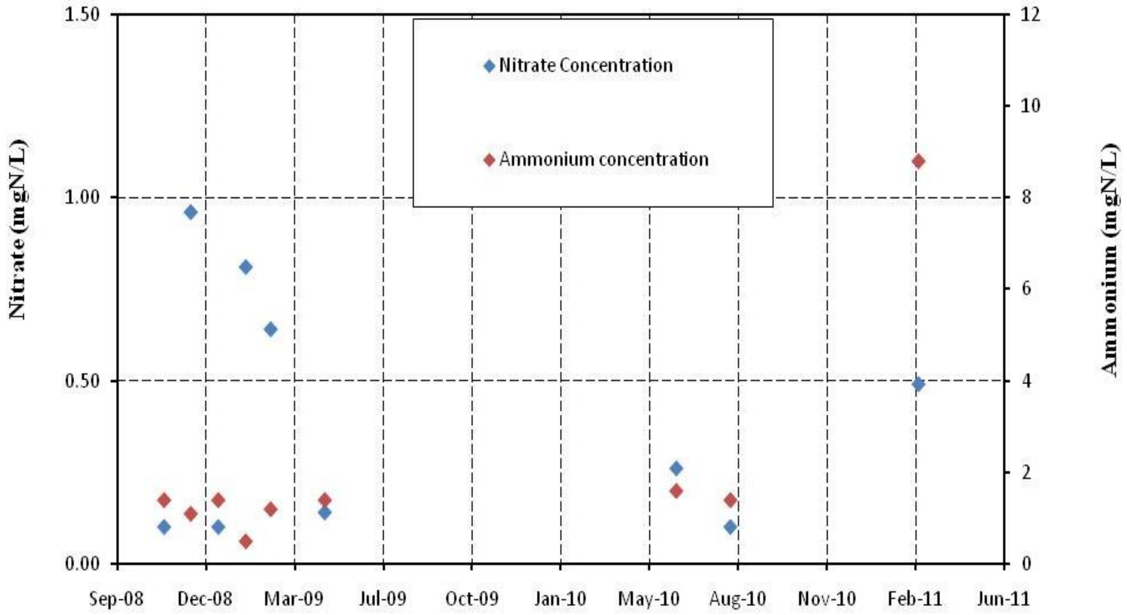


Figure 5.14a: Nitrate and Ammonium concentration in water samples from the monitoring borehole 1 at the Umlazi VIP latrine sludge entrenchment site.

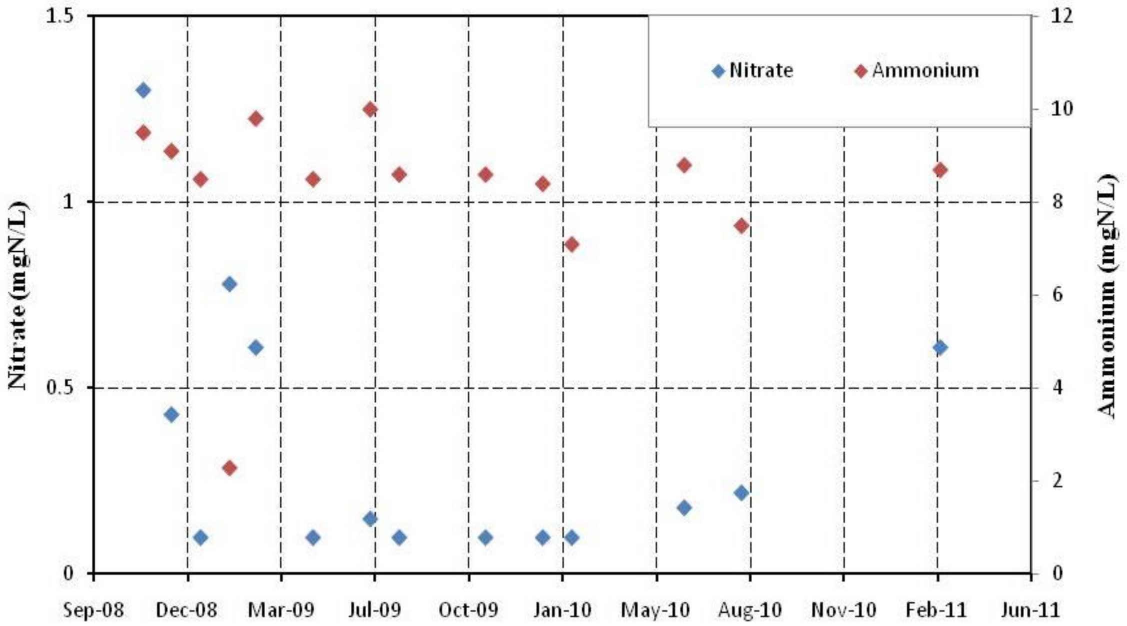


Figure 5.14b: Nitrate and Ammonium concentration in water samples from the monitoring borehole 2 at the Umlazi VIP latrine sludge entrenchment site.

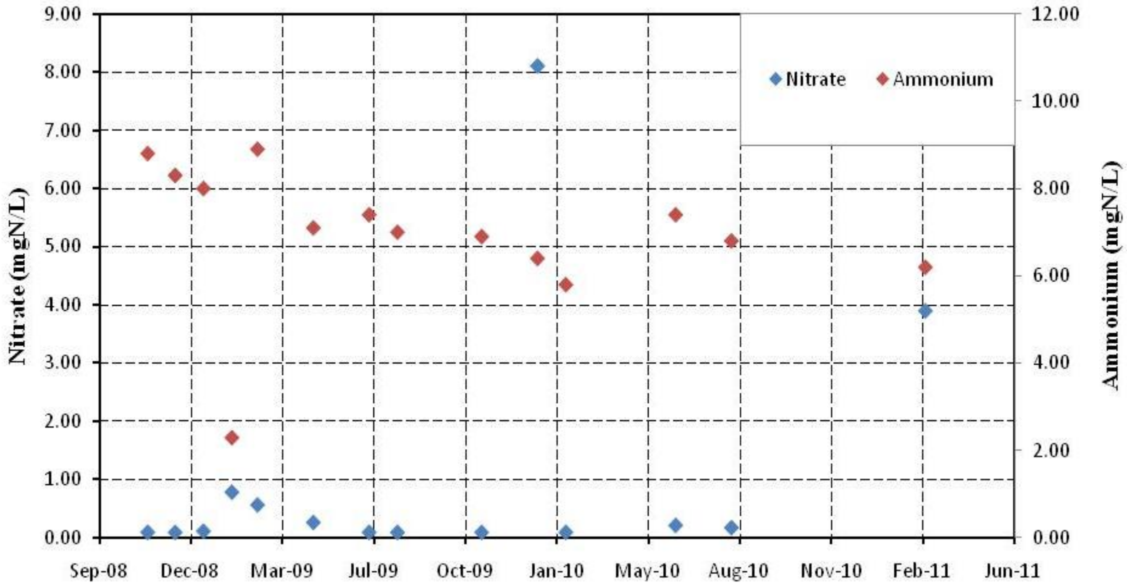


Figure 5.14c: Nitrate and Ammonium concentration in water samples from the monitoring borehole 3 at the Umlazi VIP latrine sludge entrenchment site.

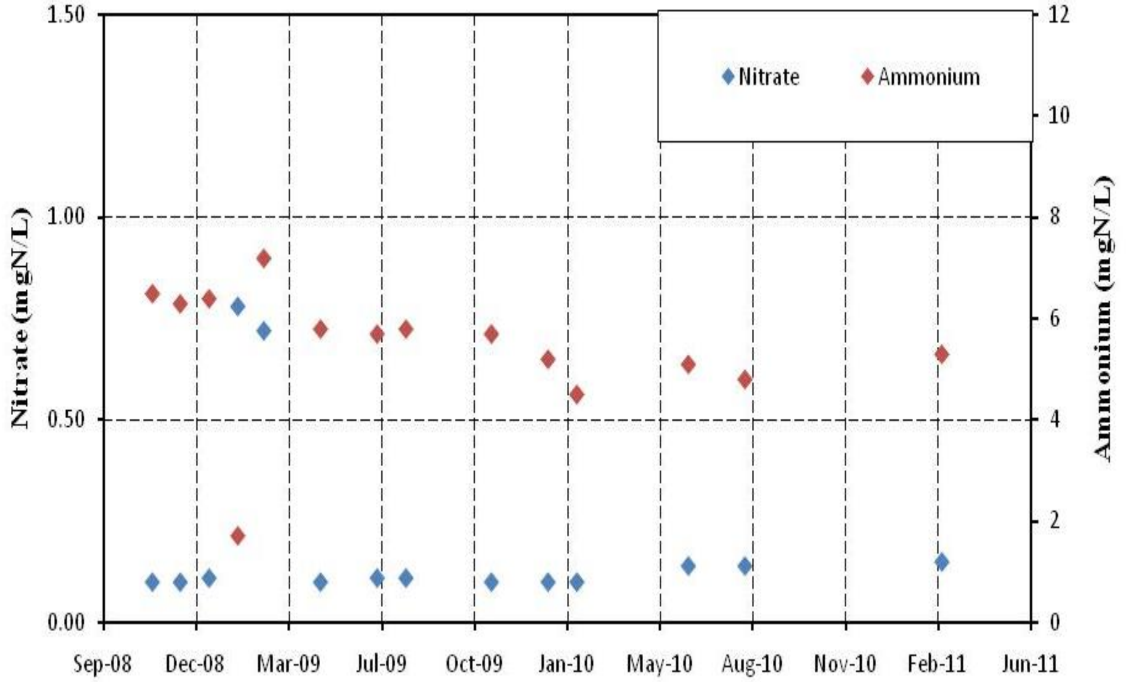


Figure 5.14d: Nitrate and Ammonium concentration in water samples from the monitoring borehole 4 at the Umlazi VIP latrine sludge entrenchment site.

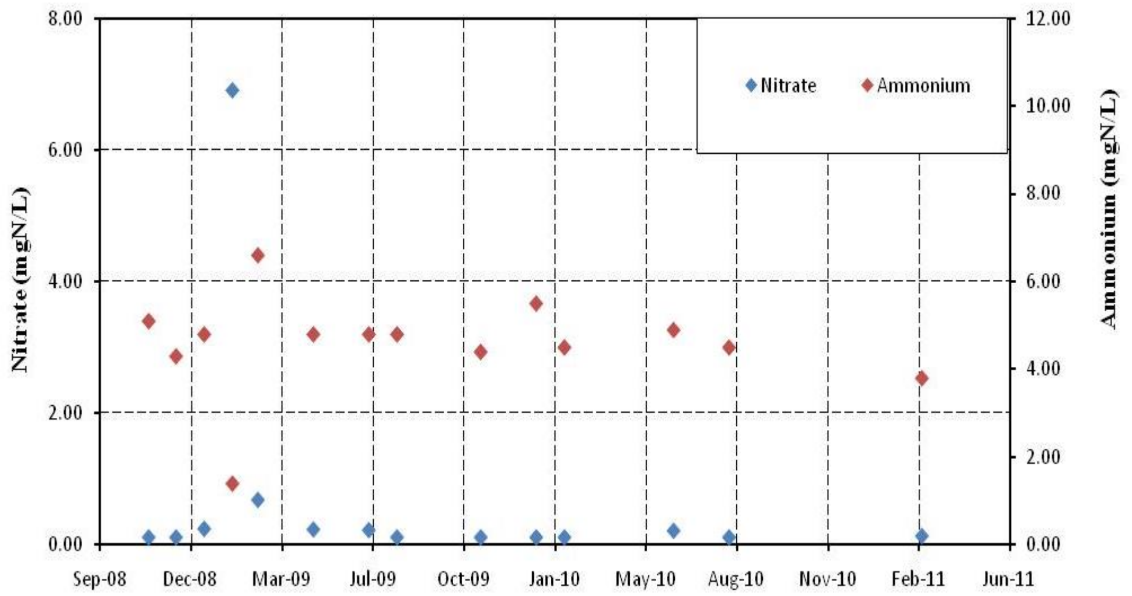


Figure 5.14e: Nitrate and Ammonium concentration in water samples from the monitoring borehole 5 at the Umlazi VIP latrine sludge entrenchment site.

<u>Orthophosphate</u>

The results of the analysis performed on water samples collected from the five boreholes for the determination of phosphate compounds are presented in **Figure 5.15.** Although there seems to be an increase in orthophosphate in borehole 2 and borehole 3, the data is very scattered and the magnitude of maximum change is very small (about 0.1 mgP/L) therefore nothing can be inferred from the data. However, since the commencement of the groundwater monitoring programme the results obtained from the laboratory analysis of collected water samples from the five monitoring boreholes never exceeded the recommended maximum limit of 10 mgP/L specified by SABS specification for drinking water.

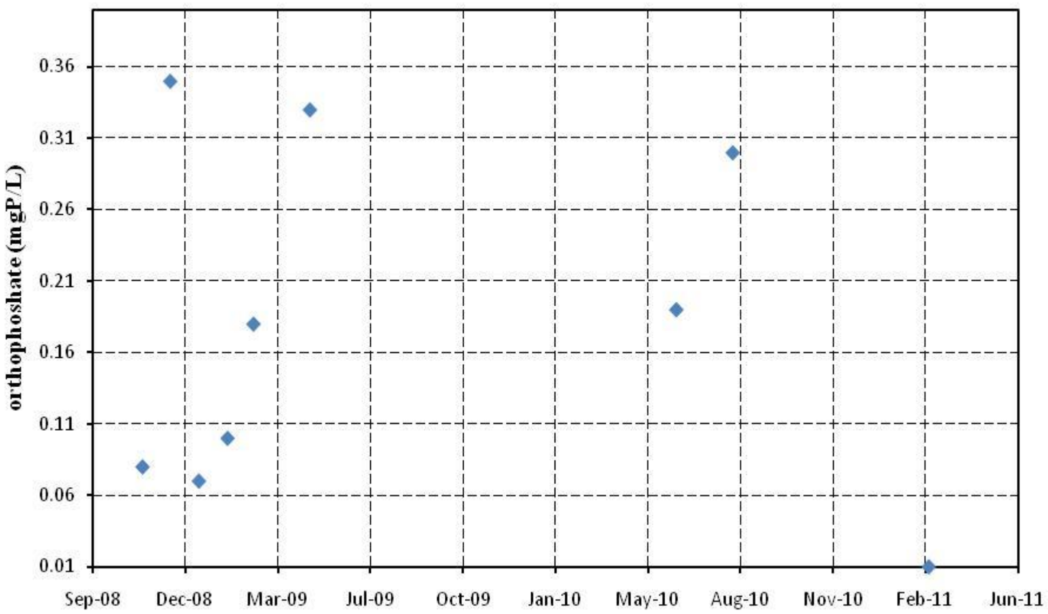


Figure 5.16a: Orthophosphate in water samples from the monitoring borehole 1 at the Umlazi VIP latrine sludge entrenchment site.

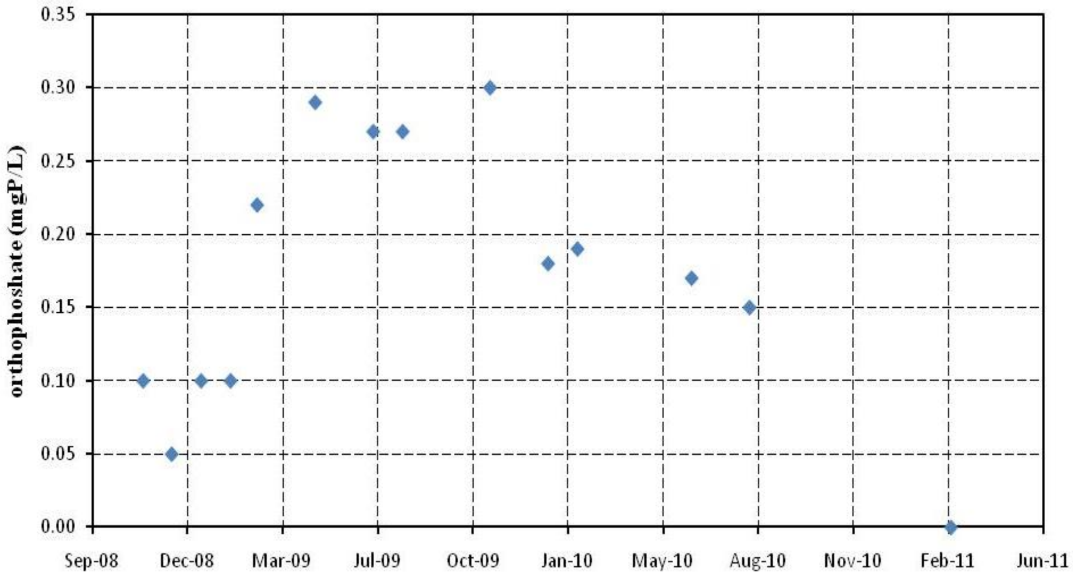


Figure 5.16b: Orthophosphate in water samples from the monitoring borehole 2 at the Umlazi VIP latrine sludge entrenchment site.

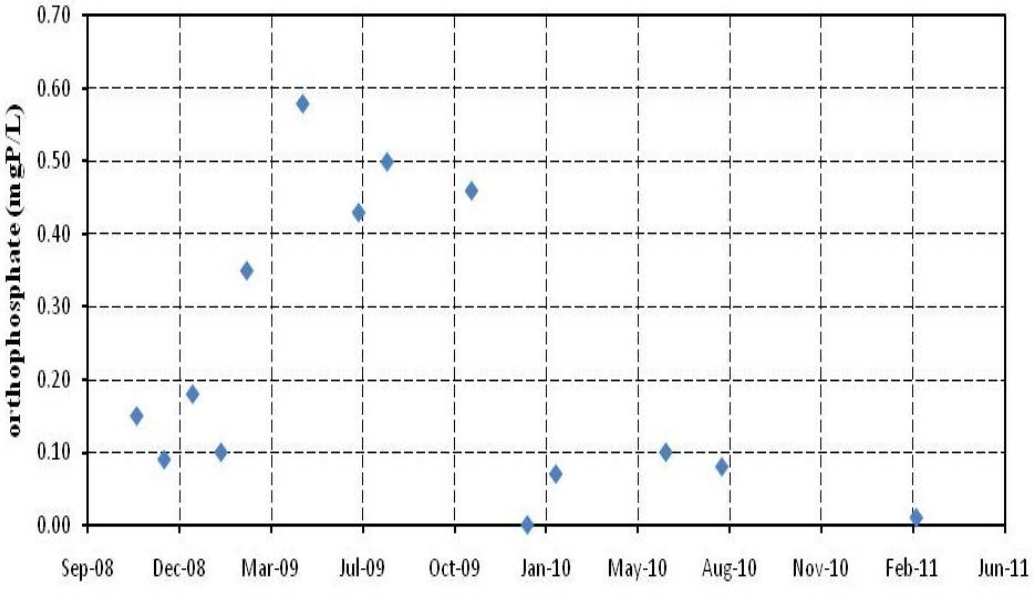


Figure 5.16c: Orthophosphate in water samples from the monitoring borehole 3 at the Umlazi VIP latrine sludge entrenchment site.

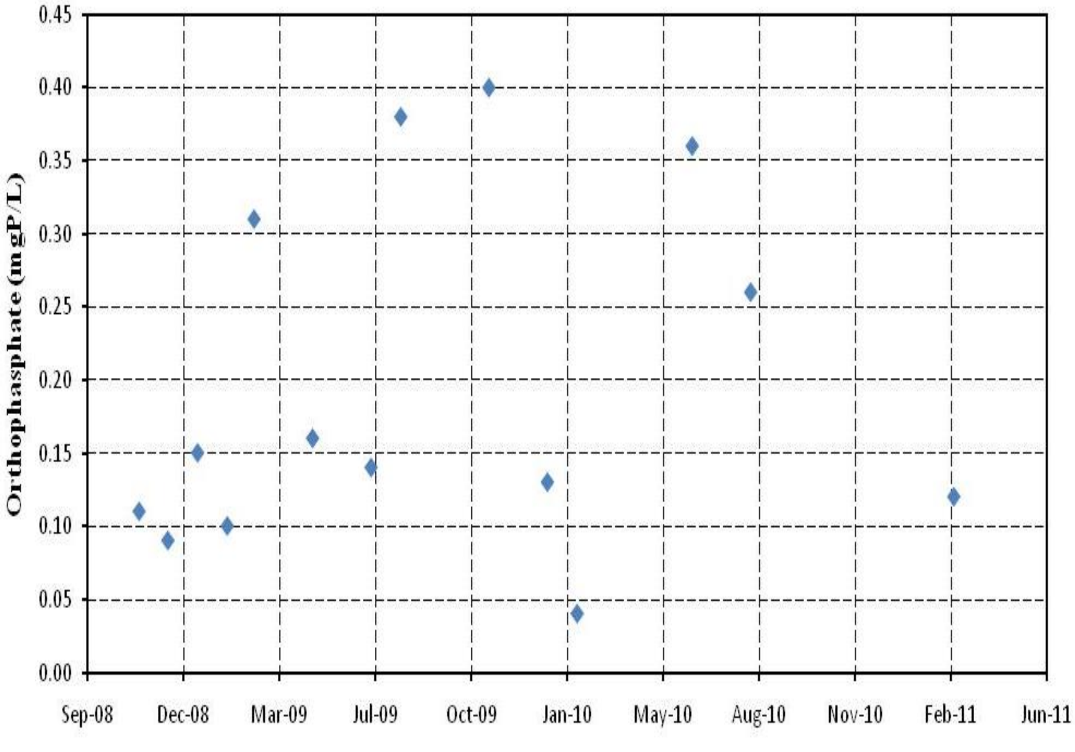


Figure 5.16d: Orthophosphate in water samples from the monitoring borehole 4 at the Umlazi VIP latrine sludge entrenchment site.

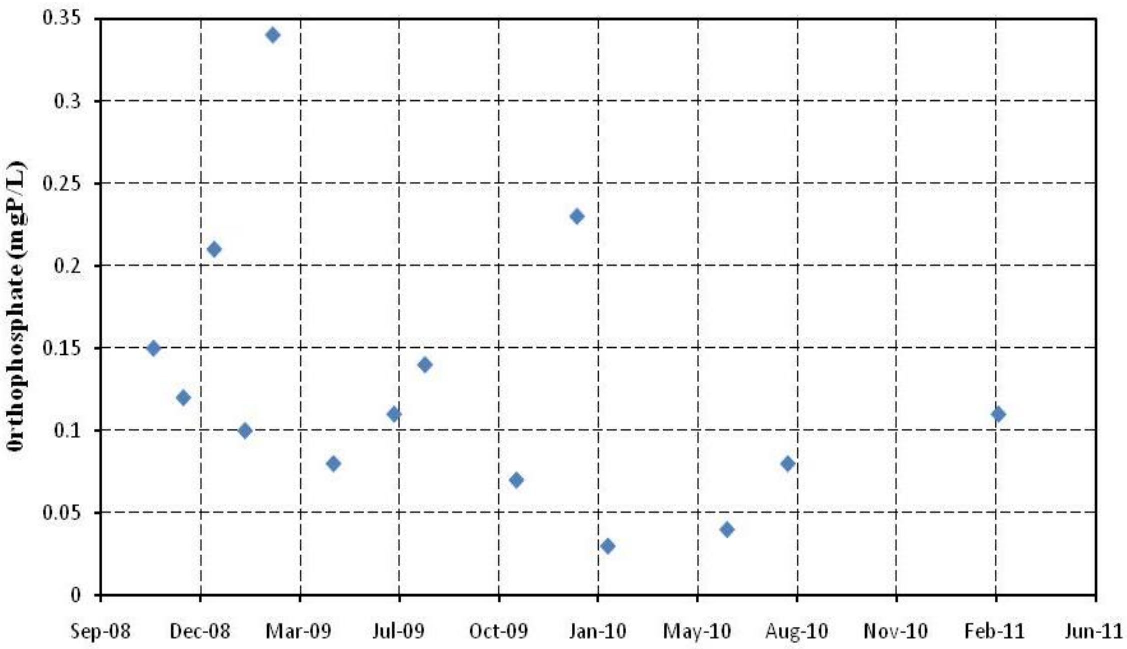


Figure 5.16e: Orthophosphate in water samples from the monitoring borehole 5 at the Umlazi VIP latrine sludge entrenchment site.

Bacteriological Results

The bacteriological analysis involved analysis of E-coli, total coliforms and also total organisms in the water samples collected from the five monitoring boreholes from the commencement of the sampling programme. Interestingly, it was found that since the commencement of the sampling programme at the entrenchment site the *E. coli* count from the water samples was zero and the other bacteriological tests were below the detection limits for these tests. The results indicate that no microbial contamination of groundwater has occurred during the monitoring period.

5.4 SUMMARY

This chapter of the thesis investigated the possible benefits of deep row entrenchment and beneficially reusing pit latrine sludge for agroforestry. The primary objective was to (i) to monitor the changes in the characteristics of VIP latrine sludge with time in trenches and (ii) to monitor the characteristics of the surrounding groundwater so as to determine the effect of entrenchment on the sludge content as well as the surrounding groundwater.

Table 5.2 presents a summary of the results obtained from the characterization of freshly exhumed VIP sludge that arrived at the entrenchment site before being buried in trenches as well as the changes in the characteristics of this sludge with time. These values were compared to similar measurements performed on samples taken from the bottom of 16 pit latrines presented in **Chapter 4** after they had been emptied. It was found that, for all of the analytes presented, sludge that have been entrenched for certain period of time (1.5yrs) were lower than the equivalent concentrations measured in samples taken from the bottom of a pit latrine although not significantly in some cases. This is an indication that biodegradation and dewatering occur in pit latrine sludge after it has been buried in trenches, although it is not clear how much of the change noted was a function of dilution by sand.

Generally, the data show high variance, but the decreasing trends are clear. It appears that an initial rapid degradation and moisture loss occurs: this is probably as a result of the most recently deposited and therefore unstabilised pit latrine contents degrading. Thereafter, a slow decrease in volatile solids, COD and moisture is observed; until final values are reached that appear to be lower than the lowest values obtained in pit latrine bottoms sludge samples presented in **Chapter 4**. This decrease below the concentrations measured in the samples taken from the bottom of full pit latrines, could be explained by the action of fungi that result in cellulase activity that reduces the remaining potentially degradable material. However this has not been proven.

Given, the extremely large variances in determinations of concentration in this type of heterogeneous material, it will be difficult to obtain further insight into these mechanisms using additional physico-chemical measurements. However, the role of fungi in stabilisation of sludge in entrenchments could be further investigated through biochemical and microscopic techniques.

Table 5.2: Summary of fresh VIP sludge contents and Trench samples. Data are presented as mean value ± 95% conf. Interval, [min, max]

Parameters	Units	Freshly exhumed VIP	1yr Trench sample	1.5yr Trench sample
Moisture	%	74.86±1.92 [62.54,89.44]	54.08±4.09 [25.40, 67.55]	42.91±3.83 [59.81,24.49]
Volatile solids	%gVS/gTS	58.90±4.98 [18.11,86.25]	28.63±3.87 [11.53,50.71]	27.24±2.87 [1.55,51.01]
COD	gCOD/gdry samples	0.25±0.04 [0.12,0.44]	0.15±0.01 [0.11,0.20]	0.14±0.03 [0.09,0.19]
Biodegradability	% g/g samples	28.90±4.21 [22,36]	14±1.87 [12,19]	

Table 5.3 presents a summary of the results obtained from the groundwater quality measurement at the entrenchment site. The boreholes were sunk parallel to the trenches and it was expected that should there be a significant release of nutrients; the direction of the contamination plume would be in a generally eastern direction from the trenches towards the river. Therefore it is expected that potential contamination from the trenches would first be observed in borehole 3 and probably in borehole 2.

As presented in **Table 5.1**, the soil at the entrenchment site is predominantly composed of sand (approximately 97 %). Thus it is expected that of all soil types, entrenchment in sandy soil would result in the biggest risks of groundwater contamination by leachate generated from the sludge in the trenches (Sikora et al, 1978). This is based on the fact that hydraulic conductivity is usually very high in sandy soils and therefore the movement of leachate would be relatively fast (Morris and Johnson, 1967; Todd, 1976 and Sikora et al, 1978). It is expected that high levels of NO_3^- and NH_4^+ would be produced in sandy soils (Sikora *et al*, 1978). Typical groundwater plume velocity in sandy soil ranges between 2 m/day to 2 m/year and the flows could be accelerated by mechanisms such as wells and drains if found around the entrenchment site (Todd, 1976). Thus if it is assumed that the groundwater plume velocity for the entrenchment site is approximately the same or within the range presented by Todd (1976) then it would be expected that significant levels of nutrient contaminant would be observed in the monitoring boreholes at the entrenchment site between 28 days – 28 years. However, the analysis of water sample collected from the five monitoring boreholes at the Umlazi entrenchment site has indicated that the burial of sludge in trenches did not have a profound effect on groundwater for the duration in which monitoring was carried out.

However, caution is advised in drawing conclusions from these results presented because it is possible that any plumes may not have reached the boreholes during the monitoring period. Possibly a range of different distances from the trenches might have helped to better observed any pollution peak that might have occurred especially if it was a fast moving, once-off release.

It should also be noted that the results presented are for approximately 3 years of monitoring. This may not have been a long enough period to either support or refute the fact that there would be low or negligible impact of entrenching VIP latrine sludge on the surrounding groundwater. It is also not possible to conclude whether nutrients released by biodegradation were taken up by trees, although the evidence suggests this may be the case. An overall nutrient balance of the site would be required. In summary, it is not possible to conclude that no groundwater contamination will occur on the basis of this study, but given the relatively high loading rates, poor soil quality, the length of the monitoring period and the improved growth of trees, it seems unlikely that groundwater contamination will be a major concern in this option of pit latrine sludge disposal.

Thus, the entrenchment of VIP latrine sludge for agroforestry could offer several benefits:

- It allows the slow release of nitrogen compounds from the sludge which carries less risks of leaching compare to chemical fertilizers.

- It minimizes the possibility of contact between human and pathogens in the sludge, providing a safe disposal option for the sludge.
- It eliminates the risks of surface water contamination by pollutants that exists with the surface application of synthetic fertilizers
- There is less reliance on synthetic fertilizer which makes use of increasingly scarce phosphorus which as it grows increasingly expensive, increases food prices.

Table 5.3: Summary of results obtained from groundwater monitoring programme compared with SABS specification for drinking water. Data are presented as [min, max]

Parameters	Units	BH 1	BH 2	BH 3	BH 4	BH 5	SABS Limits
pH		[6.60,7.14]	[6.70,7.1]	[6.50,710]	[6.50,7.20]	[6.5,7.5]	6-9
Conductivity	mS/m	[63, 95]	[48,85]	[44,58]	[45,61]	[53,70]	300
DO	mg/L	[1.03,3.20]	[1.10,3.05]	[0.35,3.10]	[0.30,3.20]	[0.2,3.4]	
Sodium	mgNa/L	[67,84]	[46,108]	[48,58]	[48,57]	[55,64]	400
Chloride	mgCL/L	[75,86]	[58,160]	[58,76]	[63,73]	[68,93]	60
Nitrates	mgN/L	[<0.1,0.96]	[<0.1, 1.3]	[<0.1,0.79]	[<0.1,0.78]	[<0.1,6.9]	10
Ammonium	mgN/L	[<0.5,0.14]	[2.3, 10]	[2.30,8.80]	[1.7,6.5]	[1.4,6.6]	15
Orthophosphate	mgP/L	[0.07,0.35]	[0.05,0.30]	[0.09,0.58]	[0.09,0.40]	[0.08,0.34]	10
E-coli	Cfu/100 ml	0	0	0	0	0	0
COD	mg/l	[<30,91]	[<30,91]	[<30,99]	[<30,91]	[<30,91]	65

6 EFFECTS OF PIT ADDITIVES ON SLUDGE CONTENT IN VIP LATRINES

It was established in **Chapter 4** that the digestion process taking place within pit latrines is predominantly anaerobic digestion; however it is believed that aerobic digestion could also take place at the surface of the pit and sometimes on the side of the pit if the pit is not lined and if there is contact with the soil. The process of anaerobic digestion of pit latrine sludge content is relatively slow, resulting in build up of organic waste, odour production and fly nuisance which could pose significant risks to public health and the environment. Various suppliers and manufacturers of commercial pit latrine additives claim to provide solutions to the perceived odour and fly problems including; reducing the rate at which sludge builds up in pits and even reducing the volume of sludge content within pit latrines as well decomposing the pit latrine sludge to compost. These claims have led to considerable interest in the use of these products for controlling sludge accumulation rates in pit latrines by households and authorities around the country.

However from the available literature reviewed in **Chapter 2** on the efficacy of pit latrine additives, there is no basis for pronouncing whether any of the additives have any reliable benefits, or what the scientific explanation for any of the alleged benefits could be. A summary of the main conclusions of the studies presented in the literature are:

- The Taljaard study concluded that the use of pit latrine additives might be beneficial; however the interpretation of the result obtained in this study was challenge by Foxon *et al* (2009) who stated that the Taljaard study used application rates many times higher than the prescribed application rates.

- In the study conducted by Sugden (2006), it was concluded that all the four stages of anaerobic digestion took place in all the trials but there was no evidence to show that the use of any of the bio-additive either enhance or inhibited the anaerobic digestion process.

- Foxon *et al* (2009) concluded that the use of commercial pit latrine additives to treat pit latrine sludge content was unable to accelerate biodegradation rate and mass loss in laboratory test units.

- In the field trial to test efficacy of pit latrine additives presented in Buckley *et al*, (2008) it was also concluded that the addition of pit latrine additives to sludge content in the pit did not have any significant effect on sludge accumulation rates or sludge volume reduction in the pit. However it was indicated in that study that the use of simple height measurement do not provide accuracy in the measurement of volume reduction in pit latrines. It was proposed that a stereographic measurement technique using a number of photographs of the pile of pit contents could be used to determine the shape and depth of the pit surface using image recognition software.

In this chapter because of the discrepancy in the findings of previous studies, research into the efficacy of pit latrine additives in reducing sludge accumulation rate or sludge volume in pit latrines was conducted. This was conducted to fill the gaps in previous studies conducted and to provide evidence supporting or refuting claims by pit latrine additive suppliers that their products do assist in pit latrine sludge management and to assess how much effort is required to adequately measure changes in pit sludge contents. Thus it was hypothesized that:

- Available commercial pit latrine additives can significantly affect rate of mass loss or reduce pit sludge accumulation rate or sludge volume in a pit latrine by increasing bacterial activity through augmentation of the bacterial population or addition of enzymes.

- A detailed surface map of the pit contents is required at two different times to quantify the amount of sludge that has accumulated during that time interval.

Both laboratory and field trials were undertaken to determine whether the two kinds of trials would give similar indication as to whether the use of pit latrine additives might be promising in controlling sludge accumulation rates within pit latrines. It is expected that the effect of the additives on sludge content will differ considerably between different pits even if the measurement technique is accurate. This is due to the fact that a number of factors (such as number of users, presence of macro-invertebrates, rubbish deposited, temperature, availability of oxygen within the pit, moisture content etc) which influence the biological activity within the pit differ from pit to pit.

6.1 PROTOCOL FOR TESTING THE EFFICACY OF PIT ADDITIVES

Commercially available pit latrine additives which have been used in various research studies into the investigation of the efficacy of additives on pit latrine sludge content were listed and suppliers were contacted. Four out of the numerous suppliers contacted responded and supplied additives for the trials. Two products were selected since in a previous study (Foxon *et al*, 2009) eleven different additives were tested in laboratory trials and no significant difference was observed between the different treatments.

6.1.1 Pit Latrine Additive Description

The two additives selected for this investigation are identified as Product A and Product B. According to the description provided by the supplier of Product A, the additive is a concentrated powder containing freeze dried bacteria with a total bacterial count of about 5 billion cfu/g. The product is said to be used as a waste digestant in septic systems, ventilated improved pit latrines, grease traps, drain lines, food processing plants and for similar waste and odour control problems. Product A has a characteristic yeast like odour, is a free flowing powder, has a neutral pH and is reported to be most effective within pH and temperature ranges of 5.5 - 10.5 and 7-60°C respectively. Product B was a brownish powder and described by the suppliers as being effective in:

- Elimination of bad odours at pit toilets
- Removal of flies and insects
- Stopping the spread of diseases from the sewage
- Reducing solids level
- Decomposing sewage to compost

6.1.2 Laboratory Trials for Testing Pit Additives

The laboratory trials for testing the effect of pit additives on sludge content collected from pit latrines followed the same laboratory protocol developed by Foxon *et al* (2009). Representative samples of sludge content from a pit latrine were collected from the surface of the pit beneath the pit pedestal through the back plate using a long shovel and hand fork. Samples were collected in plastic bags and placed in buckets which were tightly sealed to limit the exposure of collected sludge samples to air. This was done in order to limit the biological oxidation of collected sludge samples and also to ensure that sludge samples collected from the pit latrines do not substantially differ to the sludge in the pit. Often when the samples were transported to the laboratory, the trials commenced immediately but if the trials were not commencing immediately, collected sludge samples were stored in the cold room at 4°C. Sludge samples collected from the surface of the pit latrine were thoroughly mixed in order to obtain homogeneity of sludge content in each treatment and replicates. After thoroughly mixing the sludge sample, it was then divided into sub-samples of known mass (approximately 300 g each) and then placed in 300 mℓ screw-top honey jars. The mass of the honey jar was measured before and after being filled with the mixed pit latrine sludge to quantify the mass. The experiment was divided into different treatments (i.e. with different additives and reference treatments) which are explained in the following section of the thesis.

For the additive treatments, pit additive treatment rate was determined as mass (or volume) of additive per surface area of the pit [g/m^2] based on the manufacturers recommended dosage, and the same dosing rate was applied to the smaller surface area of the honey jars according to **Equation 6.1**.

$$dose[g] = \frac{recommended\ dose[g] \times surface\ \ area\ of\ \ honey\ \ jar\ [m^2]}{surface\ area\ of\ \ pit\ latrine\ [m^2]} \qquad \textbf{[6.1]}$$

It should be noted that the surface area of a pit varies with pit design. Thus an average value of 1.2 m^2 was used in this calculation. The calculated recommended dosage for each additive was then added to the prepared sludge samples for the additive treatment placed in the honey jars. For additive A, each honey jar containing a known mass of representative VIP latrine sludge was dose with 0.4 g of additive mixed with 10 ml of water. Another set of honey jar containing a known mass of representative VIP latrine sludge was dose with 0.02 g of additive B mixed with 10 ml of water. For each set of additive trials, five replicates were performed.

Two reference treatments (or controls) were included for comparative purposes. These were:

- No addition of water or additives (control)
- Addition of water (water reference)

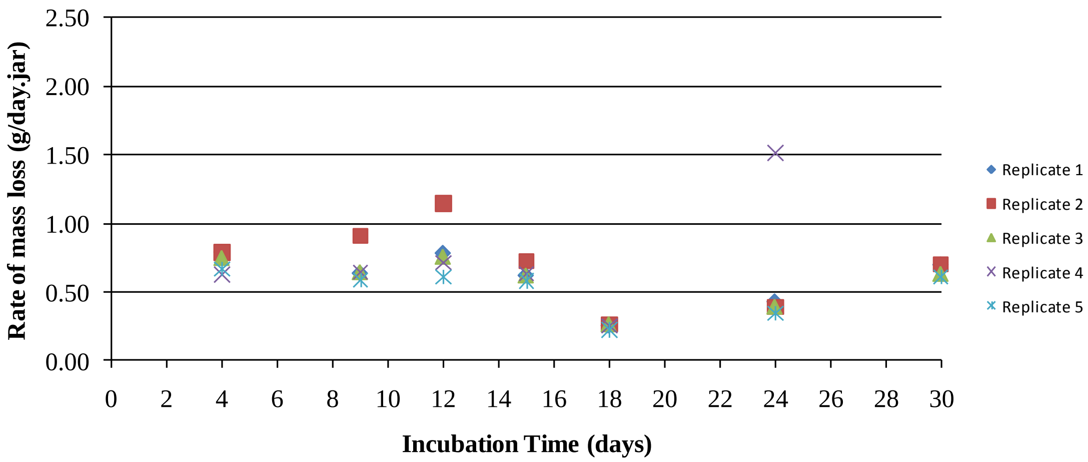
The reference treatment in which neither water nor additive was added to the sludge content in the honey jars serves as a control in order to be able to quantify the uncontrolled effect of natural degradation and dehydration of pit latrine sludge. Five replicates were also performed. For water referenced jars, the same amount of water was used in the water reference units and for diluting the additives in the test units. The water reference units were included as part of the reference treatment to be able to quantify the effects of dilution and water transport on the laboratory trials in the absence of additives, that is to separate the effect of adding water from the effect of adding additives. The weight of all the honey jars used for the treatments were carefully measured before being placed into storage boxes in the fume cupboards. All the lids of the storage boxes were closed and holes were drilled to the sides of the boxes so that air movement/diffusion was not hindered. In each of the storage boxes, two or more open honey jars containing water were also added to maintain the humidity in the storage box, thereby reducing the effect of dehydration on the mass of each test treatment.

The honey jars were incubated for 30 days at approximately constant temperature in a fume cupboard and the mass of each jar was recorded over time. These data were used to determine the rate of mass loss from each jar as a result of biological activity in the jar. Mass loss due to dehydration may also have occurred, but was limited by maintaining a high relative humidity in the fume cupboard and thus reducing the driving force for evaporation. The mass loss data was used to determine the rate of mass loss from each sample for each measurement period. The rate of mass loss was calculated as the change in mass of honey jar content over defined periods of time for each honey jar and expressed in terms of g mass loss per day per jar.

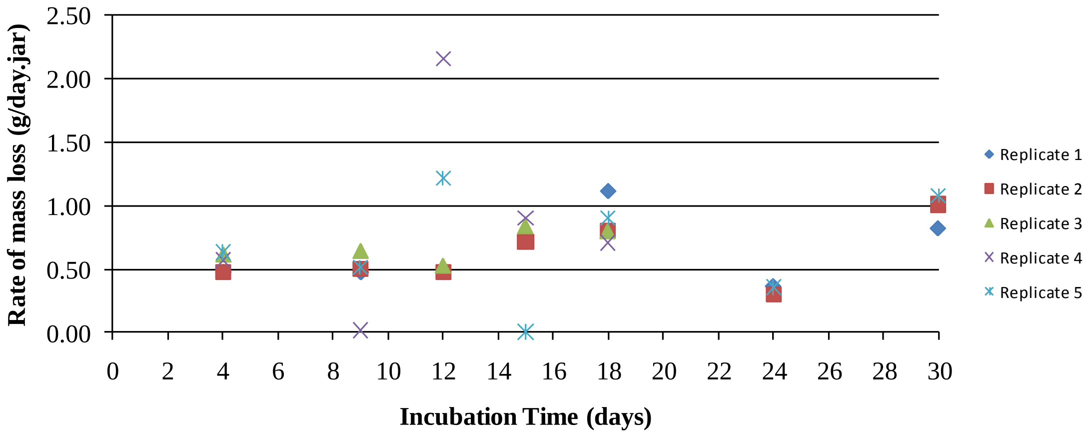
6.1.3 Results of Laboratory Trials for Testing Pit Additives

The laboratory trials aimed at testing the efficacy of pit additives on sludge collected from a number of pit latrines within eThekwini municipality. There were five replicate set up for each treatments and for each replicate within a treatment, two to five pseudo-replicate of mass loss rate were obtained. Fewer than five replicates indicate that some units were sacrificed occasionally to perform certain analysis.

Figure 6.1 presents a plot of the rate of mass loss with time for each replicate over the entire period of the laboratory trials for both Product A and Product B. It was found that there was no systematic change in the rate of mass loss with time over the entire duration of the laboratory trials for Product A and Product B. The average rate of mass loss in honey jars in which Product A was applied was found to be 0.62 g/day·jar and that of Product B was found to be 0.69 g/day·jar.



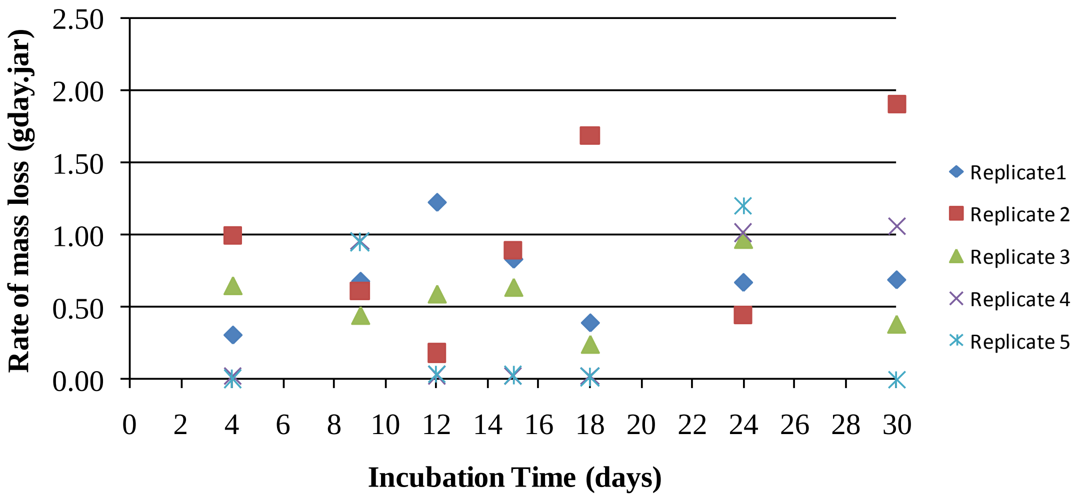
(a)



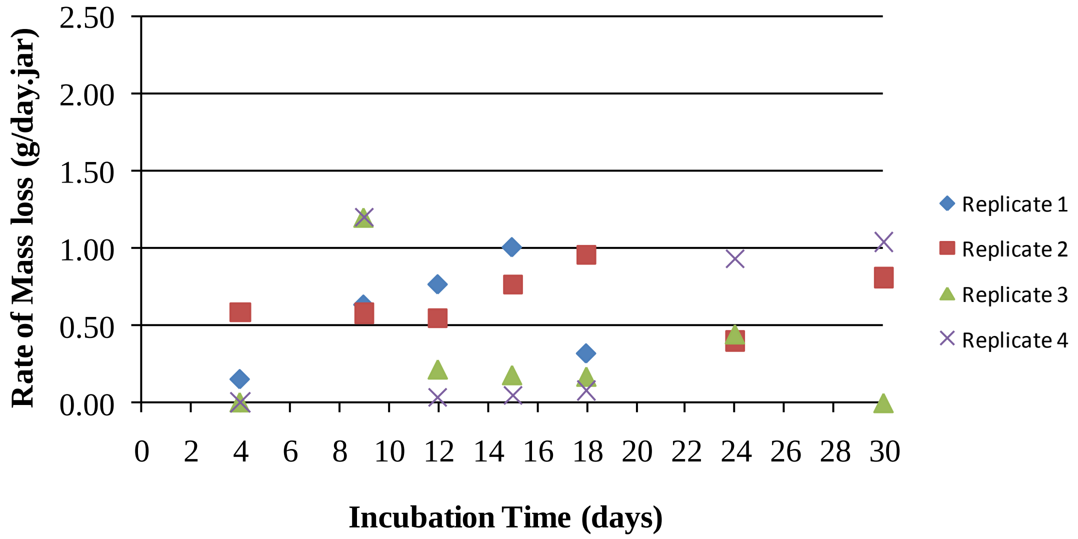
(b)

Figure 6.1: Rate of Mass loss with time for each replicate after 30 days of incubation for Product A and Product B; (a) Product A and (b) Product B

Also it was found that there was no systematic change in the rate of mass loss with time over the entire duration of the laboratory trials for the two reference treatment as shown in **Figure 6.2**. The average rate of mass loss in honey jars in which there was no addition of additives or water was found to be 0.69 g/day·jar and that of the reference treatment in which only water added to sludge content in the test units was found to be 0.63 g/day·jar.



(a)



(b)

Figure 6.2: Rate of Mass loss with time for each replicate after 30 days of incubation for the reference treatments; (a) No addition of water or additives (b) Addition of water only

A Student T-test was performed to determine if there exists significant differences between the rates of mass loss with time in pit latrine sludge samples in which Product A and Product B was added showed that there was no significant difference statistically ($p>0.05$) between the effect of Product A and Product B on the rate of mass loss with time on pit latrine sludge samples over the entire duration of the laboratory trials. The rate of mass loss for each additive treatment and the reference treatments was then averaged and the 95% confidence intervals on the mean were calculated. The results are presented graphically as shown in **Figure 6.3**.

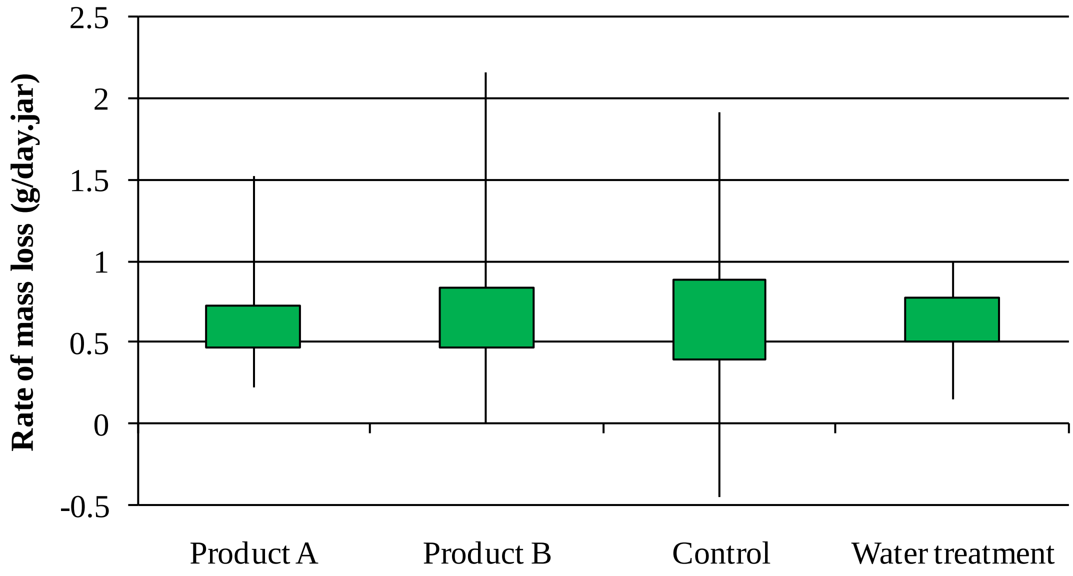
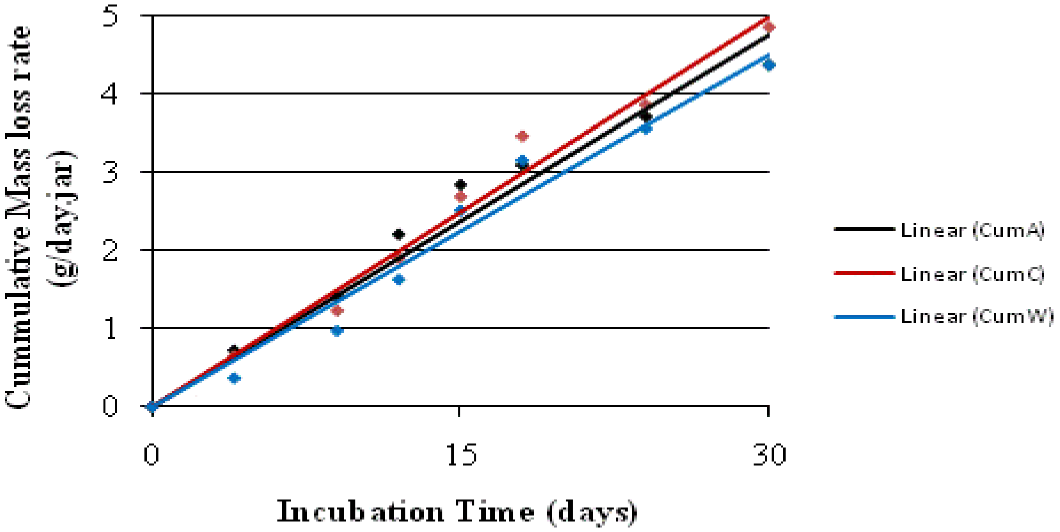
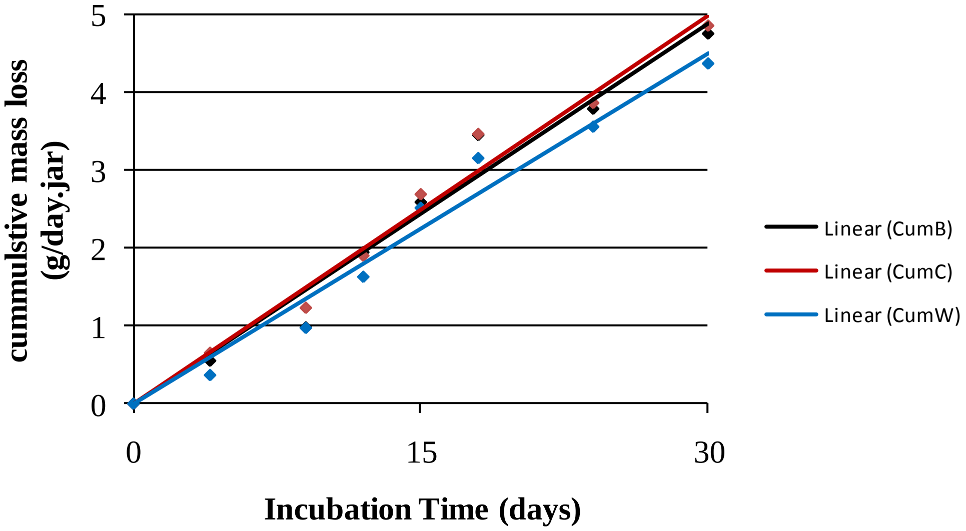


Figure 6.3: Box and Whisker plot showing rate of mass loss from honey jar containing pit latrine sludge samples subject to different treatments. The box for each data set represents the range of the 95 % confidence interval on the mean, while the whisker shows maxima and minima from within each data set.

The box and whisker plot as shown in **Figure 6.3** suggests that significant variation does exist in the measured mass loss rate for each treatment in the laboratory trials within and between treatments. However, differences between the rates of mass loss for each of the four treatments were not significant. In order to present the relationships between the four treatments in more detail, the cumulative rate of mass loss for each additive treatment is compared to the equivalent rate of mass loss obtained from the water reference and the control treatment and each data set is fitted with a straight line using linear regression as shown in **Figure 6.4.** There is clearly no increase in mass loss rate as a result of treating with additives. It has been proposed by Foxon *et al* (2009) that the amount of active micro-organisms added in a dose of commercial pit latrine additive is insignificant when compared to the amount of naturally occurring micro-organisms present in pit latrine sludge. Thus the enhancement of biological activity within a pit due to the addition of commercial pit latrine additives would be insignificant relative to natural degradation processes occurring within the pit as result of the presence on natural occurring bacteria. The result of this study is in support of this hypothesis.



(a)



(b)

Figure 6.4: **Cumulative Rate of Mass loss for Product A and Product B over 30 days of incubation period (a) Product A and (b) Product B. Each graph shows data from between 3 and 5 replicates of each treatment.**

Thus, the laboratory trials conducted have shown that the use of commercial pit latrine additive for the treatment of pit latrine sludge content under laboratory conditions had no statistically significant effect on the rate of mass loss of pit latrine sludge content under the conditions tested. Therefore the hypothesis that commercial pit latrine additives can decrease sludge accumulation rate was not supported. This finding supports the conclusions of Foxon *et al* (2009), Buckley *et al* (2008) and Sugden (2006). However the findings of this study refute the conclusions drawn from the study conducted by Taljaard *et al* (2003) which indicated that commercial pit latrine additive could be of beneficial use in reducing sludge accumulation rate in pit latrines by enhancing the biological activity within the pits. Foxon *et al* (2009) challenged these findings and a parallel study was conducted by Montessuit (2010) to demonstrate the effect of high dosage rate of commercial pit latrines on pit latrine sludge content under laboratory conditions. In this study the recommended dosage provided by the manufacturer of the additives was used and this dosage was increased up until the dosage used was 100 times the recommended dosage supplied by the manufacturer of the additives. It was observed in this study that although a dosage rate per unit area 100 times greater than the recommended dosage rate appeared to result in a bigger mass loss rate but the difference was statistically insignificant. The study concluded that this difference cannot be attributed to the effect of additives alone because the amount of water used in diluting the additive was 5 times more than that required for the recommended dosage. Thus the differences in the amount of water use in diluting the additive could also contribute to the differences observed. Even if this study had shown that using a dosage of 100 times more than the recommended dosage by the manufacturer would be beneficial towards the reduction of sludge accumulation rates in pit latrines and sludge volumes in pits, this would not be an economical viable practice because of the cost of the additives as well as the required amount of water needed for diluting the additives.

6.2 FIELD TRIALS FOR TESTING PIT LATRINE ADDITIVES

The laboratory trials conducted to test the efficacy of pit latrine additives indicated that the use of pit latrine additive on collected sludge samples from various pit latrines do not have any significant effect on the rate of mass loss in laboratory test units. It is speculated that laboratory trials might not really represent the true conditions that could be found in pit latrines, specifically because fresh material is constantly added to pit latrine while the laboratory trials has a batch sample that is only added once. This section of the thesis presents field trials to test the effect of direct application of pit latrine additive on sludge content in pit latrines. The field trials were undertaken to determine whether the field trials would give similar results as found by the laboratory trials.

Thirty pit latrines which were still in use were selected from a community within eThekwini municipality. The major challenge faced was that majority of the available pit latrines within the community and around eThekwini municipality were completely full or recently emptied. Those that were not recently emptied, sludge level in the pits were very low. In order be able to correlate the effect of the pit additives on pit latrine sludge content in the field trials to that of the laboratory trials, the same set of additives used in the laboratory trials were used in the field trials. According to the two additive suppliers, the sludge content in the pit latrine should be adequately wet and if it is known that any chemical or substances has been added to the sludge in the pits, significant amount of water need to be added before the treatment commences. Therefore, all pits except the control pits were flushed with 20 litres of water so as to neutralize the effect of whatever substances/chemicals that may have been added previously to the sludge content in any of the pits. The water addition also served to flatten the pit contents at the start of the trial. **Table 6.1** presents the pit latrine additive dosing schedule for the field trials. For easy comparison between the laboratory trials and the field trials, the additives were identified as Product A and Product B as for the laboratory trials. Product A was tested on eight pit latrines selected randomly from the community and Product B was also tested on eight pit latrine selected randomly from within the community, making a total of sixteen pit latrines which had additive treatment. All pit latrines were dosed according to the recommended dosage given by the manufacturers. **Table 6.2** presents a summary of the different treatments allocated to the thirty experimental pit latrines.

Table 6.1: Pit latrine dosing schedule for the field trials as recommended by the manufacturers (Bakare *et al*, 2010)

Additive	Recommended dosage
A	Pour 10 litre of water into the pit before adding the additive 200g every second month
B	2 table spoon into 10 litre bucket of water and add on a weekly basis

Table 6.2: Allocation of treatments to 30 experimental pit latrines (Bakare *et al* 2010)

Pit Number	Treatment
1-8	Product A
9-16	Product B
17-23	Water Reference
24-30	Control

Figure 6.5 shows the preparation of the additives before application to the pit.

Figure 6.5: Preparation of Pit latrine additives for application to Pit Latrine (Bakare *et al*, 2010).

The remaining fourteen pit latrines out of the selected thirty pit latrines were used as the reference and control experiments. Since the additive suppliers indicated that the additives should be added with water to the sludge contents in the pit latrines, the selected pits use for the reference experiment (i.e. only water added to sludge content in the selected pit latrines) aimed to isolate the effect of adding water to sludge contents in pit latrines on the accumulation rates of sludge within the pit latrine. Ten litres of water was added to each of the selected seven reference pit latrines on a weekly basis while the remaining seven pit latrines (the control) were not subjected to any additive or water addition. All these four types of treatment were randomly allocated to the selected 30 pit latrines on a geographical basis to reduce the probability that any differences could be attributed to geographical differences.

The field trials was carried out over a period of six months and measurements of the sludge present in all the pits were taken initially before the commencement of the treatment after initial flushing with 20 litres of water and repeated after 3 months and at the end of the 6 months field trials in order to be able to determine any significant changes that might have occurred.

Two measurement techniques were used; the first approach measured the distance between the pedestal and the pit surface at three different locations within an area of approximately 0.06 m^2 using an infrared laser distance measure. These measurements were averaged so as to give an indication of the distance between the top of the sludge heap and the pedestal. The difference in sludge heap height was calculated as an indication of the rate of reduction of sludge content in the various VIP latrines.

6.2.1 Field trial results using the infrared laser distance measure

The sludge reduction results for each of the treatments of the field trials using the infrared laser distance measure are presented in **Figure 6.6**. The first three months showed a net decrease in height across all treatments except for the control which showed a net increase in height. The consistent increase in height shown by the control pits was expected because these pits were in use and no additives or water was been added to them. However, it was observed that there was no significant decrease in height across all treatment after the first three month till the end of the field trials and that for the control pits; the increment in height was not significant across all pits for the entire duration of the field trials. There was no significant difference between the height changes ($p<0.05$) for the pit in which additives was added and water reference pits, indicating that the additives did not significantly influence the height change.

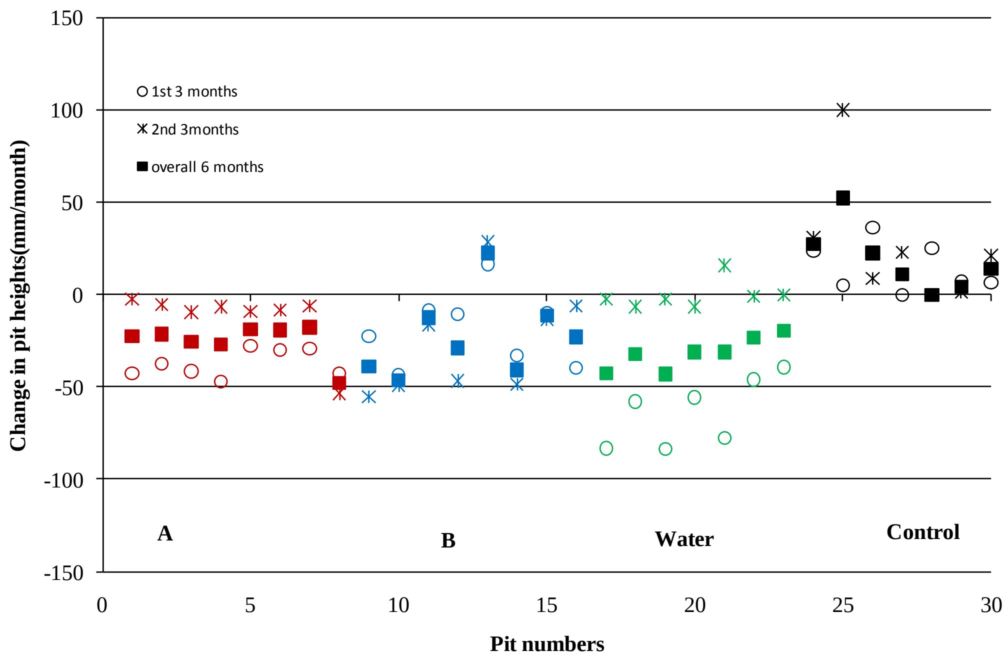


Figure 6.6: Change in pit latrine sludge height for all the treatments for the field trials using the Laser tape measure

Thus, for proper comparison between the additive treatments, water treatment as well as the control, the measured change in height for each of the treatments were averaged and the 95 % confidence interval on the mean were calculated. The results are presented graphically in **Figure 6.7.**

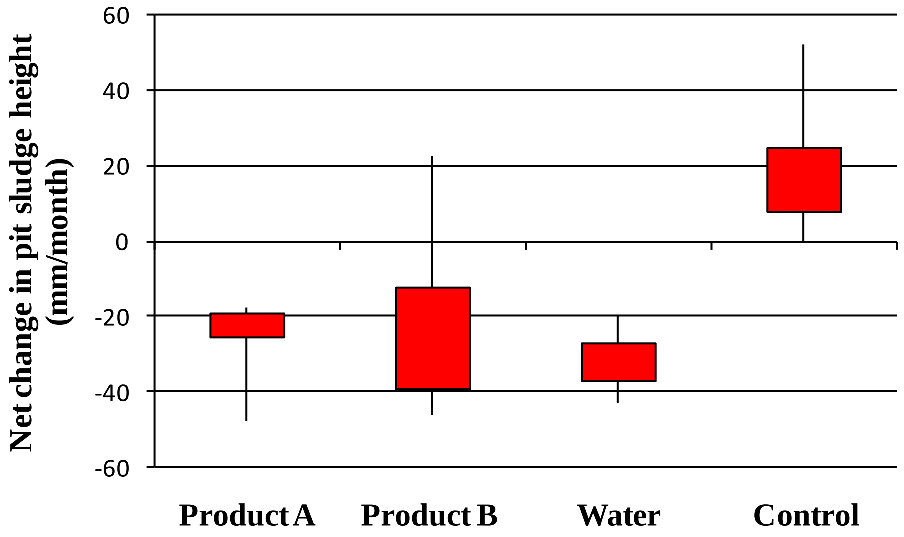


Figure 6.7: **Box and Whisker plot showing change in height of pit latrine contents over a period of 6 months for the field trials using the infrared laser distance measure. The box for each data set represents the range of the 95 % confidence interval on the mean, while the whisker shows maxima and minima from within each data set.**

For the duration of the field trials as shown in **Figure 6.7**, a net decrease in pit contents height was observed although the changes observed were small and close to the tolerance of the laser distance measure under field conditions. It is interesting to observe that the reference treatment where only water was added to the sludge content of the pit latrines showed significant differences statistically when compared to the other three treatment using ANOVA. This field trial results suggest that the use of pit latrine additives do not bring about a reduction in pit sludge contents. However, pit latrines in which water was added showed a reduction in the height measured for pit sludge content. The field trial results did not show whether the apparent reduction in pit latrine contents volume was due to flattening of the pit contents through water addition such that the overall reduction in volume was negligible or through enhanced biological degradation rates as a results of the water added. What the field trials result do show is that no apparent reduction in the rate or volume of pit latrine sludge was observed due to the treatment with pit additives. A summary of the average overall sludge height reduction results for each of the treatments of the field trials using the laser distance measure are presented in **Table 6.3**.

Table 6.3: Overall sludge height reduction results for the field trials.

Treatments	Time Interval	Measurements from the pedestal down to sludge surface
Product A	Start Finish Loss Rate	1300 mm 1450 mm 150 mm over the entire duration of the field trials 25 mm/month
Product B	Start Finish Loss Rate	1500 mm 1630 mm 130 mm over the entire duration of the field trials 21.7 mm/month
Water Reference	Start Finish Loss Rate	1540 mm 1730 mm 190 mm over the entire duration of the field trials 31.7 mm/month
Control	Start Finish Gain Rate	1500 mm 1350 mm 150 mm over the entire duration of the field trials 25 mm/month

The second approach used in taking measurement during the field trials involved the use of stereographic imaging technique to map the surface of the pit latrine sludge contents to provide a basis for the calculation of the rate of volume change in pit latrines. It was proposed by Buckley *et al* (2008) that a stereographic imaging technique for measuring the sludge level in pit latrines is a more accurate method for determining sludge accumulation rate than previously reported methods such as measuring with a string and stone or lowering a long metal rod down the pit. This is because the sludge content in pit latrines are not level but often have an irregular pyramidal shape; thus measuring the sludge level at one or two points using either the laser distance measure, a string and stone or a long metal rod might not give a clear indication of the volume of the sludge content in the pit latrine. The stereographic imaging technique uses a pair of stereoscopic digital photographs to measure the spatial coordinates of any number of points on the surface of the sludge in the pit latrine. These points are then used to map out the shape of the surface of the pit content in three dimensions. Normally, there is no need to open the pit; the digital camera may be lowered on a supporting boom through the toilet pedestal. The boom is supported by a structure which can locate the camera precisely and reproducibly in the same position on subsequent visits to the same latrine. **Figure 6.8** shows the supporting system for the photographic equipment.

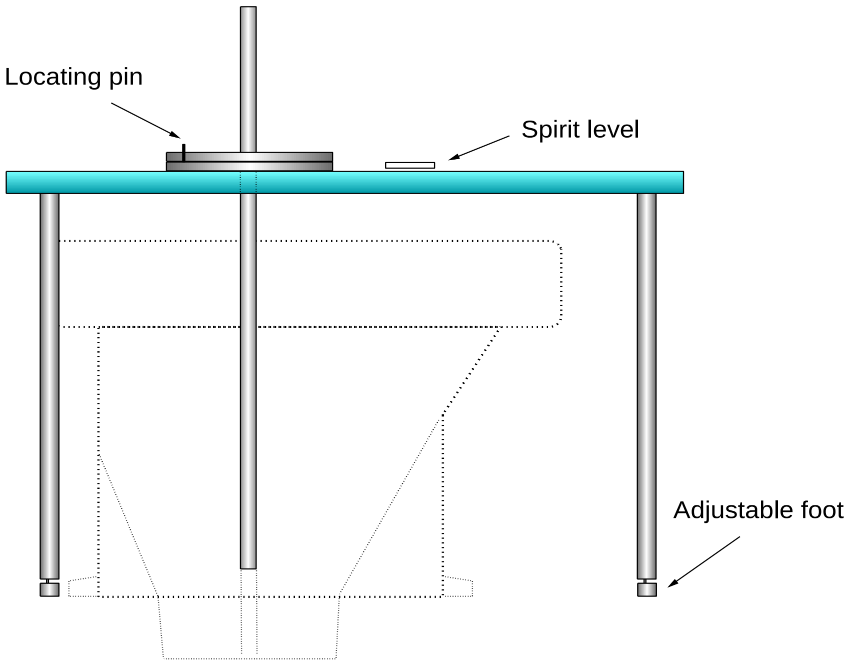


Figure 6.8: Supporting System for the Photographic Equipment.

The camera boom is supported by a table with three legs which can be accurately levelled. The camera boom can be rotated to several positions which have been preset and can be locked by a locating pin. On every visit the floor was marked with a dot of paint at each foot of the supporting table to ensure that for subsequent visits the supporting table is placed at the same position. The camera is supported at the end of the boom as shown in **Figure 6.9**. The camera support system allows the camera to be tilted at a few preset angles to allow imaging for different levels in the pit. A trigger cable allows the photograph to be initiated from outside the pit. 8 images were recorded for each pit; two photographs are taken on each of 4 sides (forwards, backwards and to either side) and the two images are horizontally displaced at a known distance.

The pictures taken were downloaded to a computer which were analysed using a program developed in Matlab. Analysis of the images was performed by selecting a series of matching points on each pair of stereographic images. A triangulation algorithm was implemented to determine the distance of each of the identified points from a reference position (at the same height as the camera). The whole procedure is calibrated beforehand by images of a surface where the positions of the points are precisely known (e.g. graph paper attached to a flat surface). Preliminary calibrations indicated that points on a surface 300 mm from the camera are located within a tolerance of about 0.7 mm when the displacement of the camera between images is 10 mm.

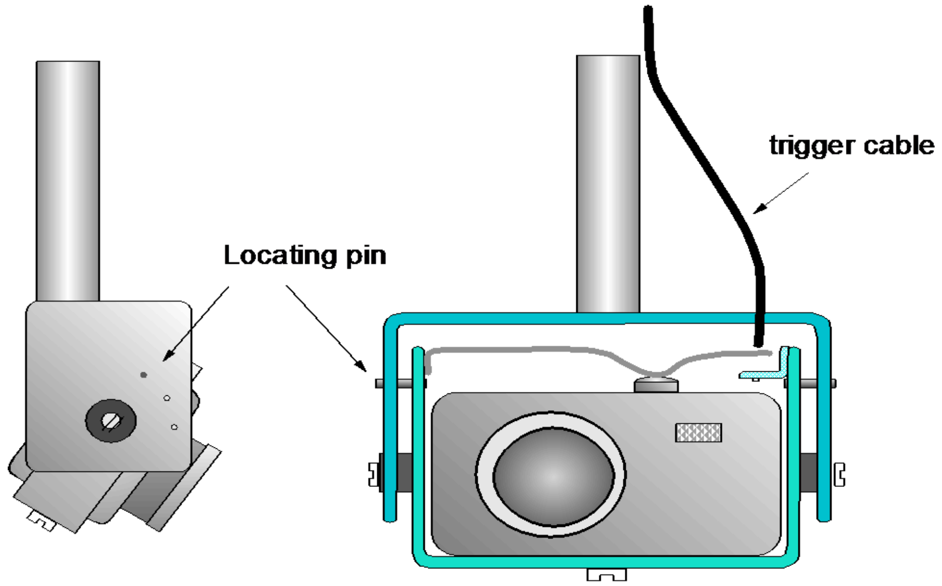


Figure 6.9: Camera Supporting System.

The triangulation calculation projects a line from the camera position to the selected point for each of the two stereographic images. Theoretically, the physical location of the object can be determined by calculating where the two projected lines intersect i.e. at what distance from the camera and in what direction. The lines from each camera to any target point must in reality intersect at the target point, but due to measurement errors the projected lines may not intersect. Thus the triangulation calculation finds the point of closest approach between the two lines projected from the camera positions to the target. To do this, one determines the equations of the lines from the angles of the target point from the camera axes, the positions of the cameras and the orientations of the camera axes. From these equations one derives an expression for the distance between any two points on the two lines, and solves for the pair of points for which the distance is minimal. The best estimate of the position of the target point is midway between these two points, and the length of the line joining the closest approach points gives an estimate of the error in determining the position.

The camera positions are $[x_1, y_1, z_1]$ and $[x_2, y_2, z_2]$. The directions in which they point are each defined by 3 angular coordinates $[\alpha_1, \beta_1, \gamma_1]$ and $[\alpha_2, \beta_2, \gamma_2]$ which describe the rotations of the camera axis about the X, Y and Z axes (in that order). The unrotated camera axis (i.e. $[\alpha, \beta, \gamma] = [0,0,0]$) is in the direction [0, 1, 0]. **Figure 6.10** shows a single image of the surface of a pit latrine indicating the back side, left side, front side and the right side in the pit latrine. When the pictures are taken and downloaded on the computer, points are selected in order to perform the triangulation calculations, an example of stereographic images of a pit surface showing how the points are selected for triangulation calculations is presented in **Figure 6.11**.

Figure 6.10: **Single images of the pit surface (Clockwise from the top left: Back; left side, forwards, right side of pit).**

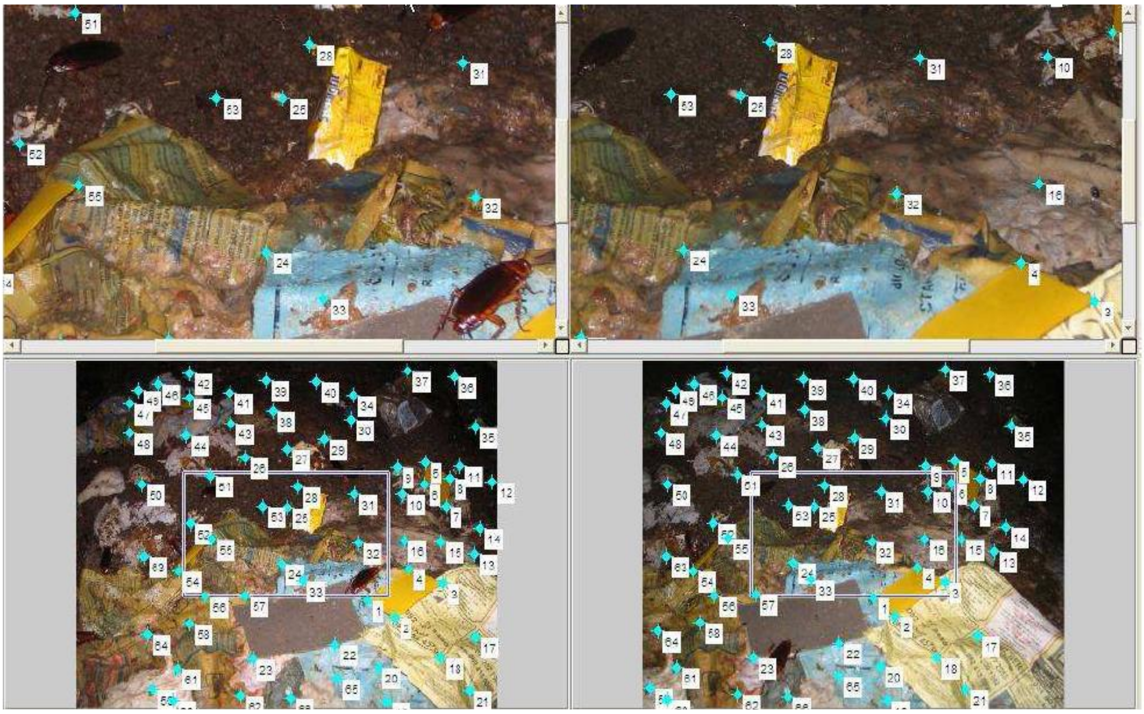


Figure 6.11: Stereographic images of a pit surface showing the points selected for triangulation calculations

After the points had been selected, the map of the sludge surface is then generated as shown in **Figure 6.12.**

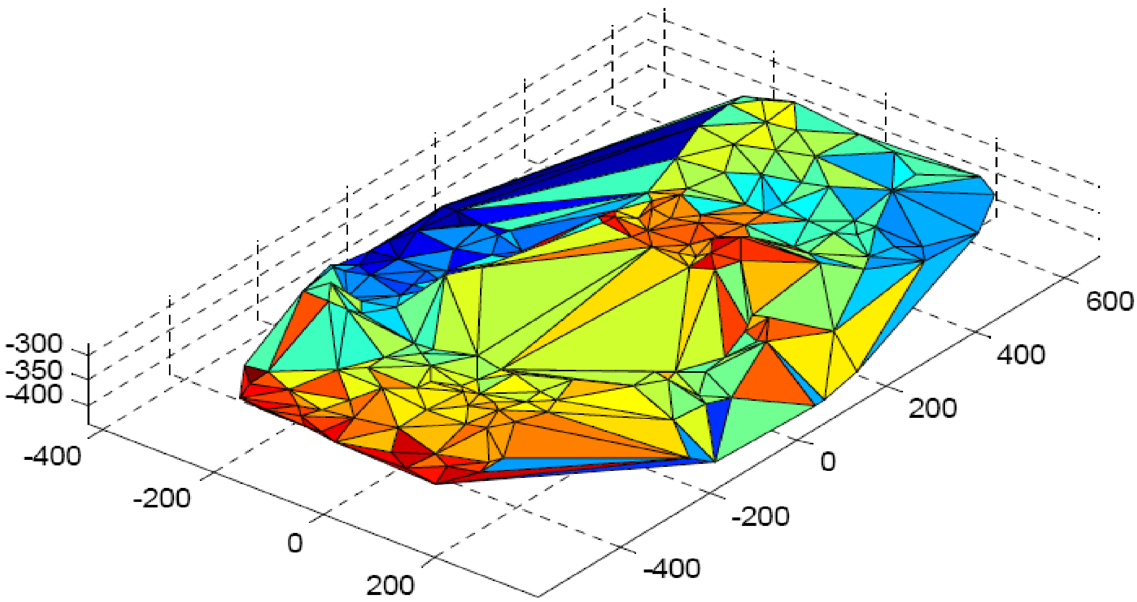


Figure 6.12: Surface Map generated by Triangulation of selected points on the images.

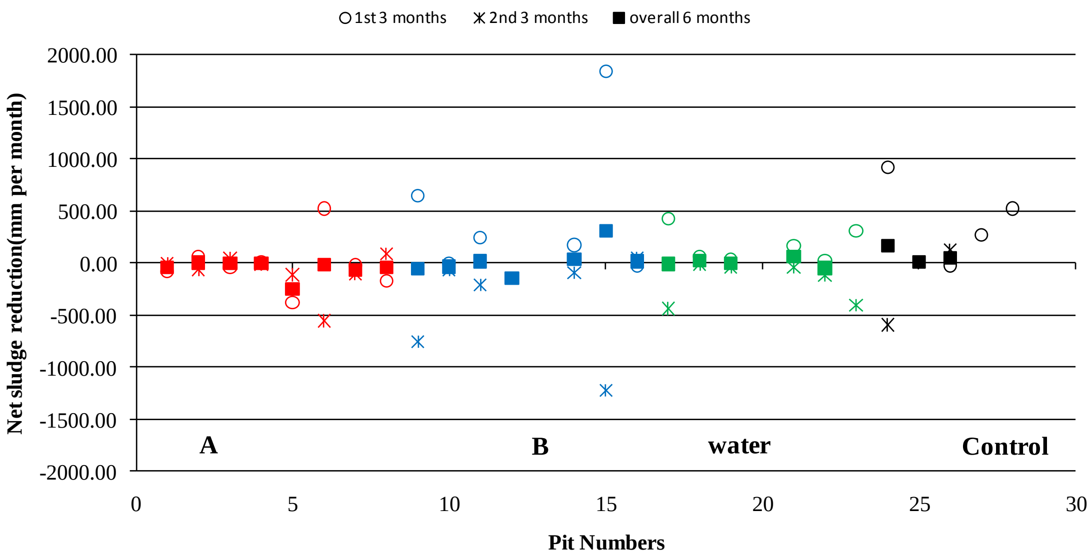
6.2.2 Challenges faced using the camera measurement techniques

The camera measurement techniques used in the pit additive study showed some difficulties in that it was very difficult to shift the camera between the two positions reproducibly with sufficient accuracy. Although the movement at the platform from which the camera is suspended is accurate, because of the length of the suspending pole, very slight changes in angle are magnified in their effect on the camera position and orientation. Also, the levelling mechanism for the platform does not have a sufficient range of adjustment to cope with the very uneven floors that are often encountered. It is usually not possible to determine from a pair of pictures whether the relative alignment of the camera was correct because this can only be done when the pictures are being analyzed back at the university.

It was also discovered after the generation of the images similar to that presented in **Figure 6.12** that the camera was unable to see all points in the pit latrines investigated and as such some sections of the surface were not mapped especially at the highest point of the pile and in the corners. This may significantly affect the accurate calculation of the volume of sludge pile in the pit latrines indicated. However this observation do not refute the initial hypothesis that a detailed surface map of the pit contents is required to accurately quantify the amount of sludge within a pit at various time interval. What this has shown is that apart from the intensive labour required, the stereographic methods have various limitations. A more sophisticated method of scanning the surface of the pit contents is required and an improvement would be the use of a scanning device. A project investigating the use of such a device has been initiated. For these reasons the average depth generated from the matlab program developed is as good a measure of change in pit contents height as compared to a detailed volume calculation.

6.2.3 Field trial results using the stereographic imaging technique

The result of the net sludge reduction per month in all the pits using the stereographic imaging is presented in **Figure 6.13.** Statistical analysis (ANOVA) was performed to determine if net sludge reduction occurred in any of the pits during the trials. The results showed that there was no significant difference between all four treatments (p>0.05) throughout the entire duration of the field trials. For the selected pits which served as the control in which no additive or water was added to the sludge content, it was observed that there was increment in sludge content in this selected pits but this increments observed was statistically insignificant.



It should be noted that some data points are missing in the above plot since:

1. **During the course of the trials some pit latrine became so full that the camera could not be lowered**
2. **There was a case in which the owner of the pit died and pit was locked up**

Figure 6.13: Net sludge reduction for all the treatments for the field trials using the Stereographic method

The net sludge reduction obtained for each additive treatment and the reference treatment (water addition and Control) was also averaged and the confidence intervals on the mean were calculated. The results are presented graphically in the Box and Whisker plot in **Figure 6.14.** These data indicated that there was no significant difference in the net sludge reduction in all treatments using the stereographic method. This contradicts the result obtained using the infrared laser distance measure where it was observed that there was significant reduction in sludge height in pit latrines in which only water was added compared to the pit latrines in which additives were added and those in which nothing was added (control). Thus, it could be concluded that the reduction in height observed in the field trial based on 3 distance measurement is an indication of pyramid flattening of the surface of sludge content in the pit by the addition of water onto the highest part of the pile since the stereographic method did not indicate a similar change.

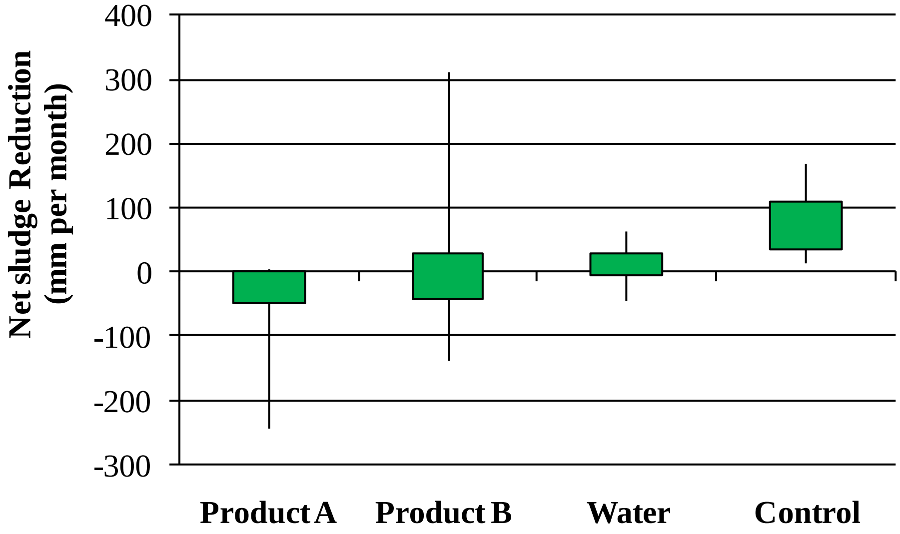


Figure 6.14: **Box and Whisker plot showing Net sludge reduction pit latrine contents over a period of 6 months for the field trials using the Stereographic methods. The box for each data set represents the range of the 95 % confidence interval on the mean, while the whisker shows maxima and minima from within each data set.**

6.3 SUMMARY

The purpose of this chapter was to investigate the efficacy of pit additives on pit latrine sludge content. Two trials were conducted to investigate the efficacy of pit additives for controlling sludge accumulation rates and/or reduction of sludge volume in VIP latrines on a laboratory scale and in the field. Because of the heterogeneous nature of sludge samples from VIP latrines, the results obtained from the laboratory trials showed a wide distribution in the rate of mass loss for all the four treatments. However, there was no systematic and statistically significant change in the rate of mass loss on sludge samples in which both additives were applied. Thus the results obtained from the laboratory trials showed no evidence that the use of pit additives had any application or use in controlling sludge accumulation rates in pit latrines.

The field trials involved two different method of measurement to quantify the effect of pit additives on sludge content in the pit. The first type of measurement was based on the use of infrared laser distance measure to measure the changes in height in VIP latrine sludge content over the entire duration of the field trials while the second measurement was based on the use of stereographic images to map the surface of the sludge content in VIP latrines in order to be able to properly quantify any change in the volume of the map surface over the entire duration of the field trials.

The results obtained from the use of infrared laser distance measure showed considerable variation from pit to pit. This might have been due to the variation in the design of the pit, age of the pit, number of users, volume of sludge in the pit and the ambient conditions of each VIP latrine. However, the data obtained indicated that there was no statistically significant reduction in sludge accumulation rate due to the treatment with pit latrine additives. What the data suggests was that lowering in height or in the rate of height increase in a VIP latrine could be achieved by the addition of water either by washing away soluble components or by improving conditions for sludge degradation by increasing the moisture content of the sludge in the pit. However similar results were not obtained in the laboratory trials. This implies that the decrease in the height of VIP latrine sludge content in the field trials due to the addition of water can probably not be explained completely as a result of increasing sludge degradation rates since this explanation would have results in higher mass loss rates in the laboratory trials. Thus, pyramid flattening of the surface of sludge content in the pit by the addition of water onto the highest part of the pile and an increase in leaching of soluble components from the pit might be the case in the apparent reduction of sludge accumulation rate in the VIP latrines.

The results obtained from the stereographic method used to take measurement during the field trials showed that there was no significant difference statistically in the use of pit additives for treatment of pit sludge content as compared to the reference treatment (water and control), however caution need to be applied in interpreting this result because of the limitation of the measuring technique used.

In conclusion, both laboratory and field trials supported the findings of previous researchers that pit latrine additives do not assist in reducing pit filling and sludge volumes.

7 DISCUSSION AND IMPLICATION OF FINDINGS

The main focus of this research work was to provide better understanding on proper management of Ventilated Improved Pit latrine sludge contents because of the growing need to put in place strategies to properly manage accumulated pit latrine sludge and sludge that will be accumulated over the years of operation of the pit. More precisely, the research work presented in this thesis aims to provide information about what approaches could be used to manage accumulated sludge during the operation of the pit and when the pit latrines become full. Design features and maintenance practices of pits could have an influence on the process of sludge degradation within the pit and also influence sludge accumulation rate in pits as well as the physical, biological and chemical composition of pits sludge content. All this has consequences for pit design and management of pit sludge during the operations of the pit and when the pits are full.

In this chapter, the implications of the field and experimental results are discussed to provide new insights gained from the research work conducted. The thesis investigated a number of different aspects related to VIP latrines and its sludge contents which could be discussed under the following, (i) sludge build up in pit latrines; (ii) characteristics of pit latrines sludge; and (iii) options for dealing with pit latrine sludges.

7.1 SLUDGE BUILD UP IN VIP PIT LATRINE

Sludge build up in VIP latrine is determined by the amount of material entering the pit, the rate and extent to which this materials degrades and the conditions in and around the pit. The literature contains very little data on pit filling rates; however examination of the literature showed that sludge accumulation rate in VIP latrines ranges from 10 ℓ/person·year up to 120 ℓ/person·year or more. Norris (2000) estimated the accumulation of sludge in pit latrines at 25 ℓ/person·year. The study was carried out in Soshanguve in Gauteng. At this rate a family of 6 would accumulate 144 litres per annum, and hence a 2.5m^3 pit would last approximately 17 years.

The average sludge accumulation rate obtained in this study was between 22 and 44 ℓ/person·year for the communities investigated. An overall average sludge accumulation rate of 31 ± 10 ℓ/person·year was obtained for all the communities investigated. These sludge accumulation rate data obtained in this study suggest that when sizing new pit latrines sludge accumulation rate of 40 ℓ/person·year could be an appropriate value for use, however higher values of up to 60 ℓ/person·year are not unusual and planning a pit emptying programme around a figure of 60 ℓ/person·year will ensure that pits that have higher numbers of users than they were designed for will still be accommodated within the emptying cycle. Thus at the rate of 40 ℓ/person·year, a family of 6 would accumulate 240 litres per annum, and hence a 2.5m^3 pit would last approximately 10 years. Sludge accumulation rate values obtained in this study are well within the range of literature values.

Apart from generally presenting and interpreting the data describing the rate at which sludge accumulates in VIP latrines, this investigation conducted has in particular provided an understanding of what happens to the materials which are added to the pit and what the likely characteristics of the material in the pit when emptied. It has been widely documented that the number of users plays a key role in the rate at which sludge accumulates in a pit. As presented in the literature (**Section 2.3.1.1**), an individual produces a total volume of 550 litres of excreta per person per year. Added to this volume is anal cleansing material (toilet paper, news paper or other materials) and if a reliable solid waste collection is not available, the VIP latrine is also likely to be use for the disposal of other household solid wastes. It is expected that liquids containing soluble materials may leach out from the pit and biodegradable materials within the pit would degrade.

The findings of this investigation based on the obtained sludge accumulation rate (31 ± 10 ℓ/person·year) and on the assumption that the volume of materials added to the VIP latrines is the same as presented in the literature (550 litres of excreta per person per year), suggest that only approximately 5 % of the materials added to the pit per person per year accumulate while the remaining 95 % of the material added to the pit either decomposes or leached out as liquid from the pit. Out of this 5 % only 1 % of the solid materials added (per person per year) to the pit accumulate as sludge. The findings thus confirms that significant degradation of the material added to the pit occurs to a great extent and that when the material in a pit is dug out, the pit content would be relatively stabilized. The findings also suggests that further biological treatment of sludge dug out of pits may not be appropriate because the investigation conducted showed that significant biological stabilization of the material added to the pit had occurred.

In the case where VIP latrines are to be designed by government, municipalities or NGOs where households will not be responsible for emptying of their VIP latrines, it is recommended that the pit latrine should be designed around the emptying programme. It should also be noted that larger pits are always very difficult to build, requires specialized equipment and professional emptier who are then subject to a high risk of helminths infection since emptier usually have to climb right into the pit to empty the lower part of the pit. Hence, if there is no capacity for an organized pit emptying program, building of shallow pits should be considered because this will enable the householder to be able to empty their own pit. If there is adequate capacity for an organized pit emptying program the pit size should be determined based on how regularly the pit can be emptied, however building of shallow pit should also be considered because this will allow the pit to be emptied quickly with reduced risk of helminths infection.

7.2 CHARACTERISTICS OF PIT LATRINES SLUDGE CONTENT

Approximately 80 % of the organic material in faeces deposited in a pit is said to be biodegradable and of which 30 % is bacteria (Buckley *et al*, 2008). The characteristics of the materials deposited in the pit will have significant effects on the type and extent of the biological activity taking place within a pit and the type and extent of the biological activity taking place within the pit will have significant effect on the characteristics of the sludge contents within a pit. How efficiently and rapidly these biological processes happen depend on factors such as temperature, pH, moisture and oxygen. Fungal organisms and other biota such as maggots, roaches and worms in the pit also play a role in making the organic material more amenable to bacterial break down (Kele, 2005). It was hypothesised that significant biological stabilization occurs within a pit with time, such that further biological treatment of sludge dug out of pits is not appropriate. However, previous research conducted suggests that significant degradation does occur within the pit (Buckley *et al*, 2008; Nwaneri, 2009).

In this present study it was found that biological stabilisation, otherwise described as the degradation of biodegradable components, occurs in a section of the pit contents that extends from the surface down to a point corresponding with material deposited some years previously, but below this section, the material has reached a composition that does not degrade further to any substantial degree with time. These results indicate that physico-chemical analyses of pit latrine contents at different depths in the pit produce profiles for COD concentration, fraction of volatile solids and biodegradable COD that correspond well with the Buckley et al (2008) theory of processes in pit latrines and therefore may be regarded as evidence in support of this theory.

From the results of the characterization of pit latrine sludge content, the following understanding of the nature of sludge in pit latrines is presented:

- This result challenges the common assumption that pit latrines act only as storage vessels for faecal waste in which no biodegradation occurs. The result indicated that significant stabilization of material added to the pit does occur and the longer the sludge residence time in the pit the more stabilized the sludge within the pit becomes.

- Characteristics of pit sludge content vary from pit to pit and within a pit, significant variations exist at different depth within the pit. This depends on several factors, however the extent of the degradative process taking place and the residence time of the material in pit are the main determining factors. Sludge content at the surface layer usually contained a significant portion of the biodegradable material and below this layer the amount of biodegradable material decreases has one digs down the pit.

- When a full pit is emptied, the sludge would consist of oldest and most fully stabilized material at the bottom of the pit and newest, least stabilized material at the top of the pit. Thus the mixed pit contents have a mixture of well-degraded and poorly degraded material.

- The degree of stabilization of pit latrine sludge samples analyzed in this study indicates that several of the proposed disposal options for pit latrine sludge content are not appropriate.

Based on the findings of this study as well as a parallel study conducted by the Pollution Research Group UKZN (2011) to determine the health risks associated with VIP latrine sludge, sludge content from VIP latrines which is still in use can be classified based on the new system of classification of sludge presented in **Table 2.4** as follows:

- Microbiological class C – potentially contaminated with faecal coliforms and helminths ova.
- Stability class 2 – fairly stabilised or with considerable vector attraction reduction.
- Pollutant class a – no potentially toxic metals and elements.

It was also observed during the emptying of pit latrines used for this study that many households dispose their refuse into the pit latrine especially if there is no available service for refuse collection. This increases sludge accumulation rates as refuse is often not degradable within the pit. However, the most serious consequences of this are difficulties encountered during the emptying of such pit latrines. It is therefore recommended that households are properly informed and educated about the consequences that could results in disposing solid waste in their pits and also appropriate educational programmes should be made available when toilets are first installed or when they are emptied for the first time.

7.3 OPTIONS FOR DEALING WITH PIT LATRINE SLUDGES

Various options for dealing with pit latrine sludge had been proposed by eThekwini Municipality. These options include:

- Options that requires the removal of sludge from the pit and transportation of sludge to where it is disposed of.
- In situ treatment with a biological product.

Options that require the removal of sludge from the pit and transported to where it is meant to be dispose of are limited by the characteristics of the VIP latrine sludge and must be managed in a hygienic and environmentally safe way. Also due to the high pathogen content of VIP latrine sludge, human contact with the sludge must be strictly limited.

One such option considered was the disposal of pit latrine sludge content into the nearest wastewater treatment works or deposition into the sewerage system at a peripheral point. The eThekwini Municipality initially believed that sludge evacuated from pit latrines could either be discharged into main sewers or transported straight to wastewater treatment works without having significant impact on the treatment works since the volume of sludge evacuated from pit latrines is relatively small when compared with wastewater flows.

However, in a pilot trial conducted in 2007, the operation of two wastewater treatment works in the municipality area was seriously affected by the addition of sludge emptied from 8 pits in a day in which the volume of the contents of each pits was estimated to be at $1.5m^3$ (Bakare *et al* 2008). **Figure 7.1** shows photographs of VIP sludge transportation and screening at the wastewater treatment works during this trial. The result of adding pit sludge to the treatment works was solids overload that took several months to recover from affecting the waste sludge capacity of the works and failure of the nitrifying ability of the treatment works which only recovered after the solids load had returned to normal.

The study indicates that the disposal of one 1.5 m^3 pit latrine into a wastewater treatment works is equivalent to the daily contribution of between 600 and 1 200 families and that the disposal of pit sludge into wastewater treatment works dramatically increases the load of slowly degradable chemical oxygen demand, solids and nitrogen to the treatment plant (Bakare *et al,* 2008).

The pilot study concluded that, depending on the particular constraints at a given wastewater treatment plant, the impact of receiving VIP sludge will be equivalent to between 0.5 and 1 Mℓ of normal sewage per emptied pit. A municipality must therefore keep the ratio between the number of pits emptied per day and the capacity of the plant in Mℓ per day at no more than 1 to 10 to avoid process failure of the plant.

(a) Transportation of sludge from Pit location to treatment works

(b) screening of sludge content at treatment works.

Figure 7.1: Transportation of manually evacuated VIP sludge and screening of the sludge during the pilot trial conducted for the disposal of pit latrine sludge into treatment works at Tongaat Central Treatment Works (Bakare *et al* 2008).

Therefore the disposal of pit latrine sludge into wastewater treatment works can rapidly lead to the overloading of the treatment works capacity. But most specifically, much of the solids added are not degradable there is no benefit from a treatment perspective. Essentially a concentrated solid waste is converted to a dilute solid problem with increased difficulty in solids removal and a significantly negative impact on the wastewater treatment plant's ability to fulfil its normal function.

Another option proposed for the disposal of VIP latrine sludge is the anaerobic digestion of VIP latrine to produce biogas for fuel. Because sludge dug out from VIP latrines usually contains lower moisture content than sewage or septage, this sludge cannot be treated in anaerobic digesters without the addition of water. This option is also costly, requires advanced management of the reactor as well as the process and also produces sludge. In a study conducted by Bwapwa (2011) on anaerobic digestion of VIP latrine sludge in an anaerobic digestion baffled reactor, an accumulation of inert solids was observed in the reactor and the methane yield was negligible. The study involved the digestion of VIP latrine sludge in a laboratory scale anaerobic digestion baffled reactor of 100 ℓ/d capacity. The reactor was supplied with synthetic wastewater made up of VIP latrine sludge and tap water. The findings from this study were similar to the same problems encountered as in the case of the disposal of VIP latrine sludge in wastewater treatment plant. Thus it could also be concluded that this treatment option has no benefit from a treatment perspective, and implies that a concentrated contaminated solid is turned into diluted contaminated slurry which is a bad sludge management practice.

In this present study, the applicability of deep row entrenchment of VIP latrine sludge for agroforestry was investigated. The overall aim was to investigate the beneficial effect of pit latrine sludge on tree growth and also investigate the changes in the characteristics of VIP latrine sludge buried in trenches over time as well as to investigate if there is any migration of pollutant from the sludge into surrounding ground water. It was hypothesised that if significant stabilisation of the sludge in a pit does occur within the pit, then the pit contents dug out of the pit for entrenchment should be relatively stable but contains certain amounts of nitrogen and phosphorus which might be available as plant nutrients without causing a negative environmental impact.

From the investigation conducted on the applicability of deep row entrenchment for agroforestry, the following are the findings:

- It was found that there was a statistically significant difference in the characteristics of the sludge that arrived at the site before burial and sludge exhumed from trenches at varying time interval. Significant reduction in measurements of moisture, volatile solids, chemical oxygen demand, and aerobic biodegradation of VIP latrine sludge samples were observed for samples of sludge that had been buried in trenches over time, indicating that a significant amount of biological degradation occurred with time in trenches.

- It was also found that over the three years of groundwater sampling from the boreholes at the entrenchment site, there was no profound effect of sludge entrenchment on the groundwater for the duration in which monitoring was carried out. It was concluded that it will take several years to trace if any, the migration of pollutant from the sludge buried in trenches to get into the surrounding groundwater and in fact, there was no indication that pollution of groundwater will occur.

- In a parallel study conducted to investigate the impact of deep row entrenchment on tree growth (Taylor, 2012; WRC, 2012), it was found that in all trials tree grown on or above entrenched VIP latrine sludge showed improved growth characteristics compared to negative control, suggesting that the nitrogen and other nutrients released from the entrenched sludge may be biologically available as fertilizer.

- Also in a parallel study conducted to investigate fate of pathogenic microorganisms during sludge entrenchment (WRC, 2012), it was clear that the exhumed sludge from the VIP latrines contained high loads of infective Ascaris ova as well as quantities of Taenia and Trichuris ova, and the sludge was regarded as extremely hazardous to health. However, after sludge has been buried in trenches and trees planted many of the helminths ova were still present in the sludge but a significant reduction in the fraction of those ova that are potentially infective has occurred. The investigation indicated that significant reduction in potentially viable helminths egg counts occurred as a result of entrenchment of pit sludge and it was concluded that buried sludge would constitute a minimal risk of helminths infection after 3 years of burial.

It was therefore concluded that unlike the disposal of VIP latrine sludge into wastewater treatment works or anaerobic digestion of VIP latrine sludge, deep row entrenchment of VIP latrine sludge for agroforestry was a feasible and potentially beneficial disposal and/or reuse option for VIP latrine sludge. There are a number of advantages that VIP latrine sludge entrenchment for agroforestry has over other methods proposed for VIP latrine sludge disposal, this include;

- Entrenchment of VIP latrine sludge allows greater quantities of sludge to be disposed in trenches, reducing the frequency of application thereby reducing costs and risks of contamination.

- In terms of the stability, entrenchment of VIP latrine sludge eliminate issues of odour and places the sludge out of reach of vectors which allows for vector reduction compare to other methods.

- In terms of microbial risks, entrenchment of VIP latrine sludge dramatically reduces the risks of contact with pathogen. Findings of a parallel study conducted into pathogen survival after entrenchment of VIP latrine sludge for 3 years indicated that significant die off of pathogens had occurred, suggesting that when workers disturb the site at harvest after 7 years, there will not be a risk of infection.

- A final consideration is the presence of rubbish which is typical of pit sludge in South Africa and has proven highly problematic in both the removal of sludge from pits and its disposal. While the presence of rubbish in sludge could obviously cause blockages at wastewater treatment facilities and interfere with natural processes of stabilization. However with deep row entrenchment it can simply be buried without being extracted from the sludge with no harm to crops.

The other proposed option which involves in situ treatment of VIP latrine sludge using a biological product. It was found that neither the laboratory trials nor the field trials provided evidence that the use of pit latrine additives has the ability to significantly reduce either the mass or volume of pit latrine sludge contents or the rate at which sludge accumulates in a pit. The following explanation suggests the possible reason why pit latrine additives might not have any effect on VIP latrine sludge contents:

- The characteristics of VIP latrine sludge contents presented in chapter 4 indicated that less than 30 % on average of the sludge content in pit latrine is biodegradable and that only the surface layer of the pit contains significant proportion of the biodegradable material while the materials buried well below the surface layer of the pit are comprised largely of the non-biodegradable components of the sludge in a pit. Hence, the residual biodegradability of material beneath the surface layer of the pit content is significantly lower when compared to the material at the surface layer of the pit. Thus, the addition of pit latrine additives to pit sludge content would not have any significant effect in reducing the mass or volume of the bulk of the buried material through biological degradation.

- The failure of the pit latrine additives to accelerate the degradation of pit latrine sludge content might be as a result of the fact that the amount of micro-organisms added in a single dose of pit additive was insignificant compared to the amount of micro-organisms naturally present in the sludge.

- It was observed both during the sampling of sludge for the laboratory trials and during the field trials that significant amount of solid waste was found in VIP latrines. The presence of non-degradable solid waste in VIP latrines is a very significant problem because biological activity has no influence on the volume of this fraction. Thus, the addition of pit latrine additive to such a pit will not have a significant effect on the mass or volume of the pit latrine sludge content.

- If assumed that pit latrine additive actually do work (although there is no evidence of this), the pit latrine additive can only slow the rate at which the pit latrine fills up and not stop the pit from getting full. Financially, the use of pit latrine additives to either enhance biological degradation, reduce mass or volume of pit latrine sludge is not economically viable. A typical additive treatment of a pit cost R20 per month (which can even be much more depending the product) and over five years this will come to a total cost of R1200 without interest or R 1500 including interest. However, a pit latrine can be completely emptied and the sludge content disposed using manual or mechanical methods for approximately R 1500 (200 USD) (WRC 2012). This is without taking into consideration of the large volume of water required to mix the additive product before pouring into the pit as prescribed by majority of the manufacturers of pit latrine additives.

8 CONCLUSIONS AND RECOMMENDATIONS

The outcome of this research has provided information on the variation of pit latrine sludge at different location within a pit, the rate at which sludge accumulates within the pit, the applicability of entrenchment of VIP latrine sludge for agroforestry and the efficacy of pit latrine additives on sludge contents within the pit. The findings of this research can also provide a technical framework for a scientific based approach to the management of ventilated improved pit latrine sludge content before and when the pit becomes full in a context, such as South Africa or other developing countries, where there is need to plan for a number of issues related to VIP latrines before these pit latrines reach their capacity.

Research into management of VIP latrines and its sludge contents was undertaken to achieve following objectives laid out in **Section 1.2**, which are:

- To determine sludge accumulation rate in ventilated improved pit latrines over their life span through field investigations which could be use for pit design and maintenance.
- To investigate the physical, chemical and biological characteristics of sludge contents from different locations within the ventilated improved pit latrine.
- To monitor changes in the characteristics of sludge buried in trenches and also monitor the effect of sludge buried in trenches on surrounding ground water.
- To investigate and quantify the effect of pit additives on sludge contents in ventilated improved pit latrines, through laboratory and field investigation.

It was hypothesised that (i) significant biological stabilization occurs in a pit latrine with time, such that further biological treatment of sludge dug out of pits is not appropriate (ii) VIP latrine sludge can be used in deep row entrenchment for agroforestry since the sludge contains nutrients that are available to plants, and that the sludge is sufficiently stable to not cause a negative environmental impact; and (iii) through biological action of microorganisms present in pit latrine additives (biological products), the overall mass of pit latrine contents could be reduced much faster than could be achieved by natural degradative processes mediated by microorganisms already available in the pit latrine contents.

This chapter presents conclusions and recommendations that have arisen from this research work.

8.1 CONCLUSIONS

This section specifically addresses the project objectives and hypotheses.

Determination of sludge accumulation rates in pit latrines

The first objective of this research work was to determine sludge accumulation rate in ventilated improved pit latrines over their life span through field investigations which could be use for pit design and maintenance. It was thus hypothesised that through the determination of sludge accumulation rate in pit latrines, an estimate of the extent to which the material within the pit have been biologically degraded over time could be calculated from the knowledge of the amount of material added to the pit and the obtained sludge accumulation rate in this study.

It was found that the overall average sludge accumulation rate obtained in this research work through field investigations (31 ± 10 ℓ/person·year) was significantly lower compared to the estimated average volume of material added to a pit (600 ℓ/person·year or more) presented in the literature. This finding suggest that significant biological stabilization had occurred in the pit latrines investigated with time and challenges the common assumption that pit latrines act only as storage vessels for faecal waste in which no biodegradation takes place.

Investigation of physical, chemical and biological characteristics of pit sludge content at different locations

The results obtained from the characterization of sludge samples collected from various VIP latrines within a community and when comparing with different communities indicated that the characteristics of sludge varied significantly within a pit and between different pits. The results suggests that below the surface layer in a pit additional stabilization of sludge content does occur and the degree of stabilization within a pit increases from the surface layer of the pit down through the bottom layer of the pit. It was also found that the material buried well below the pit surface, to be specific sludge samples from the bottom of the pit are well stabilized. Thus the results of this study confirmed the theory proposed by Buckley *et al* (2008).

The most important finding of this investigation is that it provides a general description of the life cycle of the VIP latrine as well as the fate of the organic material that enters the pit. When a pit is first built, or emptied, the material added to the pit is fairly fresh, and to begin with, the pit material has undergone little stabilisation. After a period of time, as material undergoes degradation and gets covered over with fresh material, the bottom layers become anaerobic and partially degraded. After a considerable amount of time (years) the bottom layers would have undergone degradation to an extent that they cannot degrade further under pit conditions, and may be said to be fully stabilised. Thus the age in which a pit has been in used would determine how much of stabilized material that would be present. Thus, the findings of this investigation support the hypothesis that significant biological stabilization occurs in a pit latrine with time, such that further biological treatment of sludge dug out of pits is not appropriate.

Therefore, in conclusion the results obtained provides a holistic view of the nature of the materials present in a pit and as a result provide a background to assess the feasibility of different management options for filling pits and different disposal possibilities for VIP latrine sludge contents.

To monitor changes in the characteristics of sludge buried in trenches and also monitor the effect of sludge buried in trenches on surrounding ground water

The characteristic of VIP latrine sludge obtained in this study suggests that disposal of pit sludge would depend on the inherent ability of the disposal option to accept the load of solids and organic material in the sludge, the residual biodegradability of the VIP sludge and the health risks associated with the sludge. Typical characteristics of VIP latrine sludge obtained in this study and other studies conducted by other team members within the research project indicated that, VIP latrine sludge is potentially contaminated with faecal coliforms and helminths ova, fairly stabilized with considerable vector attraction reduction and no potentially toxic metals or elements. Thus human contact with the sludge must be strictly limited mainly because of associated health risks. Therefore in terms of safety, while sludge applied by other disposal methods will be restricted based on the stability and microbial risks of VIP latrine sludge, entrenchment of VIP latrine sludge as found in this research work seems to be the appropriate disposal options.

The results obtained from the characterization of fresh pit sludge that arrived at the burial site and sludge exhumed at different time interval after burial in trenches indicated that there were changes in the composition of the sludge with time. This suggest that sludge stabilization occurred with time in the trenches. Since nitrogen, phosphorus and potassium are locked into the VIP sludge, it may be inferred that the further stabilization of sludge during entrenchment may be as a result of the slow release of this components as fertilizer for agro-forestry applications. These results are consistent with the findings of Taylor (2012) that tree growth associated with buried sludge showed dramatically improved growth characteristics compared to a negative control, suggesting that the nitrogen and other nutrients released from the entrenched sludge may be biologically available as a fertiliser.

It was also observed that the changes in the characteristics of the sludge buried in trenches did not have significant effect on the groundwater based on the analysis performed of water samples collected from time to time from the monitoring boreholes over the three years monitoring period.

Effect of pit latrine additives on pit sludge

Finally, the effect of commercial pit latrine additives on VIP latrine sludge content was investigated both on a laboratory scale and field trials. It was hypothesised that through biological action of microorganisms present in pit latrine additives (biological products), the overall mass of pit latrine contents could be reduced much faster than could be achieved by natural degradative processes mediated by microorganisms already available in the pit latrine contents.

The results obtained from both the laboratory trials and the field trials provided no scientific evidence to support this hypothesis and the use of commercial pit latrine additives as recommended by the manufacturer. It was concluded that the use of commercial pit latrine additives to enhance the rate of biological degradation and/or to reduce the mass or volume of pit latrine sludge in a pit does not have any beneficial effect on pit latrine sludge content.

Final Comments

The findings of this thesis have showed that providing adequate sanitation to all in the form of VIP latrines as proposed by the South African Government Strategic Framework for Water Services does not end with building toilets but all municipalities need to plan for maintenance during the operation and when these toilets reach their capacity.

The ultimate finding of this research work is that VIP latrine sludge have naturally undergone significant degradation and consequently the use of pit additives to enhance the degradation of materials, the disposal of pit sludge in wastewater plants, anaerobic digestion of VIP latrine sludge and/or further treatment of the sludge are not appropriate options for disposal/treatments of VIP latrine sludge; Rather the entrenchment of VIP latrine sludge for agroforestry seems to be an appropriate option for the disposal of VIP latrine sludge.

8.2 RECOMMENDATIONS

The research work presented in this thesis came up with various findings on the nature of VIP latrine sludge contents and how this sludge could be managed within the pit or when exhumed. These findings are presented in **Chapter 7** of this thesis.

The study identified that management of VIP latrine sludge should not be viewed as a one-dimensional issue; rather the management of VIP latrine should consider a wide range of different approaches that are dependent on the nature of the sludge contents. This section of the thesis makes recommendation based on the research work undertaken.

The thesis thus recommends:

- In many of the VIP latrines used in the course of this research work, it was observed that the conditions in and around the pit latrines were unhygienic and this could be mainly attributed to poor user practices. Similarly, it was observed that most of the households make use of non-degradable materials such as newspaper, plastic as anal cleansing material, also make use of the pit latrine for the disposal of solid waste and pour their laundry water into the pit latrines. This practice observed during the course of this research work has a detrimental effect on the biological activities taking place within the pit, results in rapid accumulation of pit contents and also makes pit emptying exercise very difficult to achieve. Thus, this thesis recommends that proper and effective user education should be in place for all households about the importance and purpose of the pit latrines in order to ensure that VIP latrines are able to fulfil the requirements of improved sanitation facilities. It is also recommended that a feasibility study be performed to investigate the economic benefits of providing free toilet papers.

- The difficulties encountered in obtaining properly positioned images using the stereographic imaging techniques for measuring pit content volume changes combined with the labour intensive analysis method makes this technique impractical for field investigations. This thesis recommends an infrared Laser scanner which is used in various applications such robotics should be investigated for scanning and mapping out the surface layer of the pit.

- Finally, the work presented and findings of this thesis are restricted to eThekwini municipality in Durban South Africa. Thus this thesis recommends that where possible, similar investigation should be carried out in other municipalities across the country and even in other countries such as Tanzania where there is a quite number of VIP latrines for comparison purposes.

8.3 Recommendation for Future Research work

This section of the thesis presents specific recommendation for future research work. A summarized list of recommendations for future research is as follows;

- Microbial analysis of pit latrine sludge and pit latrine additives need to be performed so as to be able to make comparison between the microbial load of pit latrine sludge and that found in pit latrine additives.
- An empirical model to predict sludge accumulation rates in VIP latrines needs to be developed. This aspect is in completion by an MSc student Kirsten Wood.
- An empirical model to determine and/or predict how long it will take for the migration of pollutant from the buried VIP latrine sludge into the surrounding groundwater at the entrenchment site. This aspect is under development in the School Bioresource Engineering and Environmental Hydrology University of KwaZulu-Natal.

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APPENDIX A

SAMPLE QUESTIONNAIRE USED FOR THE SURVEY

User Related Questions

1) How many people are using the pit? (Weekly, on weekends, and/or on the average).
2) How many of these people are children?
3) How long has the pit been in operation?
4) How many of the users reside permanently on-site and how many are visitors?
5) Have any chemicals been added to the pit? If yes,
6) What type and for what reason?
7) Has the pit been ever emptied? If yes,
8) How many times and what was the last time?
9) Has any substances/liquid other than laundry water poured into the pit?
10) Is there any collection centre for household waste or is household waste also disposed into the pit?
11) What type of anal cleansing materials is used by households?
12) By visual inspection what can be said about the sludge content; is it extremely wet or dry?

Construction/Environmental conditions related questions

13) Is it built in a convenient and accessible place?
14) Does it have a fly screen?
15) Does the toilet have a door or is the door broken?
16) Is there a water inlet from the sides of the pit?
17) Do rain or storm water enter the pit? If yes, through where.
18) Do the pit have a cover?

House Address
…………………………………………………………………………………………
GPS coordinate ……………………………………………….....................................
How full is the pit? ………………………………………………………………...
How deep when emptied …………………………………………………………
Area of pit …………………………………………………………………………...
What quantity of sludge was evacuated in terms of number of wheel bins?

Observers comments

APPENDIX B

VIP SLUDGE ANALYTICAL METHODS AND STATISTICAL METHODS

Appendix A1 presents the details of all analytical methods use for the characterization of VIP latrine sludge collected directly from the pit as well as those exhumed from the trenches at various time intervals. All statistical method use to analyze the data obtained from the characterization of VIP latrine sludge is also presented.

Analytical Methods

All analytical method, where possible, was carried out according to the standard methods (APHA, 1998) and where no appropriate method was published, adaptations of existing methods were used or entirely new methods were developed. A number of physical, chemical and biological analyses were carried out which appropriately describe the composition of VIP latrine sludge. These analytical methods are further explained as follows;

Moisture Content

On every sludge samples collected from the various pit latrine and exhumed sludge from trenches at the burial site, the moisture content was performed by taking a known mass of the representative sample from each materials collected from the either the pit or trenches. This representative sample was then place in a beaker and oven dried at a temperature of 105°C for 24hrs, thereafter the mass of the dried sludge sample was measured and recorded. The moisture content of that particular sludge sample was then calculated as follows:

$$W(\%) = \frac{M_w - M_d}{W_w} \times 100 \qquad \textbf{[B.1]}$$

Where:

$W(\%) =$ Moisture content of the VIP latrine sludge or exhumed trench sludge
$M_w =$ The initial mass of collected sludge samples before drying in the oven

M_d = The mass of sludge samples after drying in the oven at 105°C for 24hrs

Solid Characterizations

Solid characterization of collected VIP sludge samples and exhumed trench samples was carried out to determine total and volatile solids. Total solids was measured by evaporating sludge sample to dryness in crucibles in an oven at 103-105^{o}c and weighing the residue. The weight of the residue is the total solids present in the sludge sample. On ignition of the residue in the crucible in a muffle furnace at 550°C and allowing the samples to cool in a dessicator, the weight loss on ignition is the volatile solids. These two parameters indicate approximately the amount of organic matter present in the solid fraction of the sludge samples collected. The total solid and volatile solid are calculated as follows;

$$Total\ Solid\left(g/gsample\right)=\frac{M_{105°C}}{M_s} \quad \textbf{[B.2]}$$

$$Volatile\ Solid\left(g/gsample\right)=\frac{M_{105°C}-M_{550°C}}{M_s} \quad \textbf{[B.3]}$$

Where;

M_s = Initial mass of sample used
$M_{105°C}$ = Mass of sample after oven dried at 105°C
$M_{550°C}$ = Mass of sample after ignition in the furnace at 550°C

Chemical Oxygen Demand (COD)

Total COD of VIP latrine sludge samples or exhumed trench sludge sample was determined using the open reflux method for particulate samples. Sludge samples of known mass were diluted with known amount of distilled water before been oxidized with a known excess amount of potassium dichromate ($K_2Cr_2O_7$). After oxidation the sample was then titrated with ferrous ammonium sulphate (FAS) to determine the amount of $K_2Cr_2O_7$ consumed which was then expressed in terms of its oxygen equivalence. A blank sample of the reagent was also tested and this was considered as a control for each COD tests performed. The COD is thus calculated as follows after which this value is corrected using the dilution factor.

$$COD\left[{mgO_2}/{l}\right] = \frac{\left[Blank(ml) - Titration(ml)\right] \times 8000 \times M_{FAS}(mol/l)}{Sample\,volume(ml)} \quad \textbf{[B.4]}$$

8000 is the mill equivalent weight of oxygen × 1000 ml/l

M_{FAS} is the molarity of the ferrous ammonium sulphate used as a standard value which is always recalculated for each set of analysis.

Aerobic Biodegradability Test

Aerobic Biodegradability Tests were performed on sludge samples collected from VIP latrines and sludge exhumed from trenches at the burial site. These tests are simple batch tests designed to quantify the amount of biodegradable material present in the sludge samples. In order to characterize the amount of biodegradable material present during the aerobic biodegradability test, there is a need to have a gross indicator of the amount of biodegradable content present. Two gross indicator can be considered to be applicable, these are; Biological Oxygen Demand (BOD) or Chemical Oxygen Demand (COD). The major problem associated with BOD is that the test runs for 5 days and also only a small portion of the organic compounds are decomposed during the BOD test. Chemical Oxygen Demand was considered to be the most applicable gross indicator in that it is ideally a quick measurability test and nearly all the organic compound presents are oxidized during the test.

The aerobic biodegradability tests involve suspending 50g of well mixed sample in a litre of tap water in a large Erlenmeyer flask; the mass of the suspension was recorded. The suspension was then analyzed for total COD and aerated with saturated air for 5 days and the mass of the suspension was recorded after which samples were taken and analyzed for total COD. The biodegradable COD content of the sample was calculated as the ratio of the amount of COD reduced by the aeration process to the original COD content of the suspension and corrections were made for moisture loss through evaporation. This calculated value gives an indication of the biodegradability of the sample. Each analysis was carried out in triplicate on each of the samples collected and the averages of each analysis were computed for the final results. The Percentage Biodegradability of each sample is calculated using the equation given below;

$$\% Bio\deg radability = 1 - \frac{Final\ COD \times Final\ Volume}{Initial\ COD \times Initial\ Volume} \quad \textbf{[B.5]}$$

The general experimental set up as shown below;

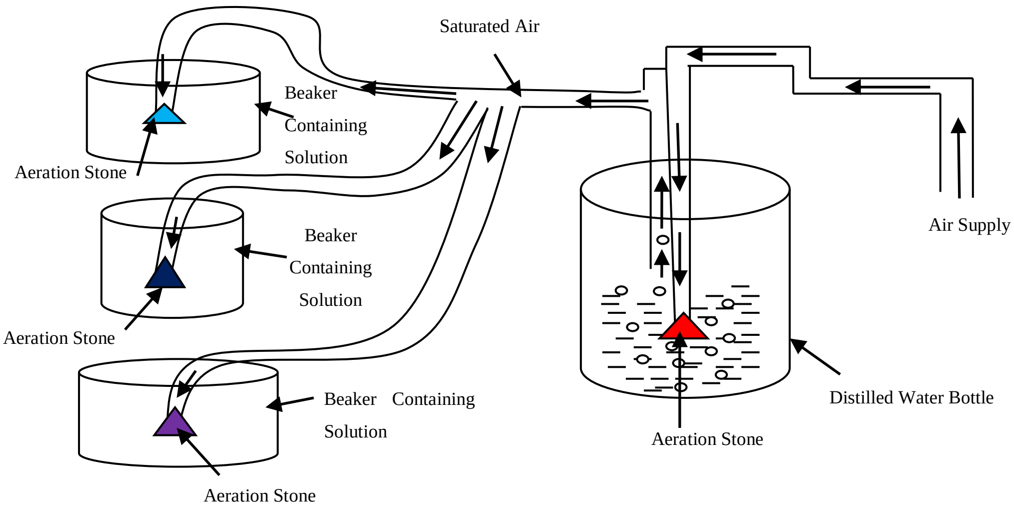


Figure B.1: Aerobic Biodegradability Set up

Statistical Methods

The analytical result obtained from the laboratory characterization of VIP latrine sludge samples and exhumed trench samples are incomplete without an estimate of their reliability. It is very important to provide some measure of the uncertainties associated with result obtained from the analytical results if the data are to have any value. This section presents a summary of the statistical methods used in this research work. All statistical analysis carried out in this research work were performed using Microsoft excel as well as SPSS 15. Each analysis was carried out in triplicate or more and in order to understand the significance of the analytical data obtained in the course of this research work, one or combination of the following described statistical theory presented as follows were used. Most of these statistical theories were drawn from

Diamantopoulos A. and Schlegelmilch B.B (1997), Ennos R. (2002) and Skoog D.A *et al* (1991).

Mean/Average value

The average value of each sludge samples analyzed was calculated by dividing the sum of replicate measurements by the number of measurements carried out in a set of analysis:

$$\text{Average} = \frac{\sum_{i=1}^{N} x_i}{N} \qquad \textbf{[B.6]}$$

Where;

x_i = Individual values of each replicate measurements
N = the number of replicate measurements

Standard deviations

The standard deviation of the analytical results obtained for each sample was calculated in order to be able to describe the closeness of each analytical result that have been obtained in exactly the same way. This was calculated as follows:

$$s\tan dard\ deviation = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - x)^2} \qquad \textbf{[B.7]}$$

Where;

x_i = Individual values of each replicate measurements
N = the number of replicate measurements
x = the average value

Confidence interval on the mean

In all the VIP sludge sample analysis carried out in the course of this research work, there is a need to have a particular value that describe the characteristics of the sludge samples for each parameters determined. The average value of that particular analytical result cannot appropriately be used to describe the characteristics of the sludge samples because statistically the determination of the exact average value of a set of analytical results requires that an infinite number of measurements be made. However, the confidence interval on the mean allows limits to be set around an experimentally determined mean value within which the population mean value lies with a given degree of probability. In this research work, the 95 % confidence interval on the mean was determined for each set of analytical result obtained. This found to be reasonably acceptable. The 95 % confidence on the mean value suggests that if analysis is carried out from another sample from the same population or analysis is carried out on the actual population, there would be a 95 % chance that the respective means would fall within the 95 % confidence limit range or clearer sentence, there would only be a 5 % chance that the respective mean value lies outside the 95 % confidence limit range. There are two ways in which the confidence limits on the mean can be calculated;

- Calculation based on large samples (> 30)

To calculate the 95 % confidence on the mean for large data sets, the standard error which gives a measure of confidence that the sample mean is within a certain range of the true population mean is multiplied by the standardized normal deviate value of 1.96.

- Calculation based on small samples (<30)

For smaller samples, the statistic ***t*** value read directly from the probability table of ***t*** is used in calculating the 95 % confidence on the mean value. This computed as follows;

$$\text{Mean value} \pm t \times \text{standard error} \qquad \textbf{[B.8]}$$

The standard error is thus calculated as follows;

$$\text{Standard error} = \frac{s\tan dard\ deviation}{\sqrt{N}} \qquad \textbf{[B.9]}$$

Where;

N = the number of replicate measurements

Statistical tests for differences

Two types of statistical tests for differences were employed in the course of this research work. The t-test was used to determine whether the means of two groups are statistically different from each other. This test is used to compare the means of two treatments, i.e. fresh VIP sample and trench sample of a year old. The t-test compares the actual difference between two means in relation to the variation in the data, expressed as the standard deviation of the difference between the means.

On the other hand, the analysis of variance (ANOVA) was used in comparing means of three or more analytical data. This test was used for comparing means of three or more samples, in order to avoid the error inherent in performing multiple t-tests (Walpole *et al,* 1978). If three set of measurements for three variables have to be compared, the test can only be used to compare two variables at a time. if more than three set have to be compared, it would be time-consuming and, more important, it would be inherently flawed, since in each t-test a 5% chance of the conclusion being wrong is acceptable (for $p = 0.05$). Analysis Of Variance (ANOVA) overcomes this problem since it allows detecting significant differences between the treatments as a whole (Walpole *et al,* 1978).

Sensitivity and Error Analysis

When performing chemical analysis, it is inevitable for the results obtained to be absolutely free from errors and uncertainties. The estimation of acceptable level of accuracy is necessary for the viability of result obtained from any analysis. This section presents the accuracy and repeatability of the results obtained in the course of this research. Every measurement is influenced by many uncertainties (Skoog *et al* 1991), however, the uncertainties in the analytical results presented in this thesis might be from two basic sources: limitation in the equipment/instrument used and/or variations due to human error and heterogeneous nature of VIP latrine sludge samples. The following section considered these two basic aspects separately and explained how this uncertainties where evaluated where possible.

Limitation on Testing Apparatus, Equipment and/or Instrument

All analysis performed in the course of this study made use of several laboratory apparatus, equipment and/or instruments (such as pipette, measuring cylinders, mass balances etc). This apparatus, equipment and/ or instruments might have a limitation on the overall result of the analysis performed. This limitation that arises from testing apparatus, equipment and/or instrument can never be completely eliminated, however, during the analytical component of this research several precautionary measures were adhere to as presented in the standard method for a particular analysis. Where necessary, calibration of equipment before use was also performed in order to reduce errors that might arise and also enhance the quality of the analytical data. In some cases if errors are detected, these errors are adequately corrected before the continuation of the analysis. Finally a number of statistical test are performed on all analytical data obtained to access the reliability and quality of all analytical measurements made.

Variation due to human error and VIP sample heterogeneity

The other aspects that might bring about uncertainties in the analytical data presented in this thesis might be due to human error and sample variations. The heterogeneous nature of VIP latrine sludge could result in a significant degree of variation in the analytical data sets. Also, variation due to human error is inevitable because of the fact that many analytical measurements require personal judgements. Examples includes measuring of liquid levels with respect to a graduation line as in the case of pipette or measuring cylinder and changes in colour of a solution during titrations. Each sample collected either directly from the pit or exhumed from the trenches, atleast three replicate analyses are carried out and the average value and standard deviation are then computed. In order to access the reliability of the analytical data obtained from the various analysis performed on the collected sludge samples, the standard deviation for each sample analysis is compiled in a histogram to access the general trend. The charts for each analysis performed are presented in the following charts.

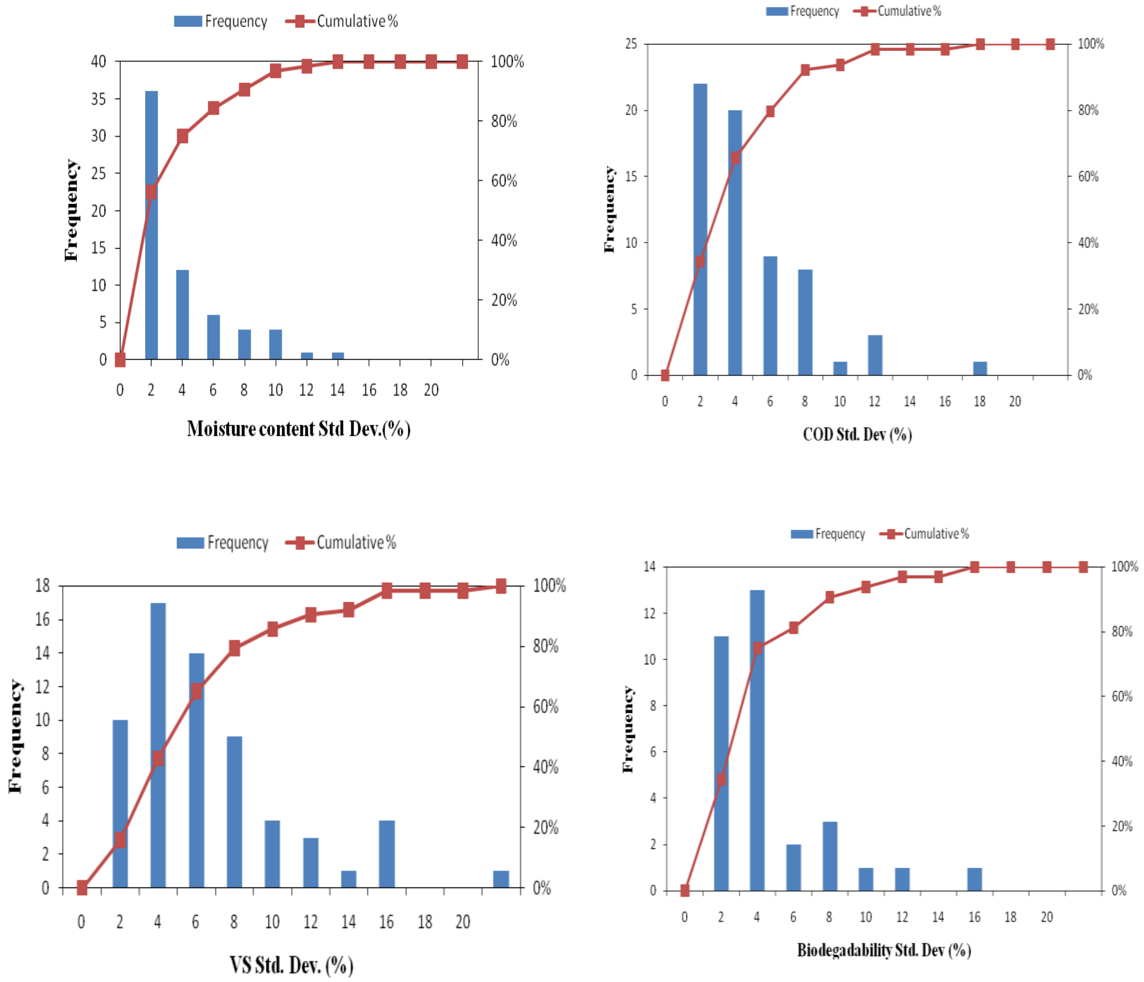
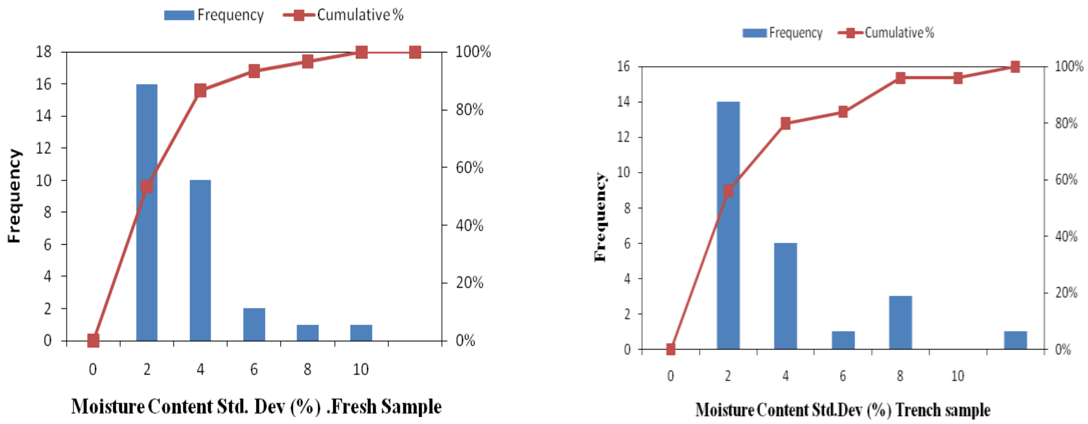


Figure B.2: Histogram for the standard deviations recorded for various parameter analysis performed for sludge samples collected directly from the pits at different layers.



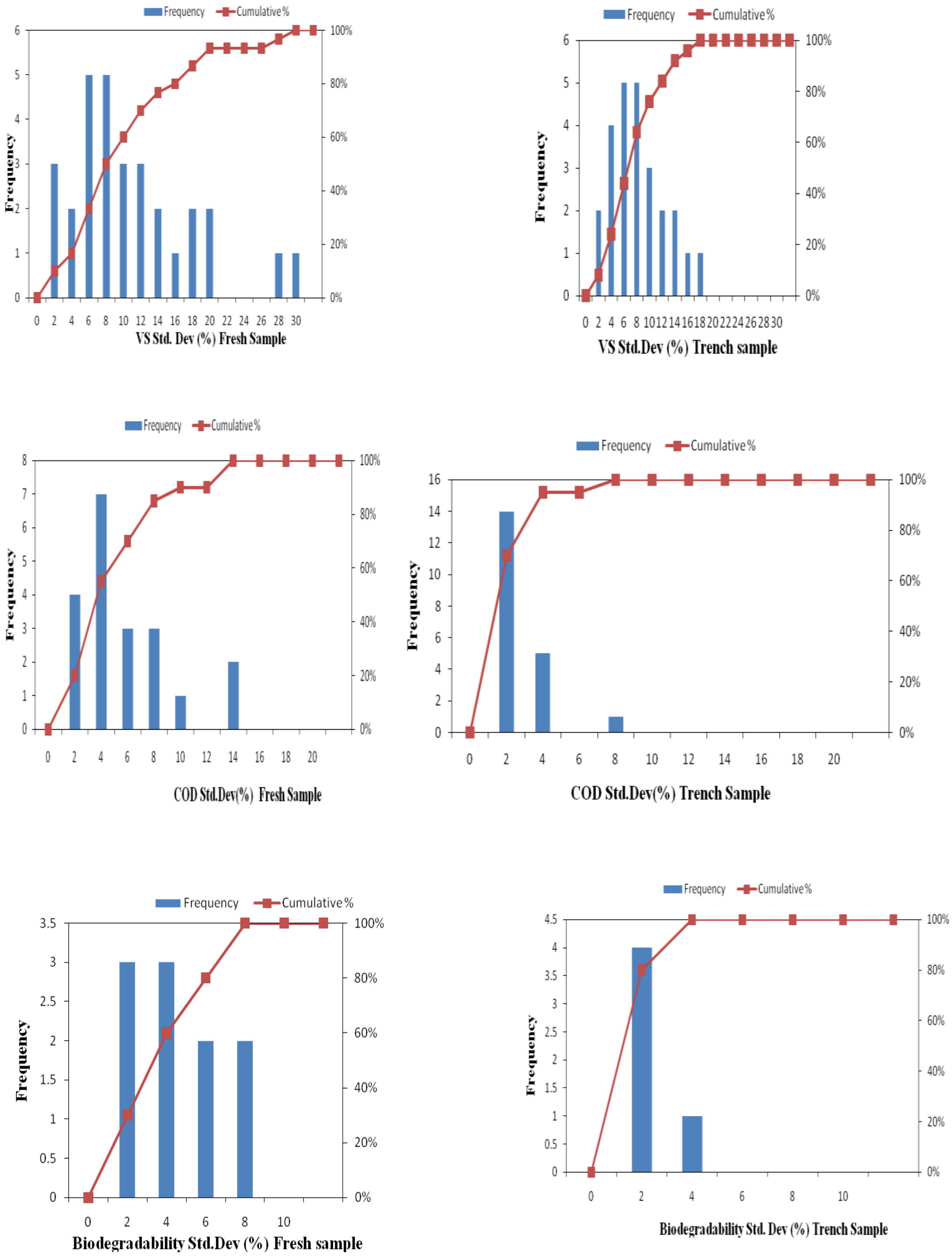


Figure B.3: **Histogram for the standard deviations recorded for various parameter analysis performed for fresh VIP sludge samples before burial in trenches and sludge samples exhumed from trenches .**

As presented in the histograms above, it is clearly shown that the results are closely grouped about their average value and most of the data indicates a standard deviation of less than 10%. Thus, through the assessment of the standard deviation of the analytical results as presented in the histogram, all laboratory analysis performed on the sludge samples could be said to be of acceptable accuracy. Hence, based on the analysis of the histograms, the following standard deviations can be assumed:

Analysis Performed on sludge samples collected from different layer within a pit;

Moisture content:	12 %	COD:	14 %
VS:	16 %	Biodegradability:	14 %

Analysis Performed on sludge before burial and exhumed sludge

Fresh sample

Moisture content:	10 %	COD:	14 %
VS:	20 %	Biodegradability:	8 %

Trench sample

Moisture content:	8 %	COD:	5 %
VS:	18 %	Biodegradability:	3 %

APPENDIX C

Analysis conducted on collected groundwater samples

pH

The pH was one of the field parameters used during the purging of the boreholes and the water sample pH was taken immediately after the field parameters became stable right at the well-head when samples are taken.

Conductivity

Conductivity was also one of the field parameters used during the purging of the boreholes and immediately the field parameter became stabilized, the conductivity for the groundwater samples was taken right at the borehole- head using a conductivity meter. The conductivity of the groundwater sample is an indication of the amount of soluble salts present in the groundwater sample.

Temperature

Temperature was also used as one of the field parameters to determine the required amount of water to be purge out of the boreholes and it was measured using a digital thermometer.

Dissolved oxygen

The measurement of dissolved oxygen is very important in monitoring groundwater quality in that, the valence state of many trace metals is been regulated by the presence of dissolved oxygen in the groundwater. It also constrains the bacteriological metabolism of organic compounds in groundwater (Domenico and Schwart, 1998). The dissolved oxygen concentration was measured at the borehole-head during the sampling process using a DO meter.

Chloride and Sodium ions

Chloride and sodium ions are among the major ions measured in groundwater, as they contribute to a large extent to the salinity in the groundwater and the quality of the water samples, since excessive amounts of these ions might affect the use of the groundwater for many purpose. The chloride and sodium ions were analyzed according to Standard methods (APHA, 1998) at the eThekwini Water and Sanitation Laboratories.

Chemical Oxygen Demand

Chemical oxygen demand is a measure of the amount of oxidizable organic material in the groundwater samples. Chemical oxygen demand of water samples collected from the boreholes was determined using the closed reflux method (APHA, 1998) at the eThekwini Water and Sanitation Laboratories.

Ammonium and Nitrate

Most groundwater monitoring programmes are usually directed towards the determination of ammonium and nitrate in the groundwater because they are usually the products of pollution in groundwater (Weaver *et al*, 2007). This is because in the presence of light and oxygen, high concentrations can lead to eutrophication and high concentration of nitrate in drinking water is toxic. Ammonium and Nitrate were analyzed according to Standard method (APHA, 1998) at the eThekwini Water and Sanitation Laboratories.

Orthophosphate

Orthophosphate is usually an important parameter in monitoring surface water but is of less interest in groundwater. However, the determination of orthophosphate was also included as one of the parameters to be used in monitoring changes in the groundwater at the Umlazi entrenchment site because of the likelihood of the presence of phosphate in the VIP latrine sludge buried and therefore changes in orthophosphate would indicate contamination by leachate from buried sludge.

E-coli, Total coliforms and Total organisms

These analyses were performed on the sampled water from the five boreholes in order to determine the general microbiological quality of the water samples and also possible faecal pollution of the groundwater which might be as a result of the VIP latrine sludge buried.

APPENDIX D

Effect of VIP Latrine sludge on tree growth

Summary of MSc Study on tree growth

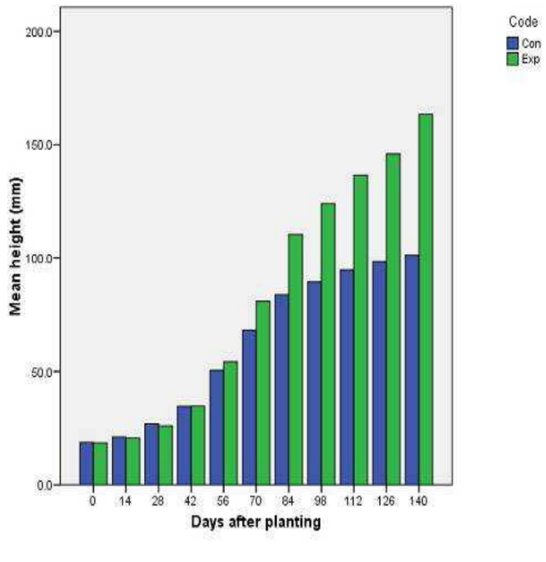
The effect of VIP latrine sludge on tree growth was tested in two ways: Firstly, an MSc project was undertaken by Craig Taylor which investigated the effect of pit latrine sludge on the growth of plant. A brief review of this study is presented in this section. In this study, two plant species were selected for the tree growth trials. These were Eucalyptus grandis and Acacia mearnsii (Flooded gum and Black wattle), a total of twenty four plant growth columns which was constructed from manhole rings 250 mm in height and 750 mm in diameter were used. The plant columns were constructed such that water could not penetrate through the base of each column. The plant columns were grouped into treatment groups which comprised of twelve columns and the remaining twelve columns served as the control groups for the experimental set up. The treatment groups were filled with pit latrine sludge collected from a local community within eThekwini Municipality and sand collected from the entrenchment site while the control groups were filled with only sand collected from the entrenchment site to the same height as the plant columns in the treatment group. The control groups were treated with fertilizers throughout the experimental duration so as to serve as a positive control experiment. A total of 24 plants were planted one in each column, six seedlings each of Eucalyptus grandis and Acacia mearnsii were planted into the treatment plant columns. The remaining six seedlings of each species were planted in the control plant columns. For all the plant columns, only healthy seedlings of similar height were selected for use and the same quantity of water was used to irrigate both the treatment and control experimental set up. In order to investigate the effect of pit latrine sludge burial in trenches on plant growth, three different methods were used;

- Measurement of plant height immediately after planting and every second week measurement were carried out thereafter for up to 140 days after planting. The plant height was measured from the base of each plant to the apical bud.

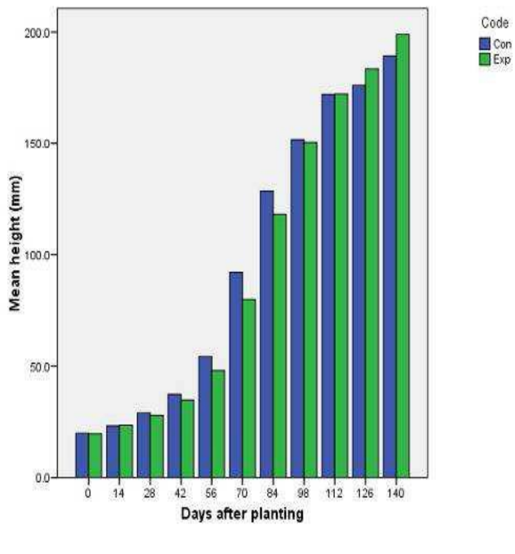
- Vernier callipers were also use to measure the diameter of the stem of each plant on a monthly basis throughout the duration of the experimental set up.

- Photosynthetic measurement in terms of light level and CO_2 concentration were also performed.

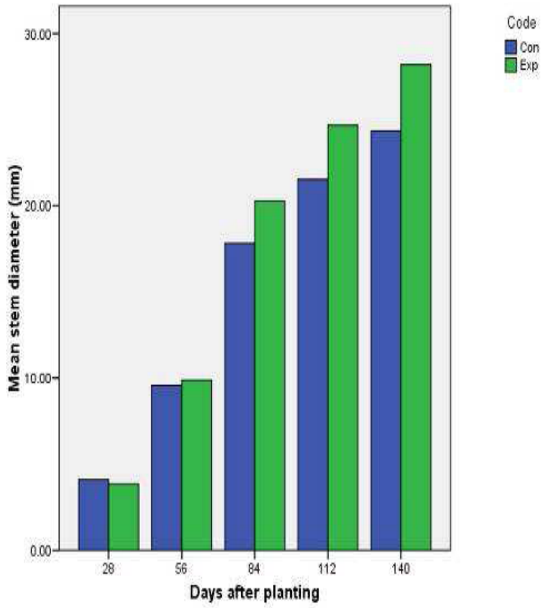
As presented in **Figure E.1 and E.2,** it was found that in all measurement performed, the application of pit latrine sludge content in the plant columns provided a valuable nutrients source for the tree planted. This was because measurements of tree height, diameter of tree stem as well as photosynthetic measurements were significantly increased in comparison to the control experiments except for the A. mearnsii plant which showed little changes in the height of the trees and stem diameter compared to the control. Thus, this study concluded that burial of pit latrine sludge in association with agroforestry has significant benefits.



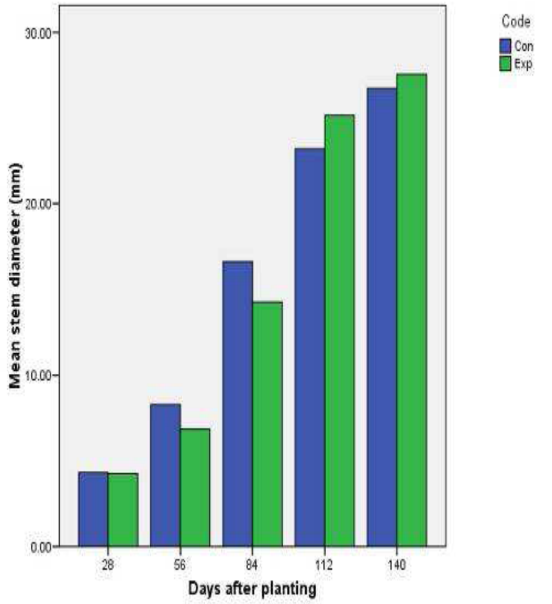
Eucalyptus



Acacia mearnsii

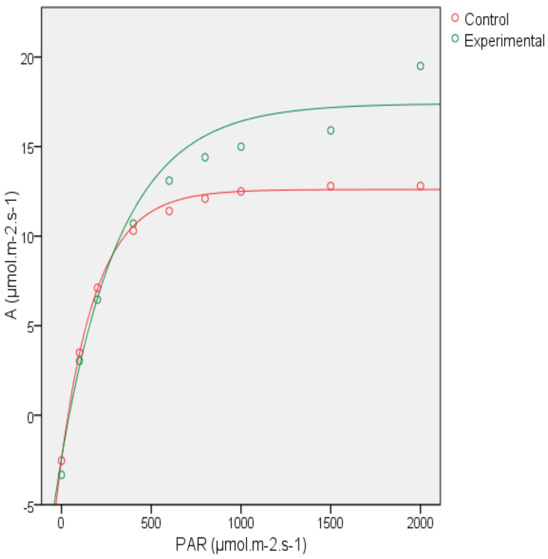


Eucalyptus

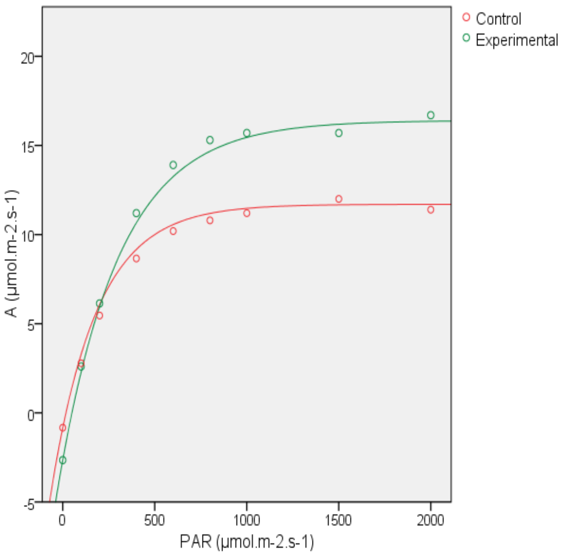


Acacia mearnsii

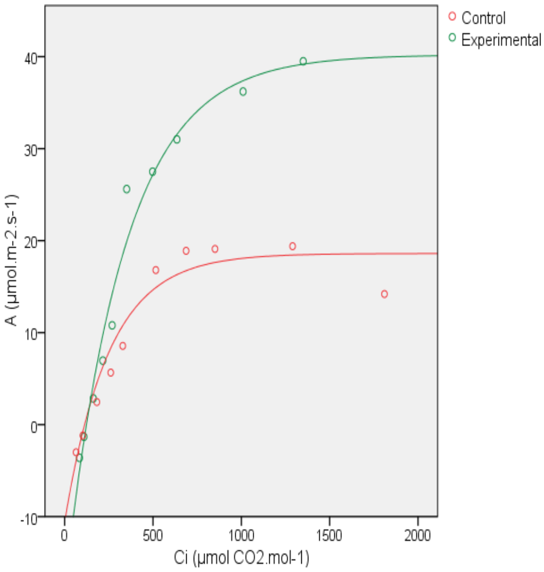
Figure E.1: Measurement of plant height and stem diameter (Eucalyptus and Acacia mearnsii) in plant columns containing pit latrine sludge compared to plant columns without pit latrine sludge (control). (Reproduced with permission from Taylor, 2011)



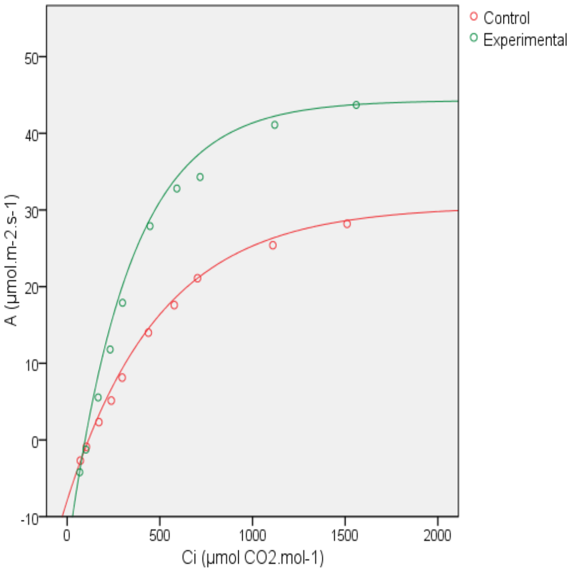
(a)



(b)



(c)



(d)

Figure E.2: **Light and CO_2 Response Curve for flooded gum tree and black wattle trees, where plot (a) and (b) represent the light response curve for flooded gum and black wattle trees respectively. Plot (c) and (d) represents the CO_2 response curve for flooded gum and black wattle trees respectively. (Reproduced with permission from Taylor, 2011).**

APPENDIX E

PUBLICATIONS ARISING FROM THIS PROJECT

This section presents a list of publication emanating from this project.

1. RESEARCH REPORT

Understanding sludge accumulation in VIPs, Urine diversion toilets and other onsite sanitation systems, and strategies to manage desludging in the future when pits are full (WRC Project K5/1745; Research report in completion)

Investigating the potential of deep row entrenchment of pit latrine and water treatment works sludge for agroforestry and land rehabilitation purposes (WRC Project K5/1829; Research report in completion)

2. JOURNAL ARTICLES

A.A-L. Couderc, C.A. Buckley, K. Foxon, C.F. Nwaneri, B.F. Bakare, T. Gounden and A. Battimelli (2008) The effect of moisture content and alkalinity on the anaerobic biodegradation of VIP contents. Water Sci Technol. **58** (2), pp. 473-477

B.F. Bakare, C.F. Nwaneri, K.M. Foxon, C.J Brouckaert and C.A Buckley **(paper accepted for publication**) Variation in VIP latrine Sludge Contents. Water Science Technology.

3. CONFERENCE PROCEEDINGS

B.F. Bakare, K.M. Foxon, R. Salisbury, C.J. Brouckaert, D. Still and C.A. Buckley (2008). Management of VIP latrines in the eThekwini Municipality. *Proceedings. 2008 Water Institute of Southern Africa (WISA) Biennial Conference and Exhibition, Sun City, South Africa, May 18-22, 2008*

C.F. Nwaneri, B.F. Bakare**,** K.M Foxon, and C.A. Buckley (2008). Biological Degradation processes within a Pit latrine. *Proceedings. 2008 Water Institute of*

Southern Africa (WISA) Biennial Conference and Exhibition, Sun City, South Africa, May 18-22, 2008

B.F. Bakare, C.F. Nwaneri, K.M. Foxon, C.J Brouckaert and C.A Buckley (2010). Pit Latrine Additives: Laboratory and Field Trials. *Proceedings. 2010 Water Institute of Southern Africa (WISA) Biennial Conference and Exhibition, ICC Durban, South Africa, April 18-22, 2010.*

B.F. Bakare, C.F. Nwaneri, K.M. Foxon, C.J Brouckaert and C.A Buckley Entrenchment of VIP Sludge: Characteristics of the buried sludge. *Proceedings. 2010 Water Institute of Southern Africa (WISA) Biennial Conference and Exhibition, ICC Durban, South Africa, April 18-22, 2010* (poster).

4. THESES

Nwaneri C. F. (2009). *Physico-Chemical characteristics and biodegradability of contents of Ventilated Improved Pit latrines in eThekwini Municipality*. Master of Science dissertation. School of Biological and Conservation Science. University of KwaZulu-Natal. South Africa.

Taylor C. (in completion). *An investigation into potential of faecal sludge for plant production.* Master of Science dissertation. School of Biological and Conservation Science. University of KwaZulu-Natal. South Africa.

Woods K. (in completion*). Biological Degradation in VIPs: An Unsteady State Mass Balance Approach.* Master of Science dissertation. School of Chemical Engineering University of KwaZulu-Natal. South Africa