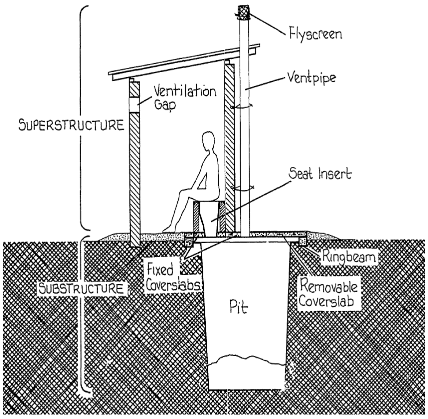
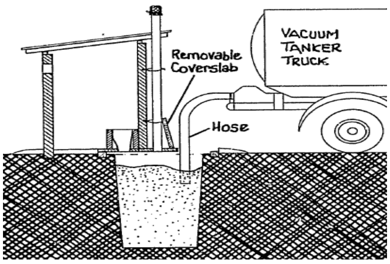
CHARACTERISATION OF PIT LATRINE CONTENTS AND DEVELOPING A SCIENTIFIC UNDERSTANDING OF PROCESSES OCCURRING IN ON-SITE DRY PIT LATRINE SYSTEMS IN LOW INCOME URBAN AREAS – A CASE STUDY OF GABORONE





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The publication of this report emanates from a project entitled: CHARACTERISATION OF PIT LATRINE CONTENTS AND DEVELOPING A SCIENTIFIC UNDERSTANDING OF PROCESSES OCCURRING IN ON-SITE DRY PIT LATRINE SYSTEMS IN LOW INCOME URBAN AREAS – A CASE STUDY OF GABORONE (WRC Project No. K5/2297/11).

Executive Summary

When a pit latrine fills up, the users typically face the difficult task of having it emptied. In rural areas, the users cannot afford the services of a vacuum truck, and in dense urban areas, vacuum trucks often cannot gain access to the pits. Improper faecal sludge management can lead to the spread of diseases through faecal contamination during emptying, transport, and through improper disposal. Improper pit emptying negates the health benefits provided by pit latrines, consequently taking a step backwards in the goal of better global sanitation.

This research project was carried out by the University of Botswana in cooperation of the Water Utilities Corporation (WUC). The project aimed to develop a scientific understanding of processes in Ventilated Improved Pit latrines (VIPs) in low income urban areas of Gaborone by characterising faecal sludge based on physical, chemical, microbial, and rheological properties.

The specific tasks in this study included:

1. Review of sanitation policies and pit emptying practices in Botswana (legal and institutional aspects of faecal sludge management).

2. A risk assessment of the operation and maintenance (O&M) of pit latrines.

3. Characterisation of faecal sludge sampled from various VIPs.

The following key findings have come out of this study:

- Faeces and urine are health hazards but also have potential for reuse if handled and treated correctly. However, negative perceptions on faecal sludge are a hindrance to companies and individuals realising this potential. This is caused by lack of knowledge about Faecal Sludge Management (FSM) among the community and the private sector.
- In Botswana, the main cause of poor FSM is the introduction of the water sector reforms, which has resulted in on-site sanitation hanging in the balance, despite the government having a good history of improved sanitation provision.
- Lack of capacity and inexperience with on-site sanitation has led to the WUC to abandon pit emptying services. The WUC is unable to cope with the demand for pit emptying services, leading to inadequate service provision.
- There is currently no clear working relationship between the WUC and private companies. Although there are policies related to sanitation, there is no clear strategy specifically relating to FSM, particularly to address issues of pit emptying. Proper and coordinated FSM strategies have the potential to improve public health and dignity as well as agricultural productivity.

FSM goals can only be adequately achieved if the community and the private sector are educated thoroughly. A thorough understanding of the characteristics of faecal sludge will assist in improving pit emptying and faecal sludge treatment techniques and could enhance potential for reuse of FS in agriculture. Government must also develop a more specific sludge management policy or strategy that emphasises pit emptying, transportation, and treatment facilities. New technologies for sludge treatment and processing must be considered and introduced as part of the FSM strategy to add value to the FSM process.

Poor coordination among stakeholders renders the sanitation sector difficult to manage. The WUC should involve and engage a wide range of stakeholders, including households and representatives from the communities and key faecal sludge management stakeholders (such as local authorities, emptying companies, transporters (Small and Medium Enterprises – SME), relevant government authorities and sanitation experts). In order to consider resource recovery during FSM, a new FSM model is needed in Botswana. Promotion of resource recovery and reuse (RRR) of FS can go a long way in avoiding long-distance travel by vacuum tankers to the wastewater treatment plant (WWTP). Decentralisation of services may be achieved by constructing planted drying beds (PDBs). To manage FS in a more sustainable manner, WUC must start viewing FS as a resource rather than a waste and keep cost recovery in mind.

Acknowledgements

This work was made possible through the generous support of the Sanitation Research Fund for Africa (SRFA) co-funded by the Water Research Commission (South Africa) and the Bill & Melinda Gates Foundation (BMGF) (BMGF, Grant ID: OPP1044943). The authors extend their gratitude to the Water Utilities Corporation (WUC) and all stakeholders who participate in the workshops. Special thanks goes to the following students: Mr. Innocent Thukwi, Mr Mohau Mhoeshoe, Mr. Lamong Tshenyego, Mr. Ontiretse Dintwa, Mr. Ditebogo Nage and Mr Able Keitseng, for the outstanding assistance they offered in this project.

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Acronyms

AMBIC	Ammonium bicarbonate
APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DDW	Double distilled deionised water
DWMPC	Department of Waste Management and Pollution Control
ESPP	Environmental Sanitation and Protection Pilot Programme
EU	European Union
FS	Faecal Sludge
FSM1	Faecal Sludge Management
GBC	Gaborone City Council
GoB	Government of Botswana
GWWTP	Gaborone Wastewater Treatment Plant
IC	Ion Chromatography
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectrometry
MDG	Millennium Development Goals
MDWS	Ministry of Drinking Water and Sanitation
MoH	Ministry of Health
MoH&W	Ministry of Health and Wellness
MPN	Most Probable Number
NDP	National Development Plan
NRSP	National Rural Sanitation Programme
O&M	Operation and Maintenance
PDB	Planted Drying Bed
PFA	Pathogen Flow Analysis
PL	Plastic Limit
QMRA	Quantitative Microbial Risk Assessment
RR	Resource Recovery
SDG	Sustainable Development Goals
SHHA	Self-Help Housing Agency
SME	Small and Medium Enterprises

TS	Total Solids
TSR	Total Solids Residue
UN	United Nations
UNICEF	United Nations Children's Fund
U.S EPA	U.S Environmental Protection Agency (EPA)
VIP	Ventilated Improved Pit
VS	Volatile Solids
WHO	World Health Organisation
WUC	Water Utilities Corporation
WWTP	Wastewater Treatment Plant

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1 Introduction

1.1 Background

Provision or improvement of sanitation facilities in Botswana has always been driven by the need to protect the environment and public health. Through various policy documents since the 1970s, government has attempted to introduce different sanitation technologies and has signed international treaties, such as the United Nations (UN) Millennium Development Goals (MDGs), to show commitment to issues of the environment. This paper reviews the sanitation situation in Botswana in relation to the MDGs. Rapid urbanisation is occurring across the developing world, and most of this growth is concentrated in informal or slum areas. This scenario is true in Botswana as more people migrate to urban cities to look for work. This puts water supply and sanitation service providers under strain due to increased demands. Providers face formidable obstacles in meeting the demand, and often these obstacles are due to policy constraints.

Sanitation in Botswana generally falls into one of two broad categories: flush-and-discharge or drop-and-store. The type of sanitation system used depends on the area and the socio-economic status of the community as well as availability of water. Flush-and-discharge has generally been regarded as the ideal technology, particularly for urban areas and communities with access to water. However, the drop-and-store method has proven to be the preferred type of sanitation system for communities without access to water.

The Government of Botswana (GoB) regards safe drinking water and sanitation as basic to human survival, dignity and productivity. Lack of potable water supply and adequate sanitation is one of the main underlying causes of diseases and death, especially among children in developing countries. Therefore, to improve the health and living conditions of the nation, the GoB introduced the Urban Sanitation Research Project (USRP) in 1971 to provide latrines at subsidised costs to households in urban areas. The main aim of the project was to improve the poor sanitary conditions in growing towns and cities, with particular focus on the Self-Help Housing Agency (SHHA) areas using a self-help approach. Ventilated improved pit latrines (VIPs) were later introduced in Botswana through the USRP. Later, double vault VIPs were adopted as the standard sanitation facility in urban areas. The councils resolved to provide sub-structures for the latrines, and households were to provide the superstructure. By 1980, the USRP was extended to provide on-site sanitation in rural areas through an Environmental Sanitation and Protection Pilot Programme (ESPP) aimed at testing and evaluating approaches to health education and developing an appropriate rural sanitation technology that is affordable and easy to understand by the community.

Until recently, responsibilities for sanitation and wastewater management in Botswana were fragmented between several organizations. The Department of Waste Management and Pollution Control (DWMPC), under the Ministry of Environment, Wildlife and Tourism, is currently responsible for establishing regulatory frameworks governing sanitation and wastewater planning and service provision. The WUC recently took over the mandate for on-site systems, which was previously the responsibility of district councils. However, it is apparent that the WUC does not fully understand who is responsible for on-site dry sanitation, which has led to extensive confusion during the transition of responsibilities.

1.2 Aims and objectives of the research

This research project was carried out by the University of Botswana in cooperation of the WUC. The project aimed to develop a scientific understanding of processes in VIPs in low-income urban areas of Gaborone by characterising faecal sludge of on-site VIPs based on physical, chemical, microbial, and rheological properties.

The specific tasks in this study include:

1. Review of sanitation policies and pit emptying practices in Botswana (legal and institutional aspects of faecal sludge management).

2. A risk assessment of the operation and maintenance (O&M) of pit latrines.

3. Characterisation of faecal sludge sampled from various VIPs.

1.2.1 Research problem

When a pit latrine fills up, the users typically face the difficult task of having it emptied. In rural areas, the users cannot afford the services of a vacuum truck, and in dense urban areas, vacuum trucks often cannot access the pits. Improper faecal sludge management can lead to the spread of diseases through faecal contamination during emptying, transport, and improper disposal. Improper pit emptying negates the health benefits provided by pit latrines, consequently taking a step backwards in the goal of better global sanitation.

The Water Research Commission funded projects around Southern and Eastern Africa to establish knowledge-based solutions to on-site dry sanitation challenges in Sub-Saharan Africa through *Characterisation of pit contents and developing innovative techniques for pit desludging and subsequent sludge management in low income urban areas.*

1.3 Definition of faecal sludge

Faecal sludge (FS) is generally defined as the undigested or partially-digested slurry or solids resulting from storage or treatment of blackwater or excreta. “Faeces” refers to human excrements excluding urine or water. In this work, faecal sludge refers to human excrements stored in pit latrines. Faecal sludge is therefore synonymous to pit sludge. A typical adult excretes an average of 0.4 kg of faeces per day, which comprises 0.1 kg of dry mass and a moisture content of approximately 70-80%. Approximately 80-90% of faeces is organic matter which can degrade.

1.4 Study area

Botswana is a landlocked country bordered by Namibia to the west, Zambia to the north, Zimbabwe to the northeast and South Africa to the south as shown in Figure 1-1. This study was carried out in the Gaborone city, in Mogoditshane and Broadhurst. The two areas represent rural peri-urban portions of Gaborone city. Gaborone is the capital and largest city in Botswana and is home to about 231,626 people, 10% of the total population of Botswana (Statistics Botswana, 2013). The latitude and longitude of Gaborone is 24°40'South and 25°55'East. The FS from these areas is treated with municipal wastewater at the Gaborone Wastewater Treatment plant, about 10 km northeast of Gaborone city.

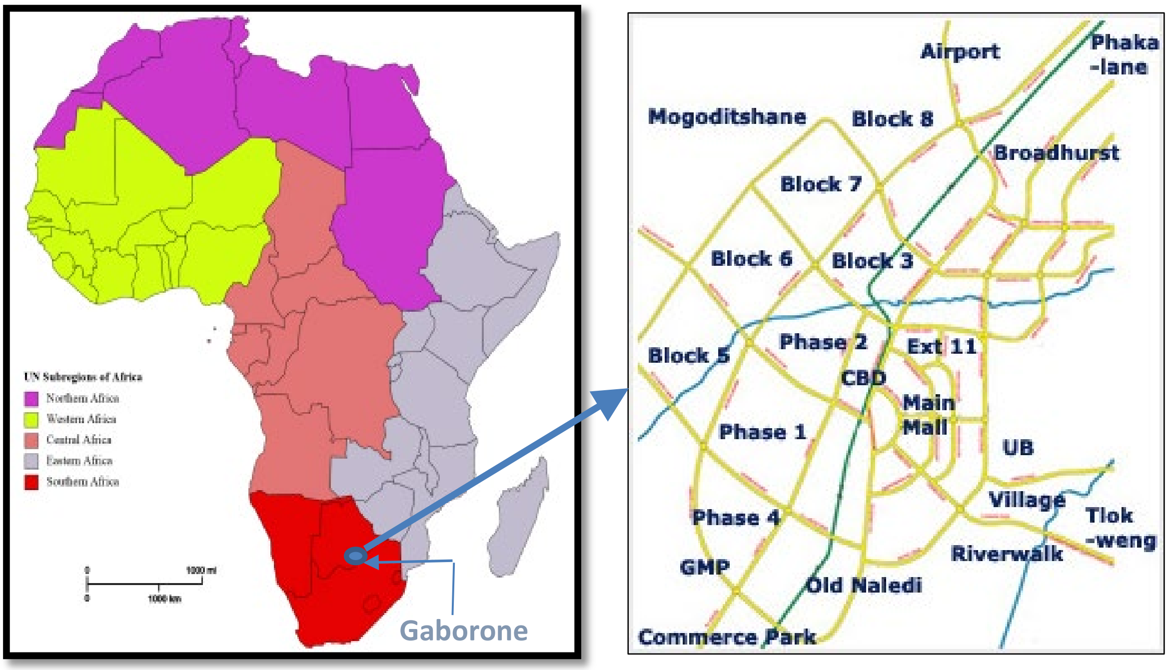


FIGURE 1-1: MAP SHOWING LOCATION OF GABORONE, THE STUDY AREA

1.4.1 Climate

Gaborone is influenced by the local steppe climate and receives very little rainfall. The driest month is July, with 3 mm of rainfall, while in the wettest month is January, with 85 mm on average. The average annual precipitation is 457 mm, and the average annual temperature is 20.3°C. Climate has a direct influence on FS characteristics, mainly due to temperature and moisture (Niwagaba, 2014). As a tropical country, Botswana has one season with moderate rainfall, referred to as the wet season, and a dry season. Temperatures may be lowest during the dry season and highest during the wet season. Typically, the highest demand for FS collection and transport services occurs during the rainy season, as heavy rainfalls result in overflowing and flooding of on-site systems. Rates of biological degradation are also temperature-dependent, and rates increase with warmer temperatures.

1.4.2 Soil characteristics in Gaborone

The soil characteristics in Gaborone differ throughout the city and the characteristics at a location are partially determined by the underlying bedrock and the influence of anthropogenic factors. Soil in Botswana contains minerals such as silicon, iron, aluminium, sodium, calcium and magnesium (Ekosse & Anyangwe, 2012).

1.5 Brief descriptions of water quality parameters

The heavy metals in sludge may come from several sources, including domestic sources (Carrondo et al., 1978). These metals include chromium, manganese, cobalt, iron, arsenic, zinc, lead, cadmium and mercury. Knowledge about the levels of heavy metals in sludge is important for treatment since these may have adverse effects on public and environmental health. A study by Carrondo et al. (1978) reported that the exposure to excessive concentrations of cadmium and mercury has adversely affected health in certain communities.

Nickel (Ni) is a heavy metal used to produce stainless steel and nickel alloys. Intake of nickel by food is much more common than intake from water. Nickel is carcinogenic both if inhaled and in metallic form. Increase in pH may reduce leaching of nickel. The World Health Organisation's (WHO) guideline for nickel in drinking water is 0.07 mg/ℓ (WHO, 2011).

Zinc (Zn) is a heavy metal, which can be found in almost all food and potable water as salts and organic complexes. There is no guideline from WHO regarding zinc in drinking water because levels found in drinking water are of no health concern. However, zinc might affect taste of water in concentrations above 4 mg/ℓ and it may not be acceptable to consumers at levels above 3 mg/ℓ. Zinc is not typically found in surface water and groundwater in concentrations higher than 0.01 and 0.05 mg/ℓ, respectively (WHO, 2011).

Chromium (Cr) is widely-distributed in the earth's crust and exists in different valences. The major intake source for chromium is through food and chromium (III) is an essential nutrient. The WHO guideline for chromium in drinking water is 0.05 mg/ℓ. The concentration of chromium in drinking water is typically lower than 0.002 mg/ℓ but concentrations up to 0.12 mg/ℓ have been reported. Inhaling chromium (VI) is stated as carcinogenic (WHO, 2011).

Manganese (Mn) is a very common heavy metal in the earth's crust and usually found together with iron. Manganese is used as an oxidant for cleaning, bleaching and disinfection in production of iron and steel alloys. Manganese often occurs naturally in surface water and groundwater and is naturally present in many food sources. Thus, intake by food is also the most common route of exposure. Manganese is an essential element for both humans and animals. The levels of manganese found in drinking water are not of health concern, and therefore WHO has no guideline for manganese in drinking water. There is a health-based value of 0.4 mg/ℓ, but because that level is usually not found in drinking water, there is no formal guideline. To consumers, a manganese concentration of 0.1 mg/ℓ is usually acceptable, but above this, the manganese may cause a bad taste and the water can stain sanitary ware and laundry (WHO, 2011).

Copper (Cu) is an essential element in soil for plant growth and copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$) is the typical copper fertilizer source (Alloway 1995; Salam & El-Fadel, 2008). However, its accumulation in soils is of great concern because of its persistent, bioaccumulative, and toxic (PBT) properties. These properties may present increasing long-term toxic effects to human health and the environment, even if released in small amounts (Salam & El-Fadel, 2008). Copper does not appear to leach significantly from soil due to its high binding capacity.

1.5.1 Hygienic quality of faecal sludge

Nematode eggs are often used as indicators to determine hygienic quality and safety of sludge, especially where it is to be used as a soil conditioner or fertilizer. According to the WHO nematode guideline, the helminth egg concentration should be less than 1 egg/ℓ if FS is to be used in agriculture (WHO, 2006). The concentration of helminth eggs in FS largely depends on the prevalence and intensity of infection in the population from which FS is collected. Therefore, if the objective is to use FS in agricultural activities,

1. Treatment of FS must be implemented to reduce helminth egg counts and viability or
2. FS must be stored for long periods of time to reduce the helminth egg concentration.

Table 1-1 shows the helminth pathogens that can be found in faeces of infected human beings and their transmission routes**.** In this work, *Ascaris* eggs were used as the indicator of hygienic quality of FS, because *Ascaris* eggs are very resistant to deactivation (Konè, 2007). *Ascaris* is transmitted through humans to soil, indicating that the application of FS in soil can lead to contamination of soils. Thus, communal defecation areas and crop contamination are reported to be the main mechanisms of helminth transmission (Ministry of Drinking Water and Sanitation [MDWS], 2016).

Table 1-1: Helminth pathogens in human excreta (MDWS, 2016)

Helminths	**Common name**	**Diseases**	**Transmission**
Ancyclostoma duodenale	Hookworm	Hookworm	Human-soil-human
Ascaris lumbricoides	Roundworm	Ascariasis	Human-Human-soil
Taenia saginata	Beef worm	Taeniasis	Human-Cow-Human
T. solium	Pork Tapeworm	Taeniasis	Human-Pigs-Human

Trichuris trichura	Whipworm	Trichuriasis	Human-Soil-Human

1.5.1.1 Factors influencing helminth egg inactivation

The prevalence and intensity of infection among the communities, along with various other factors determining parasite survival, influences the concentration of helminth eggs in FS (WHO, 2006). Literature shows that temperature, dryness and UV light are the main factors influencing die-off. Helminth eggs can survive 10-12 months upon excretion under tropical climates (Larsen & Roepstorff, 1999; Sanguinetti et al., 2005). Provision of toilets and treatment of excreta prior to discharge or reuse are regarded as the main interventions to reduce transmission of *Ascaris*.

2 Materials and methods

2.1 Desk study

A comprehensive desk study of government policies related to waste and sludge management was compiled and reviewed, such as master plans and by-laws for districts.

2.2 Field survey and questionnaires

A field survey of the study area began with a visit to households where occupants were provided with a consent letter for signing. A questionnaire was administered to those households taking part in the research to get the feedback on their practices and use of VIPs. The plot numbers for the consenting households were recorded along with coordinates and observations of the local conditions. A survey of literature and sanitation stakeholders was conducted to understand the roles played by various stakeholders and challenges they face in FSM. In total, 50 households in Gaborone were visited.

2.3 Stakeholder meeting

A stakeholder meeting was convened to discuss challenges faced by municipalities with faecal sludge management, including emptying pits, transportation, and sludge handling. The stakeholders included service providers, such as the WUC, the Department of Water Affairs, and the Department of Sanitation and Pollution Control (DWMPC), Gaborone City Council (GBC) and Private Firms. The meeting aimed to define the roles and responsibilities of each stakeholder in sludge management.

The stakeholders were considered in the FSM service chain included:

1. Household (users), who were required to answer a structured questionnaire
2. Private collection and transport businesses that empty the faecal sludge with vacuum trucks and transport it to the treatment facility
3. WUC, who is responsible for O&M of on-site sanitation and the faecal sludge treatment plant
4. The Department of Waste Management and Pollution Control (DWMPC) and the Department of Environmental Affairs

Discussions and workshop revealed discrepancies in sanitation policies and practices.

2.4 Faecal sludge sampling and preparation

Faecal sludge sampling protocols were followed carefully to prevent contamination during sampling and transportation, which could affect the results. The protocols used in the study were approved by the Departmental Ethics Committee. Overall, 50 pits were sampled in two localities of Gaborone (25 pits in Mogoditshane and 25 pits in Broadhurst) representing different socioeconomic groups. Samples were obtained from the pit using a multi-stage sludge sampler through either the pedestal hole or the inspection chamber, as shown in Figure 2-1.

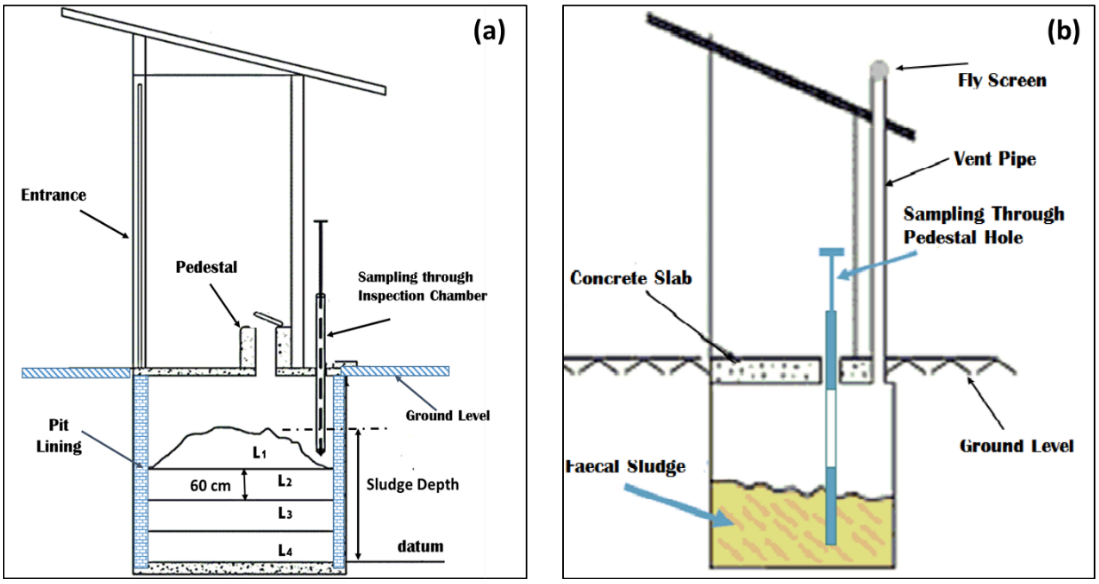


FIGURE 2-1: VIP LATRINE SHOWING FS SAMPLING PROCEDURE THROUGH THE INSPECTION CHAMBER (A) AND THROUGH THE PEDESTAL (B). L DENOTES FS LAYER, WHERE L1 IS THE NEWEST SLUDGE AND L4 THE OLDEST

FIGURE 2-2: PREPARATION OF THE SAMPLER FOR SAMPLING (A) AND THE SAMPLING PROCESS THROUGH THE SQUAT HOLE (B)

2.4.1 Pit depths

Mogoditshane VIP pits were 1.83 metres deep on average, while Broadhurst pits were 1.37 metres deep on average. Broadhurst pits were constructed by government under the Self-Help Housing Agency (SHHA) and National Rural Sanitation Programme (NRSP) programmes, making them generally standardised. Mogoditshane pits, on the other hand, are constructed by individuals, leading to great variation in pit dimensions.

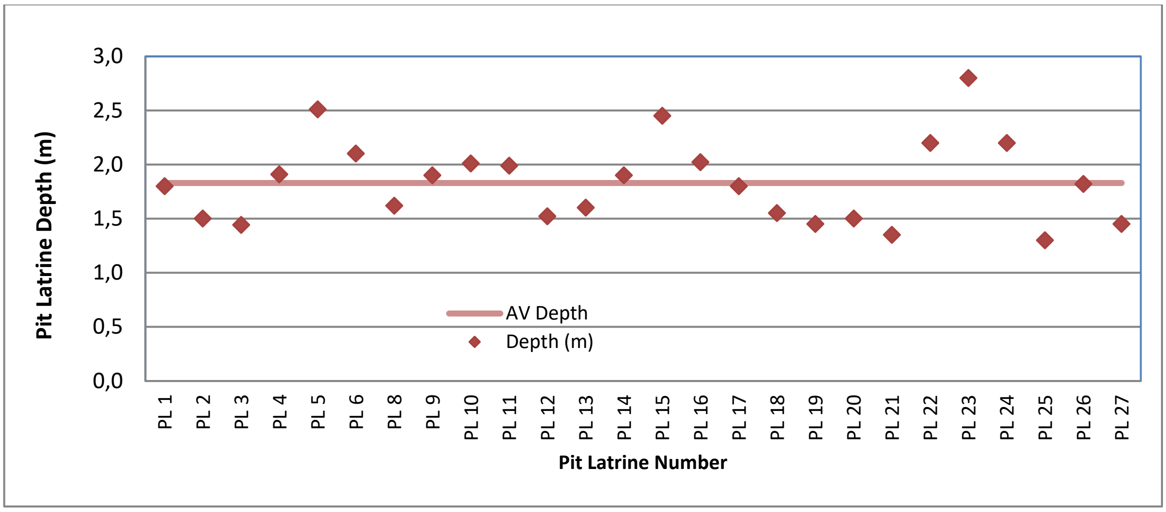


FIGURE 2-3: PIT DEPTHS MEASURED IN MOGODITSHANE

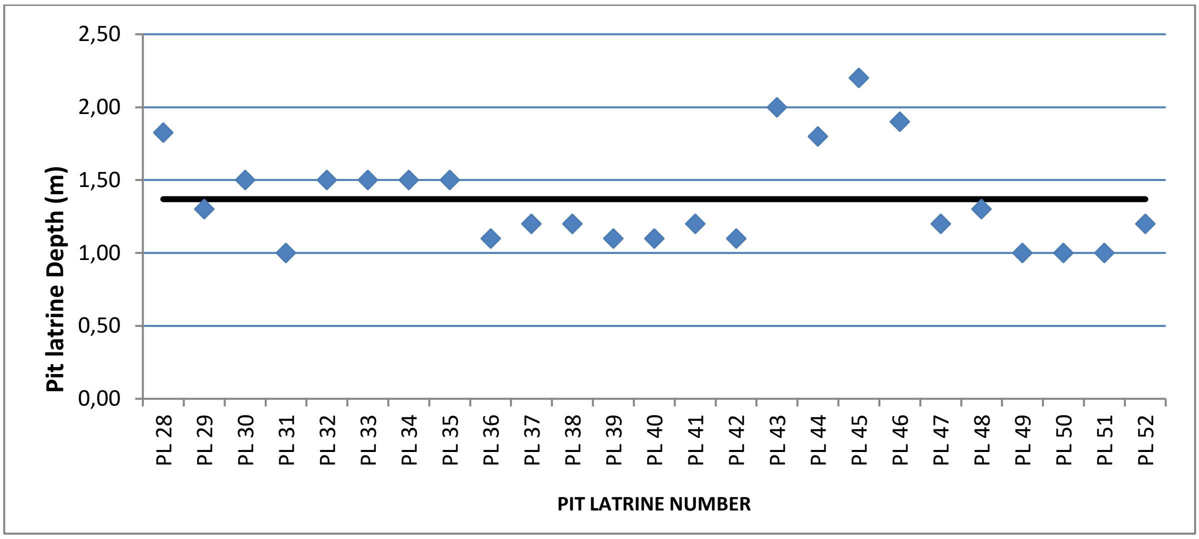


FIGURE 2-4: PIT DEPTHS MEASURED AT BROADHURST

2.4.2 Sample collection and preparation

Sludge samples (about 3 kg) were collected in polyethylene containers and transferred to the cold room at the Chemistry Department. For chemical analyses, samples were taken from the cold room and air-dried for five days to allow water to evaporate from the sample and also to avoid fungal development. Once the samples were dried, they were crushed with a mortar and sieved to 150 µm. The sieved samples were thereafter stored in sealed bottles at room temperature until the day of analysis.

2.5 Analytical methods

Faecal sludge samples were securely transported to the laboratory and analysed for heavy metals (such as copper (Cu), iron (Fe), lead (Pb), cadmium (Cd), zinc (Zn), manganese (Mn) and arsenic (Ar)), nutrients, and microbial parameters (such as *Ascaris*). All analyses of faecal sludge samples were performed according to methods outlined in the Standard Methods for the Examination of Water and Wastewaters (APHA, 2005).

2.5.1 Metal Analysis by ICP-OEP

Briefly, 0.5 g of each sample was placed in a pre-washed conical flask. 100 mℓ of double distilled deionised water (DDW, 18 MΩ cm^{-1}) and 12 mℓ of concentrated HNO_3 (analytical grade) were added to digest the sample. The samples were heated until the volume of the solution was approximately 0.5 mℓ. Samples were then cooled to room temperature. DDW was then added. The obtained solution was filtered through Whatman No. 42 filter paper and transferred to a 25-mℓ volumetric flask and diluted with DDW to a final volume of 25 mℓ. Each sample was analysed in triplicate for Cd, Cr, Cu, Ni, Pb, Mn, Sn, Fe, Zn, As, Na, K, Mg and Ca using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES).

All reagents used were of analytical grade and deionized water (18.2 MΩ cm) from a Millipore Milli Q system was used. All the extraction procedures were performed using laboratory glassware and polyethylene bottles, pre-cleaned with HCl and rinsed with double distilled water.

2.5.2 Nitrate, nitrite and phosphate analysis by ion chromatography

0.5M aqueous NaOH was added to 0.5 g of each sample and sonicated at 40°C for 20 min and then filtered using a Whatman filter paper (No. 1). The aqueous phase was collected in a beaker. 0.5M $ZnSO_4$ was added drop-wise to this aqueous phase until the white $Zn(OH)_2$ precipitate no longer appeared. The aqueous phase containing nitrite and nitrate ions was filtered through a 0.45 µm Minisart® plus syringe membrane filter into a 50-mℓ volumetric flask and then DDW was added to produce a 50-mℓ sample. All extractions were carried out in triplicate to confirm reproducibility of the experimental results. The concentrations of nutrients in the three layers were averaged and presented as mean values.

Analysis was then carried out using a Dionex ICS-2100 Ion Chromatography System fitted with an autosampler and Chromeleon® Chromatography Data System software. The chromatography system was fitted with a 2 x 250 mm IonPac AS18 Analytical Column, preceded by a 2 x 50 mm IonPac AG18 Guard Column. The EGC III KOH Cartridge was used as an eluent source set to produce an eluent of 32 mM potassium hydroxide. The column temperature was set to 30°C and the flow rate set to 0.25 mℓ/min. Detection was carried out using a DS6 heated conductivity cell. All analyses were performed in triplicate.

2.5.3 Rheological analysis of faecal sludge

The rheological properties of faecal sludge were measured using an Anton Parr MCR51 rotational rheometer with a cone-plate setup (CP50-2 attachment) and Couette geometry (CC27 attachment). The rheometer torque resolution is 100 nNm, which directly impacts the precision with which measurements are taken. The magnitude of experimental error is determined by the torque resolution and the geometry of the experimental setup. The rheometer was calibrated using a standard calibration fluid of alpha-olefins. The rheometer possesses operational limitations, which affect the shear rate range for testing, namely a minimum measurable torque value of 250 µNm and a maximum shear stress of 2 350 Pa. Only data which fell within these limits was considered reliable. Rheological properties of FS determined in this study included shear stress, shear rate, apparent viscosity and density.

2.5.4 Microbiological characteristics

Human excreta may contain large amounts of pathogenic organisms (Langergraber & Muellegger, 2005). *Ascaris lumbricoides* is reported to be the most prolific soil-transmitted helminth, and there are about 1.3 billion cases of Ascariasis globally (Navarro et al., 2008; Jimenéz, 2007). Ascariasis is endemic in Latin America, the Far East and Africa, with children under the age of fifteen greatly affected (Jimenez, 2007). *Ascaris* is an indicator organism, because its inactivation or removal from faecal matter may indicate the inactivation of all other pathogens (Jimenéz, 2007; Norup & Aberg, 2015).

The concentrations of different groups of indicator bacteria in faecal sludge samples and urine were determined. Indicator organisms in three groups were assessed to determine the risk of pathogens in FS, namely enteric bacterial pathogens, enteric viruses and parasites. For the detection of enteric pathogenic bacteria, a modified version of multiple-tube fermentation (Most Probable Number – MPN) method was used, and for the detection of faecal coliforms, United States Environmental Protection Agency (U.S EPA) Method 1680 was used. The method described by Lasobras et al. (1999) for the enumeration of somatic coliphages was used to determine levels of enteric viruses. The ammonium bicarbonate (AMBIC) method for recovery of *Ascaris* ova was used to determine the helminth population (Hawksworth et al., 2005). In addition, microscopic and macroscopic methods were used for identification of microorganisms.

2.5.4.1 Determination of *Ascaris* ova

This study utilised the AMBIC method for the recovery of *Ascaris* ova, as described by Hawksworth et al. (2005). Four replicates were conducted for each faecal sludge sample. In brief, 1 gram of faeces was weighed into a 15-mℓ conical centrifuge tube. The faecal solution was re-suspended by adding 12 mℓ of ammonium bicarbonate solution with intermittent vortexing between additions. The tubes were vortexed for 30 minutes and then centrifuged for 3.5 minutes at 1389xg. The supernatant was discarded and the pellet washed with 14 mℓ of deionised water. The pellet was re-suspended with 14 mℓ of zinc sulphate with a specific gravity (SG) of 1.3. The centrifuge tubes were spun for 3.5 minutes at 617xg and the supernatant carefully removed using a pipette and collected into three tubes containing 5 mℓ of deionised water. Each of the tubes was then topped up with deionised water to a volume of 14 mℓ. The tubes were again centrifuged for 3.5 minutes at 964xg and the supernatant discarded. The deposits obtained were then pooled together into a single tube and spun for 3.5 minutes at 964xg. The supernatant was removed using a pipette and the final deposit examined under the compound microscope. The *Ascaris* ova were enumerated into viable and non-viable based on morphological characteristics.

2.6 Sludge age and depth relationship

The extent of anaerobic digestion of the organic content in VIPs depends on the age of the FS. A deeper sample is an older sample, which has had a longer residence time to undergo degradation and whose characteristics may be affected by the mechanisms that occurred since being deposited in the pit (Buckley et al., 2008).

2.7 Data analysis

Results of this study are expressed in terms of means, standard deviations and p-values, which were computed using Microsoft Office Excel 2007. To assess the health risks within a sludge management system, Pathogen Flow Analysis (PFA) was used. The approach focused on quantifying pathogen concentrations, pathogen flows and their respective reduction, and inactivation or increase at various depths in VIP pits.

2.7.1 T-test analysis

A t-test analysis was performed to determine the difference between the two sets of data from Mogoditshane and Broadhurst areas in Gaborone. The two areas are rural and peri-urban, respectfully. The t-test was performed using the following equation;

$$t = \frac{\bar{x}-\bar{y}}{\sqrt{\frac{{s_x}^2}{n_x}+\frac{{s_y}^2}{n_y}}}$$

EQUATION 2-1

Where

x	=	Mean value for sample 1
y	=	Mean value for sample 2
n	–	Number of samples
S	=	Standard deviation

3 Situational analysis

The launching of National Rural Sanitation Programme (NRSP) during National Development Plan 7 (NDP 7) (1991-1997) saw a rapid increase in the provision of both conventional and improved pit latrines in the rural households of Botswana. There has been an extensive local development of different types of latrines, such as the ventilated improved pit latrine (VIP) in Botswana. While VIPs have improved sanitation by providing dignity to the rural poor, in some areas, they have also contaminated groundwater with bacterial and nitrate pollution (Gbodi & Atawodi, 1987; Lewis, Farr, & Foster, 1980; Nkotagu, 1996; Reed, 1994). Some latrines are designed to be emptied regularly while most are just pits that are abandoned once they fill up. The deterioration of the quality of groundwater resources in some parts of Botswana has led to the development of a National Policy on Wastewater and Sanitation, which requires that all on-site sanitation technologies used in the country satisfy the following criteria:

1. Operational effectiveness and reliability
2. Minimal public health risks
3. Cultural and social acceptance
4. Affordability
5. Free from offensive smell and unsightly conditions
6. Inability to attract flies and other insects
7. Minimal groundwater pollution risks
8. Minimal water usage
9. Easy maintenance by the user

VIPs comply with most of the criteria mentioned and are regarded as more socially and culturally acceptable to users; structurally and functionally sound; and sanitary. However, VIPs that pollute groundwater do not meet items 2 or 7. Pit emptying and sludge management are overlooked in this policy.

The main aim of this chapter is to determine the status of FSM in Botswana and determine which policies are in place to influence FSM.

3.1 Methodology

A desktop study was undertaken to review regulations and policies relevant to the faecal sludge management practices in Botswana. A survey was conducted to understand the roles played by various stakeholders and challenges they face with FSM. Field surveys involved the use of a questionnaire, field observations and photographs and were undertaken in 50 randomly-selected households from Mogoditshane and Broadhurst suburbs. In addition, faecal sludge collection and transport businesses and the WUC staff responsible for O&M of on-site sanitation and the faecal sludge treatment plant were interviewed.

The data analysis of community questionnaires was done using Statistical Package for Social Scientists (SPSS version 20) software package. Frequencies, rates and proportions were obtained.

3.2 Access to improved sanitation technologies

Provision or improvement of sanitation facilities in Botswana has always been driven by the need to protect the environment and public health. Botswana is succeeding in sanitation provision as evidenced by a generally steady increase in sanitation access (Figure 3-1). This increase is attributable to various policy document used by the government since the 1970s to introduce different sanitation technologies. The increase can also be pointed to government commitment to international treaties, such as the UN Millennium Development Goals (MDGs), now known as Sustainable Development Goals (SDGs). A World Bank report (2007) describes rapid urbanisation across cities in the developing world, with most of the growth in informal or slum areas (WHO & UNICEF, 2013). This scenario is also true in Botswana as more people migrate to cities to look for jobs. This places a strain on water supply and sanitation services due to increased demands.

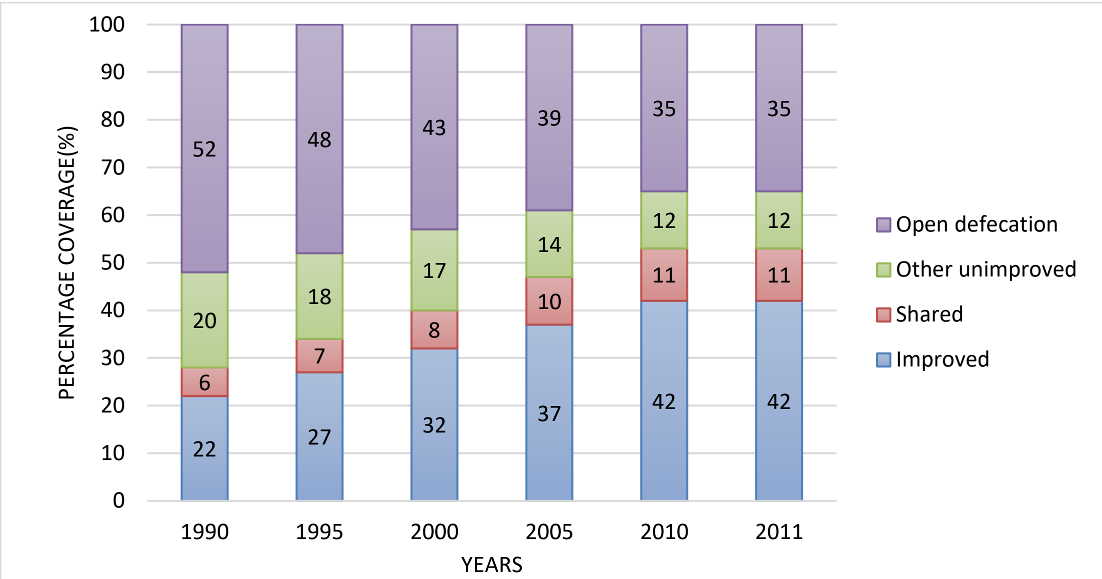


FIGURE 3-1: TRENDS OF SANITATION IN RURAL BOTSWANA (DATA ADAPTED FROM WHO & UNICEF, 2013)

Pit latrines are on-site sanitation systems designed for accumulation and stabilization of faecal matter, urine and sometimes, other materials added to the system (Bakare et al., 2010). Pit latrines are the most common forms of sanitation in the rural/low-cost areas of Botswana. However, according to the World Bank data from 2011 (Figure 3-2), there is a disparity in provision of sanitation between rural and urban populations. About 38% of the rural population still practiced open defecation in 2010 and almost 40% of the population, at the national level, only has access to unimproved sanitation/open defecation (World Bank, 2011).

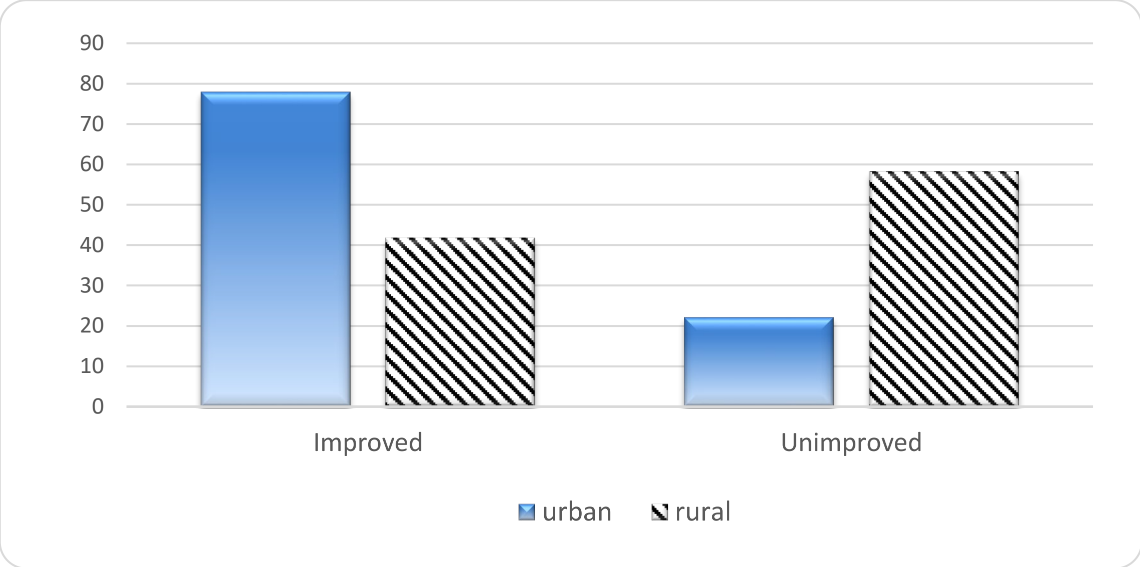


FIGURE 3-2: ACCESS TO SANITATION IN URBAN/RURAL AREAS (%)

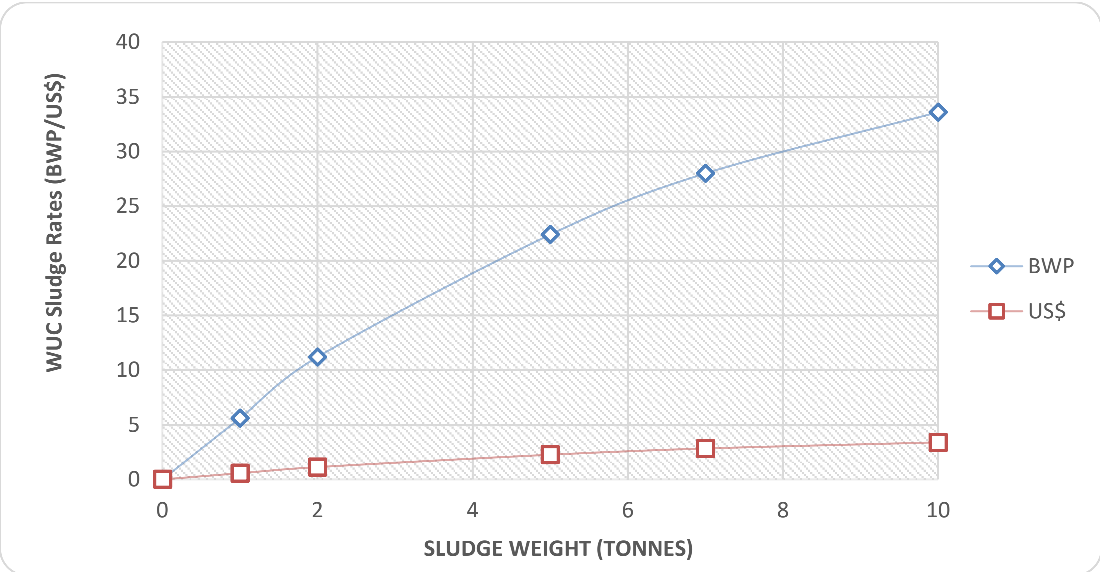


FIGURE 3-3: COSTS OF SLUDGE PER TON OF SLUDGE (BWP = BOTSWANA PULA)

3.3 Sludge management practices

Pit latrines are used to store fresh and digested faeces (Bakare et al., 2012; Mara, 1996). At present, the predominant form of sanitation in peri-urban Gaborone is the pit latrine/VIP, especially in low-income areas. On-site sanitation management involves a chain of services, including infrastructure provision (toilet facilities), pit emptying, sludge transport, and final disposal, treatment or reuse of sludge (Figure 3-4).

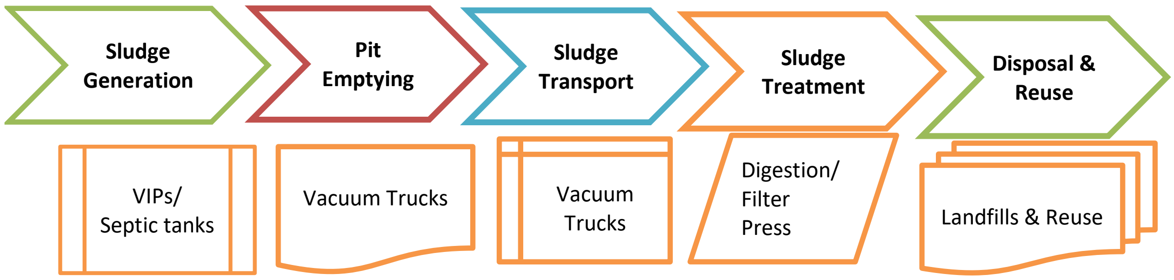


FIGURE 3-4: FRAMEWORK OF FAECAL SLUDGE MANAGEMENT PRACTICES IN BOTSWANA

VIP design is inconsistent throughout the country due to a lack of standards. The existing VIP construction manual is not available to the community and private companies. The ventilated improved pit toilet (VIP) has been described by the Botswana Building Control Act (2007) as:

> *A permanent place for decomposition of human waste being a lined or unlined pit, depending on soil conditions, not utilizing water for disposal, and provided with a screened vent to reduce odour and insect nuisance and a squatting platform constructed from impervious and durable materials, and with a pit volume of at least 10 cubic metres to service a maximum of 8 habitable rooms.*

Correctly designed, operated, and maintained VIPs have been proven to be an acceptable, cost-effective, hygienic and environmentally-friendly sanitation system. However, the challenges of poor access and poor O&M of existing sanitation systems contribute to environmental degradation. Inefficient pit emptying, which was usually done by councils, is the responsibility of the Water Utilities Corporation. Strauss and Montangero (2002) and Still et al. (2005) have reported that pit emptying constitutes a major problem in many places, both technically and managerially.

The government has invested in a number of alternative on-site sanitation technologies developed and introduced in Botswana to address the challenges mentioned above, such as ecological sanitation (ecosan) technologies. However, communities still prefer flush toilets or VIPs, due to poor performance of ecosan technologies. Additionally, VIPs take longer to fill up (at least 2 to 5 years) depending on usage. When a pit latrine is full there are two distinct options: stop using it and construct a new latrine or empty it (Pickford & Shaw, 1997).

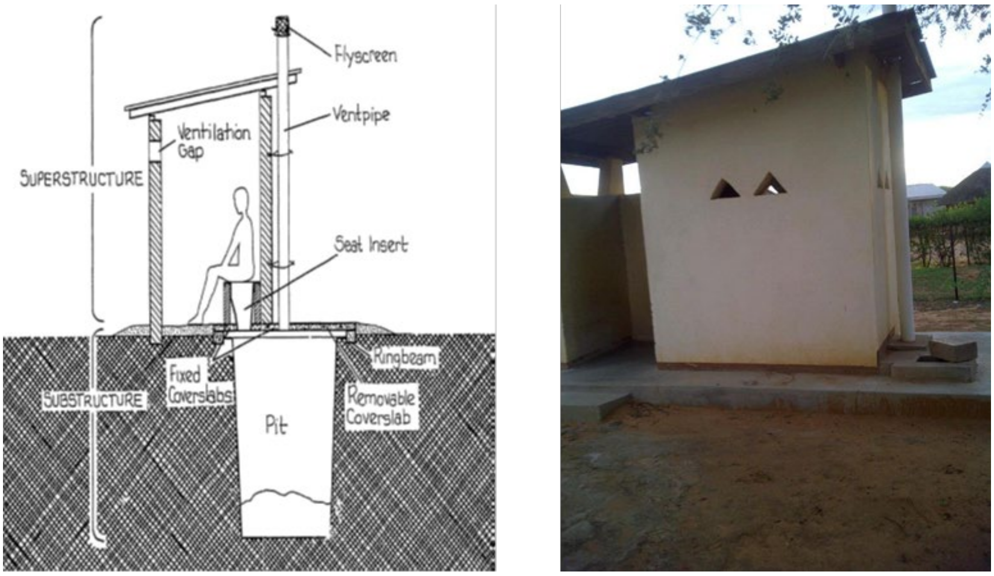


FIGURE 3-5: TYPICAL PROPER CONSTRUCTION OF A VIP IN BOTSWANA

3.4 Sludge collection and transportation methods

The toilets are serviced by vacuum pump trucks (Figure 3-6) which transport faecal sludge to a dumping pond or to a treatment plant. Figure 3-7 shows the number of truck deliveries to the Gaborone Wastewater Treatment Plant (GWWTP) in one year. Due to great distances between households and the treatment plant, transfer of faecal sludge from household level can take place by discharging into transfer stations or permanent or semi-permanent structures (Boot, 2008). In the absence of transfer stations, sludge sometimes is disposed of illegally into the environment out of convenience to the emptier (Figure 3-8).

FIGURE 3-6: METHOD OF PIT EMPTYING IN BOTSWANA (LEFT) AND A PRIVATE VACUUM TRACK DISCHARGING AT THE GABORONE WASTEWATER TREATMENT PLANT DISCHARGE BAY (RIGHT)

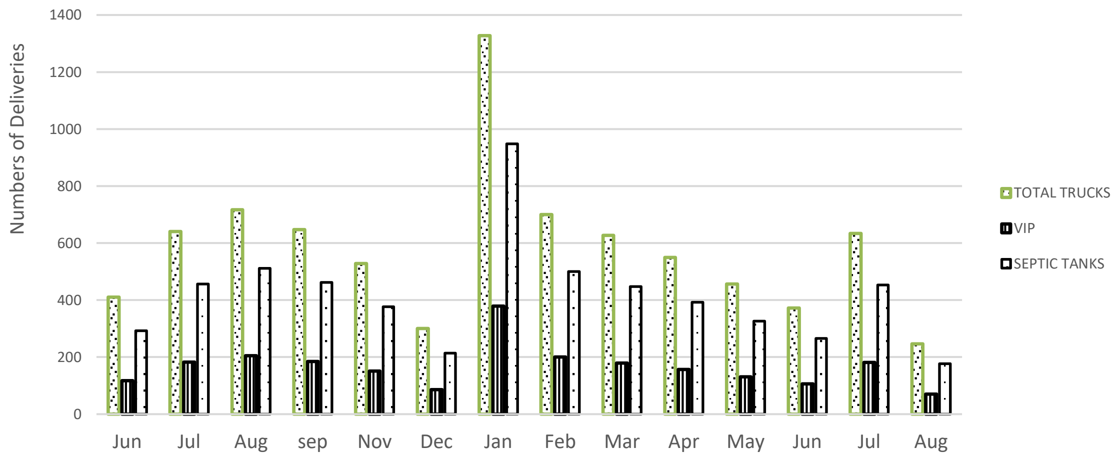


FIGURE 3-7: VACUUM TRUCK DELIVERIES OF SEPTIC TANK AND PIT LATRINE SLUDGE TO GWWTP

FIGURE 3-8: ILLEGAL DUMPING OF FAECAL SLUDGE

Some full pits are abandoned due to unavailability of service trucks or poor economic status and lack of treatment sites. According to the interview with the Department of Waste Management and Pollution Control (DWMPC), some pit latrines were not designed according to the originally prescribed design, which includes lining the pit. In such cases, emptying the pit with a vacuum truck may cause the pit to collapse and thus, the pit must be abandoned and a new toilet built.

The pits studied in this work are located in the Gaborone service area. Mogoditshane VIP pits are 1.83 metres deep on average, while pits in Broadhurst are 1.37 metres deep on average. Mogoditshane pits were constructed by individual plot owners, while Broadhurst pits were constructed by government under the SHHA and NRSP programmes. Thus, Mogoditshane pits vary greatly in depth, from 1.3 to 2.8 metres, while Broadhurst pits are more standard, with depths ranging from 1.0 to 2.2 metres. These depths are the effective depths for a vacuum tanker to lift sludge during emptying (Pickford & Shaw, 1997; Thye et al., 2011). The ability of the vacuum tank also depends on the density and viscosity of the sludge as well as the height of the tank above the ground (Thye et al., 2011),

The over two-tonne vacuum tanker (BREVAC-type machinery) is the only type of sludge transport system used in Botswana, and the operations and maintenance of these tankers are typically a challenge for operators. The service period for vacuum trucks is usually very long due to the outsourcing of such services. This reduces the efficiency and reliability of emptying, and when trucks are not regularly serviced, the quality of emptying practices is jeopardised. The quality of FS in pit latrines can also impact a vacuum tanker's ability to empty the pit. Apart from faecal sludge having varying densities (Mara, 1996), the authors have also observed solid particles, wood, stones, and plastics in pits, which are the major cause of vacuum tank failures during emptying. Some factors that affect the wide variability of FS characteristics include the range of different on-site technologies used, the use of the system, the storage duration (filling rates and collection frequencies), inflow and infiltration, and the local climate. All these factors should be considered when determining FS characteristics.

The WUC has taken over responsibility for emptying from the Gaborone City Council (GCC) and currently operates a fleet of about 3 vacuum trucks of 7, 8 and 10 m^3 in volume for the Gaborone service area. The Gaborone service area has an average radius of about 40 km and includes Gaborone city and the surrounding villages. Each truck services about 7 to 8 pit latrines a day. Prior to emptying the pit toilet, customers make payment for emptying services at the WUC payment centre. The payment centre then passes information to the operations unit. The operations unit then requests that the customer prepare the latrine for emptying, usually by adding water and stirring the pit contents. Ideally, the service provider should respond timeously for emptying, in order to maintain the standard of sanitation. However, WUC has a response time of about 2 months. According to WUC, this delayed response is attributed to several challenges, including:

1. Shortage of vacuum trucks
2. Communication lapse with customers and truck drivers getting lost due to lack of street numbering (no plot numbers)
3. Information lapse from the payment centres to operation centres of WUC

3.5 Sludge treatment

Due to limited methods for treatment and disposal of faecal sludge from pit latrines, sludge management integrated with wastewater treatment plants across the country. This practice has caused the wastewater treatment plant to malfunction due solids overload. The application of sludge for agricultural purposes is emerging as an economically and environmentally acceptable alternative to disposal through landfill and incineration (Ngole et al., 2006; Stacey et al., 2001) because of the agronomic benefits associated with it (Lindsay & Logan, 1998; Veeresh et al., 2003).

Currently the number one goal of sludge treatment at wastewater treatment plant is the protection of public health. However, it is important to consider safe recovery of resources from treatment products as a treatment goal whenever possible. The promotion of safe recovery and reuse of liquid and solid waste is an important strategy for working towards the U.N Sustainable Development Goals (SDGs) (Winkler et al., 2016). Schöbitz et al. (2013) report the success of some waste resource recovery business models in Kampala, Uganda, Hanoi, Vietnam, Bangalore, India and Lima, Peru. The success of these business models is attributed to the fact that markets for faecal sludge became competitive such that farmers bought in bulk and dried at their farms.

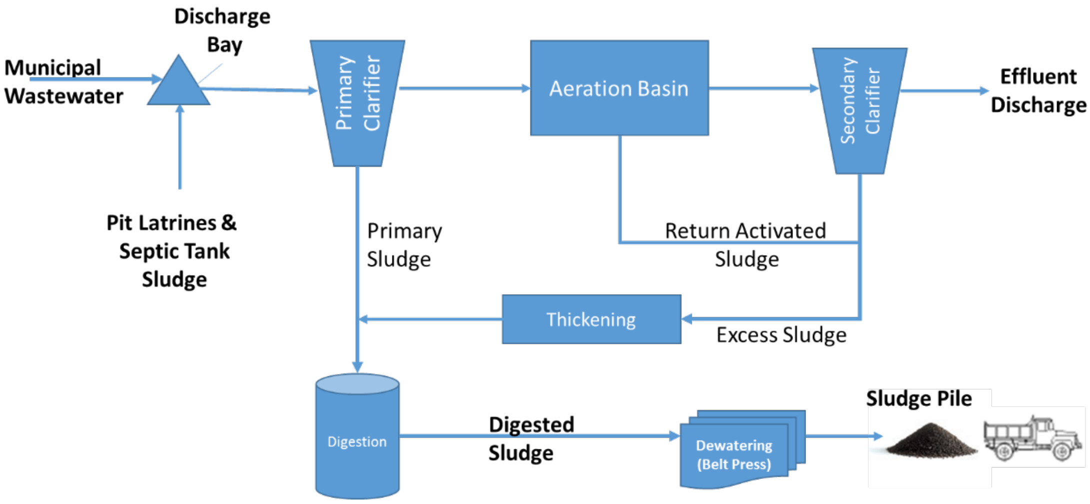


FIGURE 3-9: PIT LATRINE AND SEPTIC TANK SLUDGE MIXED WITH MUNICIPAL WASTEWATER AND CO-TREATED THROUGH ACTIVATED SLUDGE PROCESS IN GABORONE

FIGURE 3-10: SLUDGE PILES AT THE WWTP IN GABORONE

3.6 Environmental and health concerns

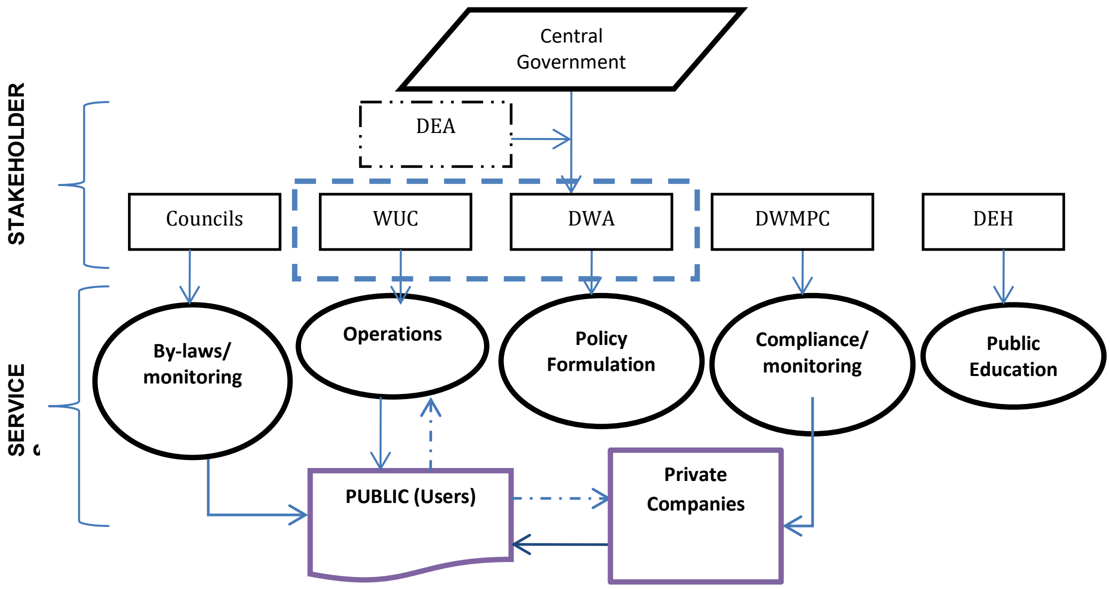
Construction of pits has raised concerns that pit latrines may cause various environmental and public health problems associated with microbiological and chemical contamination of groundwater due to lack a physical barrier. This results in pollution due to stored FS and soil and/or groundwater mixing (van Ryneveld & Fourie, 1997). The leaching of contaminants from FS into groundwater is a potential threat to human health through drinking water contamination. Proximity to pollution sources, including pit latrines, to groundwater sources have been associated with high nitrate concentrations in many countries, including Senegal and South Africa (Tandia et al., 1999; Vinger et al., 2012). Although pit latrines are associated with nitrate pollution of the groundwater, Jackson (1998) has warned against exaggerating this problem. The contribution of on-site sanitation to nitrate pollution have been studied and confirmed by Jacks et al. (1999) in Botswana. The authors established a tentative nitrogen budget for pit latrines in eastern Botswana.

In Botswana, protection of the environment and public health is paramount in deciding on sanitation technology. Resource recovery from treatment products should be considered as a treatment goal whenever possible, but the number one goal is the protection of the environment and public health. As is the case in many low- and middle-income countries, regulations for the end-use of sludge do not exist or are not enforced in Botswana. In the apparent lack of a regulatory environment, the required levels of treatment become a societal decision, as the public decide on what to use the sludge for.

The other health concern involves the personnel involved in desludging, as most admit to floating safety measures despite extensive training and protective clothing provided to them.

3.7 Institutional arrangement for FSM

Institutional arrangements refer to the mechanisms by which different governmental and non-governmental agencies and private-sector organizations can work together to achieve sustainable FSM (Robbins et al., 2013). This arrangement is depicted in Figure 3-11. In the past, sanitation issues were held under the Ministry of Local Government and coordinated by the Department of Waste Management and Pollution Control (DWMPC), with councils providing services to the community. This department was later transferred to the Ministry of Environment, Wildlife and Tourism. The DWMPC, through the National Rural Sanitation Programme (NRSP), aided communities by constructing 7 000 VIP substructures in various districts. Since the introduction of the water sector reforms, the infrastructure development of on-site sanitation facilities (VIP) has not been coordinated with wastewater service provision and faecal sludge management processes.



KEY:
- DEA – Department of Environmental Affairs
- DWA – Department of Water Affairs
- WUC – Water Utilities Corporation
- DEH – Department of Environmental Affairs
- DWMPC – Department of Waste Management and Pollution Control
- Solid line denotes Service
- Dotted line denotes Financial exchange

FIGURE 3-11: STAKEHOLDER ARRANGEMENT FOR FAECAL SLUDGE MANAGEMENT

3.7.1 The roles and responsibilities of stakeholders

In the past, councils were responsible for collection of waste from on-site sanitation facilities such as septic tanks, cesspools and pit latrines through the use of vacuum tankers at a nominal fee (50 pula =US$ 5.40). As is the case elsewhere, this assessment revealed that the roles and relationships of the stakeholders involved in faecal sludge management are not clearly defined (Agyei et al., 2011). The division of responsibilities between the WUC and local authorities is not clearly formulated. This lack of clarity results in duplication of roles, straining the relationships between partners and leading to low-quality service.

The Ministry of Health (MoH), now known as the Ministry of Health and Wellness (MoH&W), has always been actively involvement in on-site sanitation through the Environmental Health Unit, now the Division of Environmental and Occupational Health. The Environmental Health Unit has a general brief related to environmental health, including human waste disposal. At the local level, both urban and rural councils have Environmental Health Departments, which play an important role in approving and coordinating all on-site sanitation activities within their areas of jurisdiction. These departments also enforce the Solid Waste Management Act and the Public Health Act. According to Waste Management Act, a waste carrier must be registered with the Department of Waste Management and Pollution Control to be able to transport controlled waste within Botswana or across the country. Waste disposal sites and waste management facilities must be registered with the Department of Waste Management and Pollution Control to be allowed to handle controlled waste. The main hindrance to enforcement of this act is the leniency of charges.

3.7.2 The role of the private sector

In the past, it was the responsibility of the councils to provide and manage all on-site sanitation facilities in the community. Since construction of these facilities was overwhelming for the councils, that responsibility was outsourced by the councils to the private sector. Therefore, during the NRSP programme, it was the responsibility of government to hire private sector builders (usually small building companies or individuals) to construct the pit latrine substructure while the plot owners contracted the same builder to construct the superstructure under the guidance of a technical assistant from the council.

Generally, latrines are all built by private sector builders in both urban and rural communities. In urban areas, these are existing small building companies for whom latrines are an extra market. In rural areas, through the NRSP programme, members of the community were trained as latrine builders and most took up latrine building as either their full or part-time job. Therefore, these skills translated into a direct economic incentive to promote improved sanitation.

In terms of FSM, the private sector is only involved in FS collection and haulage, while the O&M of facilities (public toilets, sewerage systems, treatments systems for FS and sewage), including the collection of user charges, are the responsibility of the WUC. It is the responsibility of the user to ensure cleanliness of the facility and adequate preparation of the pit for emptying.

The private sector in Botswana has not yet found value in FSM. According to Steiner et al., (2002), the sale of treated FS can generate USD15 per ton. If treated faecal sludge is reused as organic fertiliser rather than disposed of in landfills, it will save landfill cost amount of about USD32 per ton TS. The LaDePa machine manufactured by eThekwini Municipality can provide WUC or the private sector with an opportunity for business while improving yields for farmers. The existing infrastructure developments in the sanitation and wastewater sector do not entail aspects of cost recovery despite the huge subsidies from government (Bolaane & Ikgopoleng, 2011).

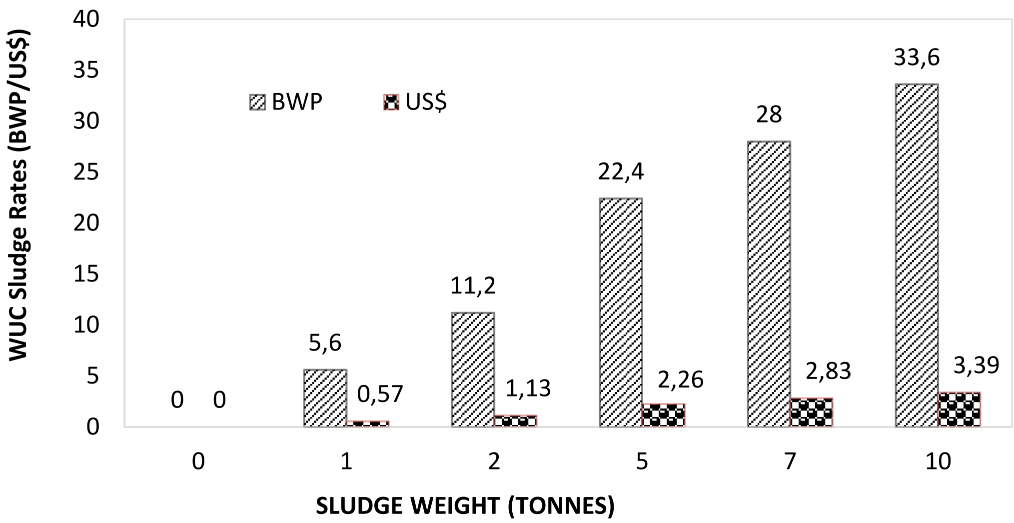


FIGURE 3-12: EXAMPLE COST OF SLUDGE PER TON OF PROCESSED SLUDGE (BWP = BOTSWANA PULA)

There is a disparity between the service costs by private companies and service costs for WUC. Private company service costs for emptying are about 10 times greater than WUC emptying costs. This disparity is probably due to WUC's lack of interest in the type of service.

3.7.3 Regulation and policies

Policies and regulations that are relevant to sludge management are discussed below and listed in Table 3-1. Although these policies are sanitation-related, they hardly address problems of FSM in Botswana. Therefore, FSM is usually embedded in other policies as described below. These policies and regulations are not adequately enough to address challenges faced by the sector.

TABLE 3-1: EXISTING LEGISLATION AND REGULATIONS ADDRESSING FAECAL SLUDGE MANAGEMENT IN BOTSWANA

Policy	Date	Enforcer	Purpose
Building Control Act	2007	Councils	Approves design plans and sanitation facilities (Pit latrines design and construction). Under review.
By-laws	-	Councils	Requires Plot Owner has to provide proper and sufficient latrine accommodation and also Require council to prohibit the use of a latrine that has become a nuisance or a danger to public health
Waste Management Act	1998	DWMPC/Councils	Ensures proper waste management practices from handling to transferring of controlled waste.
National Wastewater and Sanitation Policy	2001	DWMPC	Committed to achieving the goals of Agenda 21 which seeks to preserve, protect and improve the quality of the environment.
Public Health Act	1981	MoH (DEH)	Its purpose is to promote the personal health and environmental health within Botswana. It also Approves and coordinates all on-site sanitation activities within their areas of jurisdiction.
Environmental Impact Assessment Act	1995	DEA	The Act Approves major projects and enforces the act (not very useful in households) for the protection of the environment.

The National Wastewater and Sanitation Policy (2001), is committed to achieving the goals of Agenda 21, which calls for sustainable and environmentally-sound development and seeks to preserve, protect and improve the quality of the environment. It also contributes towards protecting public health and ensures prudent and rational utilisation of natural resources. The policy, however, embraces and acknowledges the need for cost recovery to ensure sustainability of sanitation.

The Waste Management Act of 1998 is the main legislation that expressly deals with management of waste. The main purpose of the Act is to ensure proper waste management practices from handling to transferring of controlled waste. The Act stipulates that waste produced by any establishment has to be classified and transported by a registered and licensed waste carrier. Hence, the provisions of this Act must strictly be adhered to for compliance. According to the Act, illegal disposal attract a penalty not exceeding BWP 14,000 (or imprisonment for a term not exceeding 10 years or both). However, the act is difficult to enact due to lack of institutional capacity.

The Public Health Act (1981) is used to regulate sanitation to make provisions for public health. This Act, used in conjunction with the Waste Management Act, ensures that waste is controlled such that it does not endanger public health. The purpose of the Act is to regulate all hazards, risks and nuisances that could be detrimental to the health of Botswana residents. It makes very general provisions and is enacted as an overarching act in terms of Public Health. The Act advocates for cleanliness and safety in built-up areas. Pit latrine construction alone is not sufficient to eliminate the health threat of FS; the pit contents must be disposed of appropriately and treated adequately to safeguard public health and the environment. Therefore, the Department of Environmental Health uses this act to ensure that on-site sanitation facilities do not affect animal and human health. The complexity of the environmental effects of sludge leads to uncertainty and makes sludge disposal difficult (Vesilind, 2000).

The Building Control Act requires that the minimum volume of a new pit shall be at least 10 cubic metres to service a maximum of 8 habitable rooms. Where ground conditions prevent such volumes, the approving authority may vary the size of pits and number and type of latrines to be provided. The Act also requires that an existing pit latrine may be upgraded to a standard pit latrine with the addition of an impermeable top slab and vent pipe, provided that, in the opinion of the approving authority, the receiving pit has adequate volume and the walls are stable.

The Environmental Impact Assessment legislation has been in place since 2005. The relevance of this policy to sanitation is limited to construction of treatment and disposal facilities, such as sludge drying basins and landfills.

4 Mechanical properties of faecal sludge

4.1 Physico-chemical characteristics of FS

In this study, 50 pit latrines were studied and the physico-chemical characteristics of sludge from various depths in the pits were measured. The content of total solids (TS), pH, and total volatile solids (VS) were analysed along with temperature. Both biological processes and hygienization (pathogen reduction) depend on pH, temperature, dry matter and volatile solids. Temperature is one of the major factors or variables influencing the overall digestion process of waste in anaerobic reactors (Barnett, *et al.,* 1978; Wang, 1994; Sanders, 2001; Mahmoud *et al.*, 2003). Figure 4-1 presents pH values of sludge samples from both areas included in the study, demonstrating variability in pH. This includes the pH at the various levels of the pits, which did not show significant variation.

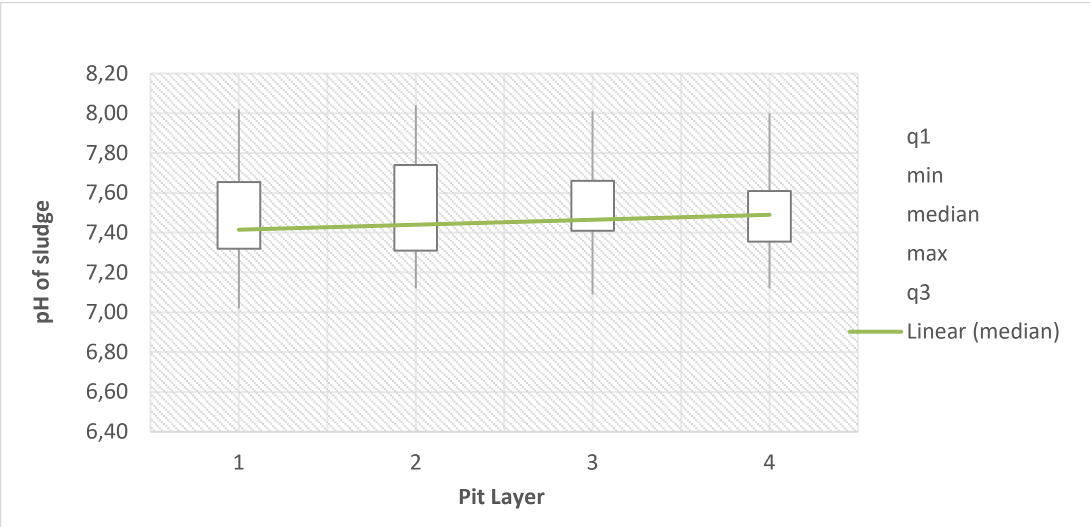


FIGURE 4-1: AVERAGE PH VALUES FOR PIT SLUDGE IN ALL 50 PITS IN MOGODITSHANE AND BROADHURST

4.1.1 Sludge moisture content

The moisture content of the pit contents can influence the microbial activity (Bakare et al., 2012). The moisture content of the sampled faecal sludge ranged from 67 to 85%. The moisture content characterisation results are presented in

Figure 4-2, with averages for each area at varying depths. Figure 4-3 shows the results for each respective area, demonstrating the variation in moisture content. In most of the pit latrines, the moisture content generally decreased with depth. This suggests that most pit latrines investigated were in areas where the pits was above the groundwater level during the time of sampling, as no evidence of groundwater ingress was observed.

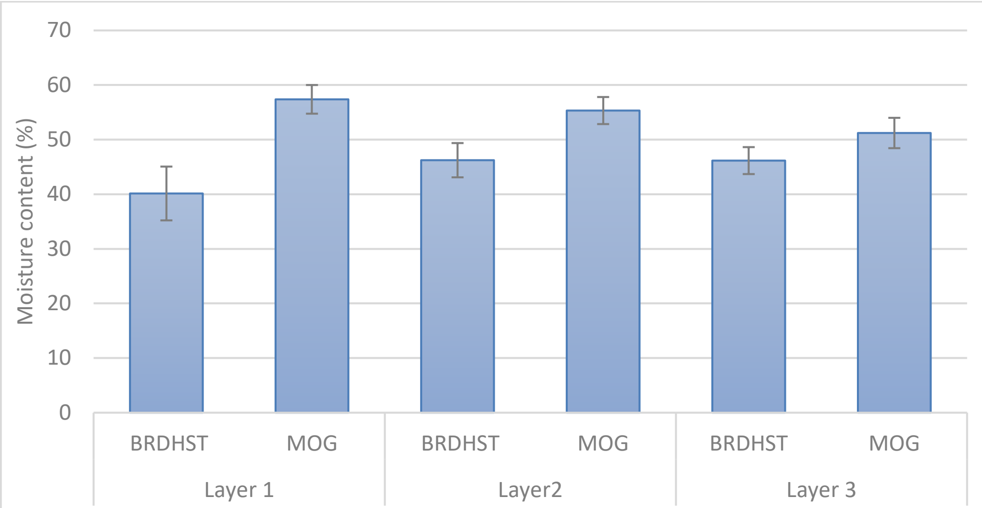


FIGURE 4-2: COMPARISON OF MOISTURE CONTENT OF VIP SLUDGE FROM BROADHURST (BRDHST) AND MOGODITSHANE (MOG)

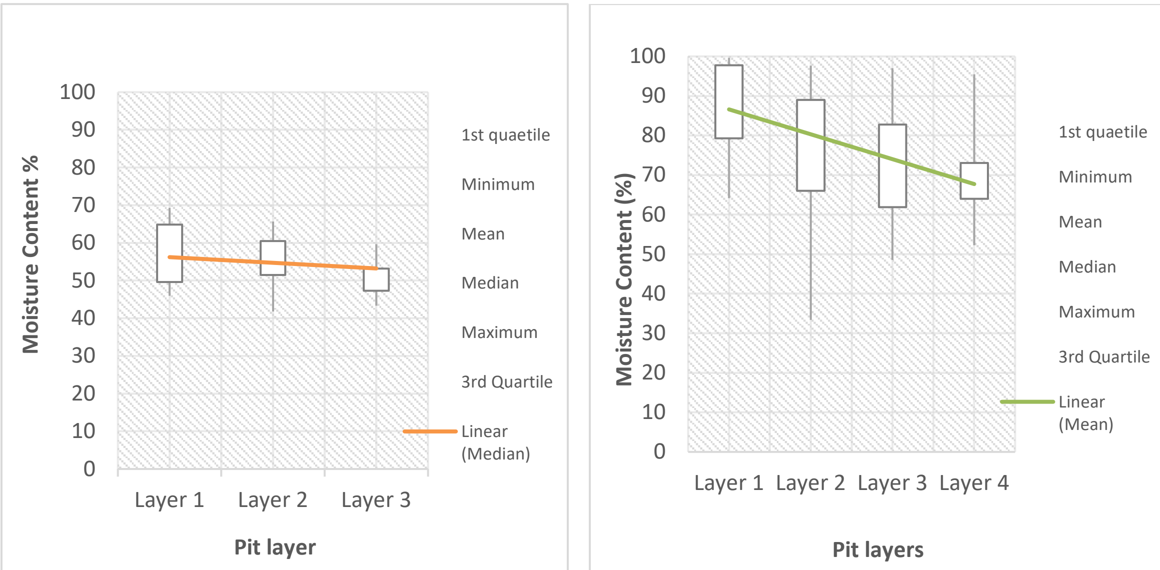


FIGURE 4-3: MOISTURE CONTENT (%) IN MOGODITSHANE (LEFT) AND BROADHURST (RIGHT)

4.1.2 Solids content

The reduction of volatile solids (VS) through stabilisation leads to a reduction of odours from VIPs. Organic matter also provides benefits on land, but changes in the content of organic matter do not significantly modify sludge applicability.

Total solids residue (TSR) is the usual method of measuring the gross solids content. It is determined by evaporating a measured amount of sludge to constant mass, weighing the residue and expressing this as a percentage of the original wet sludge mass.

Volatile solids content (VS) is measured as the mass loss on ignition of the dried sludge solids from the TSR test at a standard temperature (usually 550-600°C). VS is an indicator of the organic content of FS. Volatile solids content is usually quoted as a percentage of the total solids residue. VS indicate those solids which would be removed during incineration. Solids content remaining after ignition (ash) is termed the fixed residue (FR) and defines the mass of inorganic matter in the sludge and thus the mass of solids which would remain for ultimate disposal after incineration.

The contents of volatile solids in FS decreased from the top surface to the bottom layer, suggesting stabilisation of sludge in lower levels. These results are in agreement with those obtained by Bakare et al. (2012) and make sense, as sludge at the bottom of the pit is older.

4.2 Liquid limit

The cone penetrometer method was employed for the determination of sludge viscosity. However, this method was unsuccessful, due to the low viscosity (too plastic) of the faecal sludge. Since the sample was too wet, it could not resist the cone penetration, causing the tip of the cone to touch the base of the cup. The results of liquid limit of sludge samples are presented in Figure 4-4 and Figure 4-5.

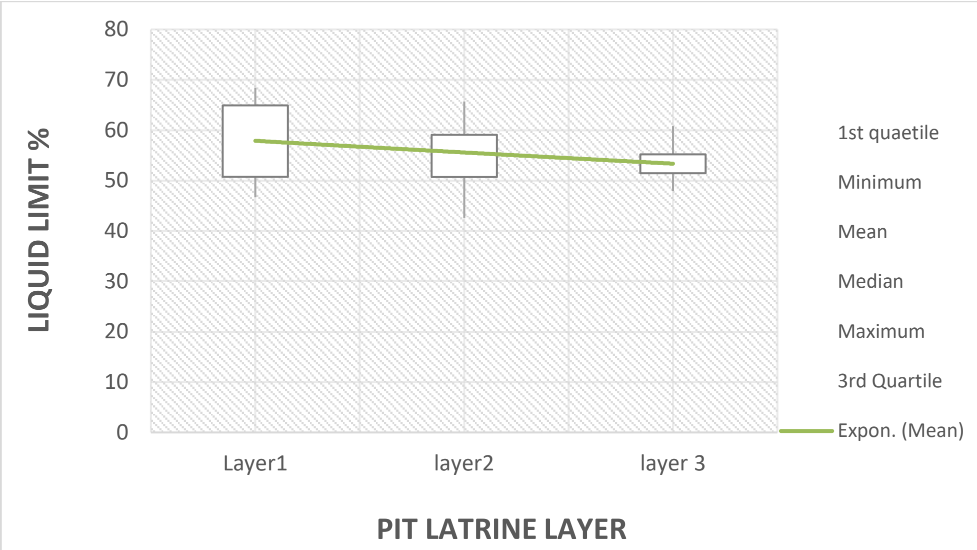


FIGURE 4-4: LIQUID LIMIT RESULTS FOR MOGODITSHANE PITS

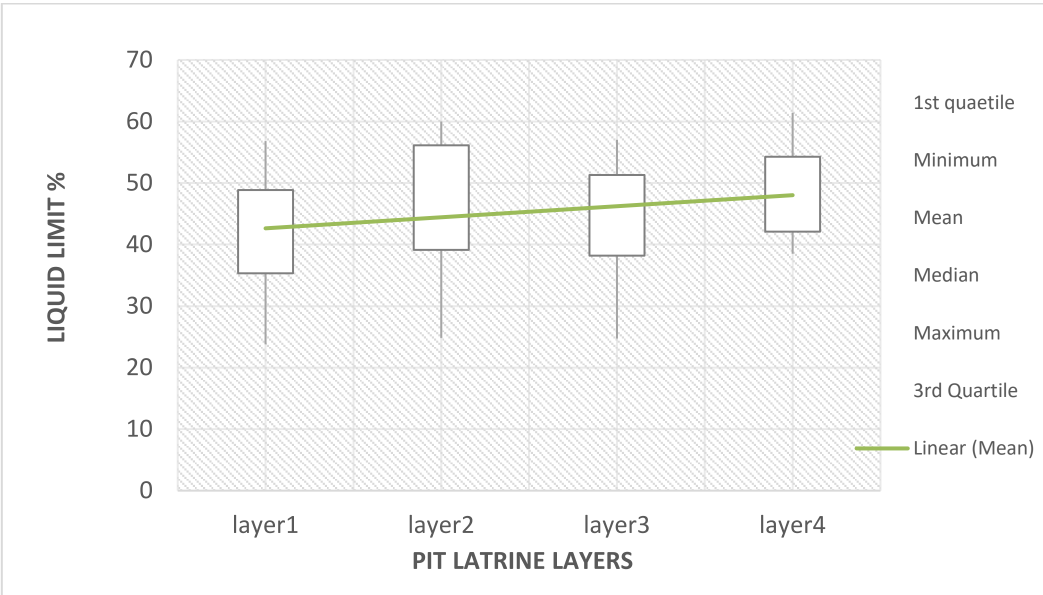


FIGURE 4-5: LIQUID LIMIT RESULTS FOR BROADHURST PITS

4.3 Plastic limit

The plastic limit (PL) of sludge is the lowest water content at which the sludge remains plastic according to AASHTO T 90. The plasticity index of the sludge is therefore the numerical difference between the liquid limit and plastic limit. It can then be described as the moisture content at which the sludge is in a plastic state.

About 150 grams of prepared sample was placed on a glass plate and mixed thoroughly with a palette knife for 10 minutes to achieve homogeneity and smoothness. Whenever necessary, a bit of distilled water was added. The aim was to achieve a reading of at least 15mm on the first cone penetration. The sample was then loaded into the metal cup, ensuring that there were no pockets of air and that the sample was smooth to the brim of the metal cup. The cone was then locked into position; the tip of the cone was lowered until it just touched the samples, and the gauge was adjusted to zero. The cone was then released into the cup and then held for about 5 seconds for complete penetration. After taking the reading, the sample was reloaded into the cup in order to repeat penetration two more times. The aim of this process was to get a penetration difference of 0.5-1.0mm. The average value was taken. About 2 grams of sample was then taken from the cup and analysed for moisture content.

The process of cone penetration was repeated on the same sample at varying moisture contents. The moisture content was adjusted by either drying or wetting the sample with distilled water until a cone penetration range of approximately 15 mm to 25 mm was reached over the course of at least 4 test runs and values were evenly distributed.

Moisture content was plotted against penetration, producing a linear graph. The moisture content corresponding to 20 mm penetration was then reported as the plastic limit. Figure 4-6 and Figure 4-7 present the plastic limits for sludge at varying depths in each area.

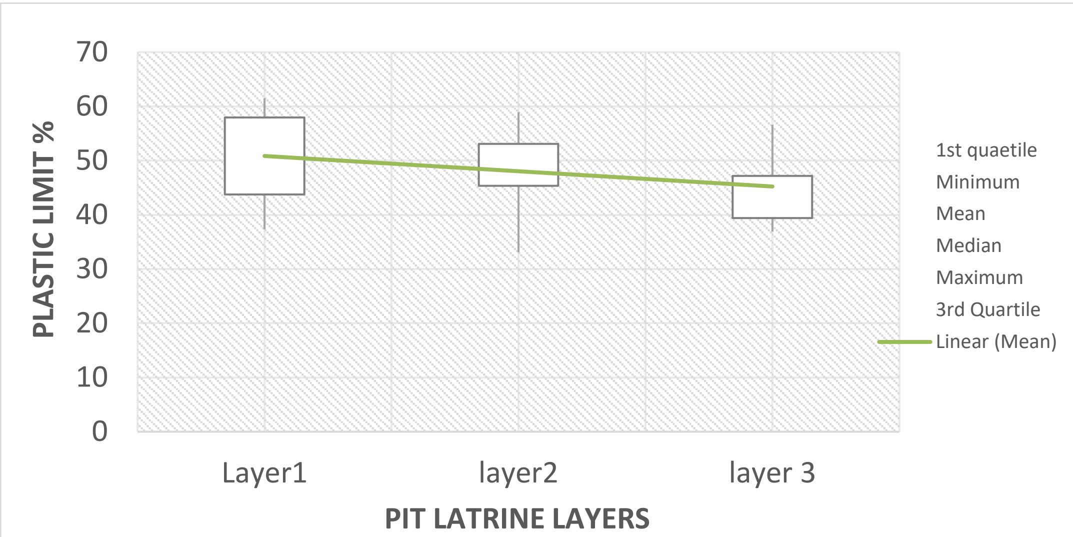


FIGURE 4-6: PLASTIC LIMIT RESULTS FOR MOGODITSHANE PITS

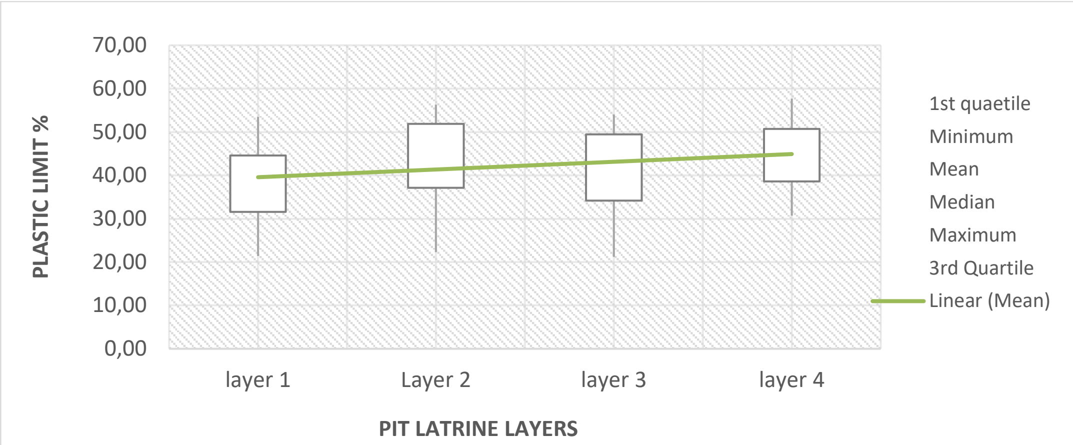


FIGURE 4-7: PLASTIC LIMIT RESULTS FOR BROADHURST PITS

4.4 Faecal sludge density

A 7.5-mℓ measuring spoon and a small porcelain dish were cleaned and allowed to dry. The mass of both the empty spoon and dish was taken in a weighing balance. Using the spoon, a portion of the sample was scooped, without overloading and compressing the sample. To remove excess sample, the bottom of spoon was wiped, and it was flattened on the top with a Stanley knife. The loaded spoon was placed into the dish and the mass was taken again. Then, calculations were done.

The mass density of sludge relates to volatile suspended solids and fixed suspended solids and can be calculated from the equation below.

$$\boldsymbol{Density} = \frac{\boldsymbol{mass\ of\ sludge}}{\boldsymbol{volume\ of\ sludge}} \qquad \textbf{EQUATION 4-1}$$

The results for sludge density are presented in Figure 4-8 and Figure 4-9. The faecal sludge from Broadhurst shows a stark trend of an increase in sludge density in deeper layers of the pit.

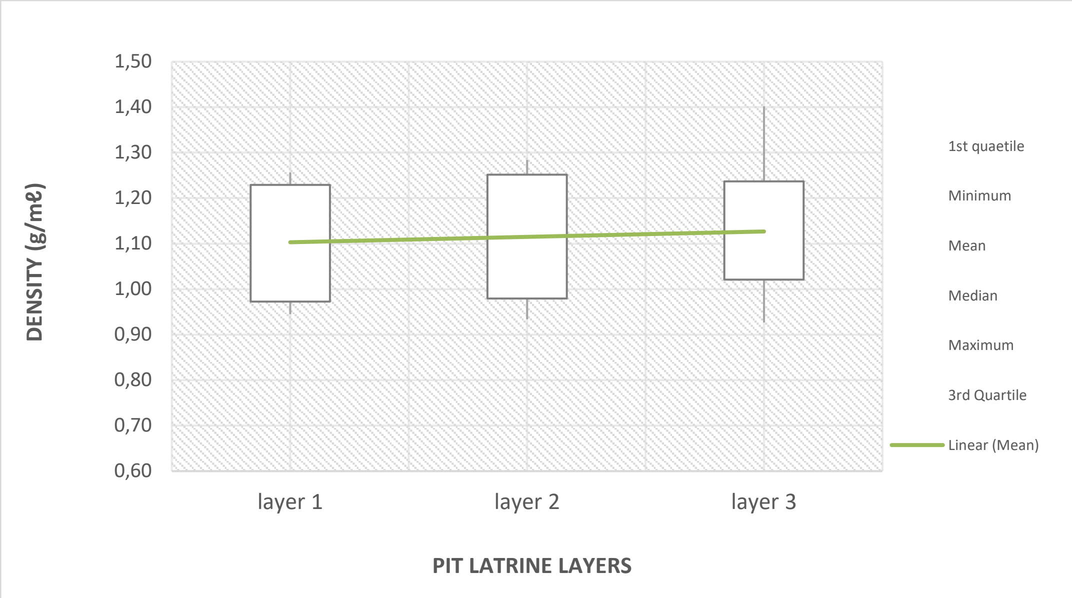


FIGURE 4-8: DENSITY RESULTS FOR MOGODITSHANE PITS

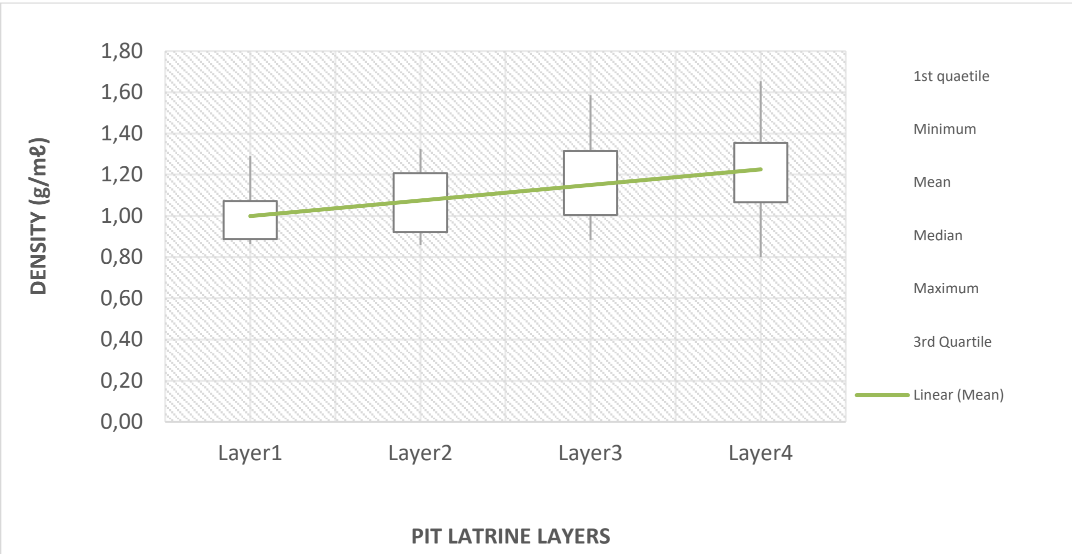


FIGURE 4-9: DENSITY RESULTS FOR BROADHURST PITS

5 Rheological properties of faecal sludge

5.1 Background

Prediction of the flow behaviour of sludge in engineering hydrodynamic processes requires accurate knowledge of the rheology of sludge (Slatter, 2011; Ratkovich, et al., 2013; Eshtiaghi et al., 2013; Baroutian et al., 2013). Slatter (1997; 2001; 2003; 2004; 2008) has consistently shown that sludge rheology plays a fundamental role in analysing the hydrodynamic behaviour of sludge as it flows through treatment processes. Therefore, a better understanding of the flow properties of sewage sludge is required in order to Barthian improve the design of sludge treatment processes and to ensure sustainable sludge management.

Overall, 50 pits were studied in two localities of Gaborone (Mogoditshane and Broadhurst) which represented different socio-economic setups. Mogoditshane is an unplanned area with a rural village setup. Here, the community constructed their own pit latrines without much supervision. The pits in Mogoditshane generally range between 1.3 to 2.8 m deep with an average depth of 1.83 m. Broadhurst is a peri-urban area, where the Self-Help Housing Agency (SHHA) provided inhabitants with a house plot free of charge, including a pit latrine substructure. The pits here are standardised in dimensions as well as completely lined to avoid pollution of groundwater.

The overall aim of this study was to determine the rheological properties of the faecal sludge from VIP latrines. The parameters tested included: moisture content, total solids, volatile solids, liquid and plastic limits, sludge density, viscosity and shear stress.

5.2 Theory of rheology

Rheology is described as the study of the deformation and flow of matter. It is concerned with the flow and behaviour of fluids and solids (Klinsksieg et al., 2007). Sludge behaves as a Newtonian fluid when dilute (Sanin, 2002), and the behavior becomes non-Newtonian, at higher solids concentrations (3-10%) for which the rheological characteristics are highly dependent on the treatment process (Lotito et al., 1997; Battistoni, 1997).

Determination of rheological characteristics of sludge is difficult for several reasons: sludge is inhomogeneous (it has a range of particle sizes); it has some internal structures that can produce yield stress; and it settles or separates if subjected to gravitational or centrifugal forces, respectively.

The importance of yield stress for the various sludge treatment operations for three different types of sludge (i.e. liquid, paste, and solid) have been discussed in the past (Spinosa & Lotito, 2003). The study highlighted that yield stress has a high impact on storage and transportation of sludge, regardless of being liquid, paste or solid.

5.3 Rheological models

Generally, sludge should be regarded as a non-Newtonian liquid. Therefore, the rheological behaviour of sludge when subjected to shear stress is represented by the Herschel-Bulkley Equation (Equation 5-1) and the Newtonian liquid is represented the Power Law equation (Equation 5-2).

$$\tau = \tau_0 + K(\gamma)^n \qquad \text{EQUATION 5-1}$$

$$\boldsymbol{\tau = K(\gamma)^n} \qquad \text{EQUATION 5-2}$$

Where, τ is the shear stress (Pa); γ is the shear rate (s−1); K is the coefficient of rigidity and is equivalent to viscosity; n is the exponent or the flow behaviour index; and τ_0 is the yield stress. The flow behaviour of materials is illustrated by means of flow curves, as plots of shear stress against strain rate, also called rheograms (Figure 5-1). The flow curve of a Newtonian fluid is a straight line through the origin of slope K and n = 1. The consistency index K is equal to the viscosity of the fluid, η. When the magnitude of n < 1, the fluid is shear-thinning and when n > 1 the fluid is shear-thickening in nature.

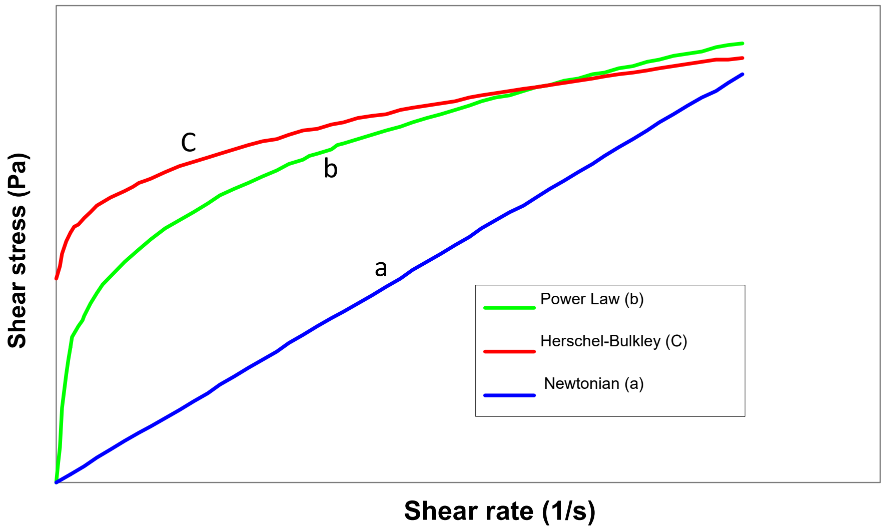


FIGURE 5-1: RHEOGRAM FOR NEWTONIAN AND NON-NEWTONIAN LIQUIDS

Physically, if a yield stress is present in a fluid, then that fluid has enough structure to retain its initial shape and will not flow until a critical force is applied. However, if the material does not display yield stress (i.e. τ_0=0), the Herschel-Bulkley model reduces to a Power Law expression (Woolley *et al.,* 2014). Equation 5-1 is widely accepted as a model to represent the flow behaviour of sludge since it contains the yield stress term (Eshtiaghi et al., 2013).

5.4 Sludge viscosity

Viscosity is evaluated by means of the flow curve and can be defined as the ratio of shear stress to shear rate (Eshtiaghi et al., 2013). Fluids with greater viscosity flow less easily (Ratkovich et al., 2013; Eshtiaghi et al., 2013). For non-Newtonian fluids such as sludge, the viscosity changes with shear rate or applied stress. In Figure 5-2 and Figure 5-3, the viscosity versus shear rate of faecal sludge decreases as shear rate increases. Viscosity tests are needed primarily for the design of the mechanical handling equipment (Wolley et al., 2014). Figure 5-2 and Figure 5-3 also demonstrate that at shear stresses above 1/s, the viscosity of the faecal material rises drastically indicating the likely destruction of the faecal material structure due to shear stress (Wolley et al., 2014).

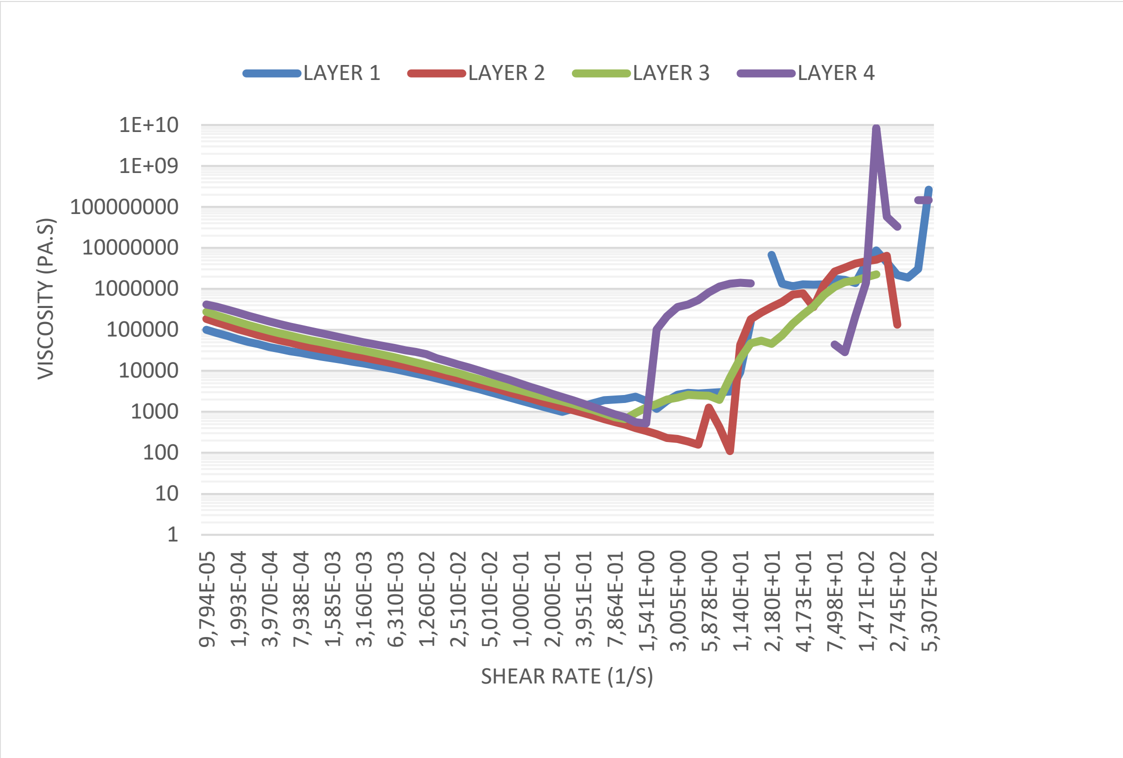


FIGURE 5-2: PLOT OF VISCOSITY VS SHEAR RATE FOR BROADHURST PITS SLUDGE FOR VARIOUS LAYERS

Figure 5-3: Plot of viscosity vs shear rate for Mogoditshane pit sludge for various layers.

According to Krylow and Fryzlewicz-kozak (2007), viscosity is the most important sludge rheological parameter as it characterises a real substance subjected to deformation (Wolley et al., 2015).

5.5 Shear stress

Shear stress-shear rate plots of many fluids become linear when plotted on double logarithmic coordinates, and the power law model describes the data of shear-thinning and shear thickening fluids. The average values of shear stress and shear rate are plotted for all pit layers in Figure 5-4 and Figure 5-5. The behaviour of sludge at all layers is the same with a yield stress (τ_0) of about 10 to 40 Pa.

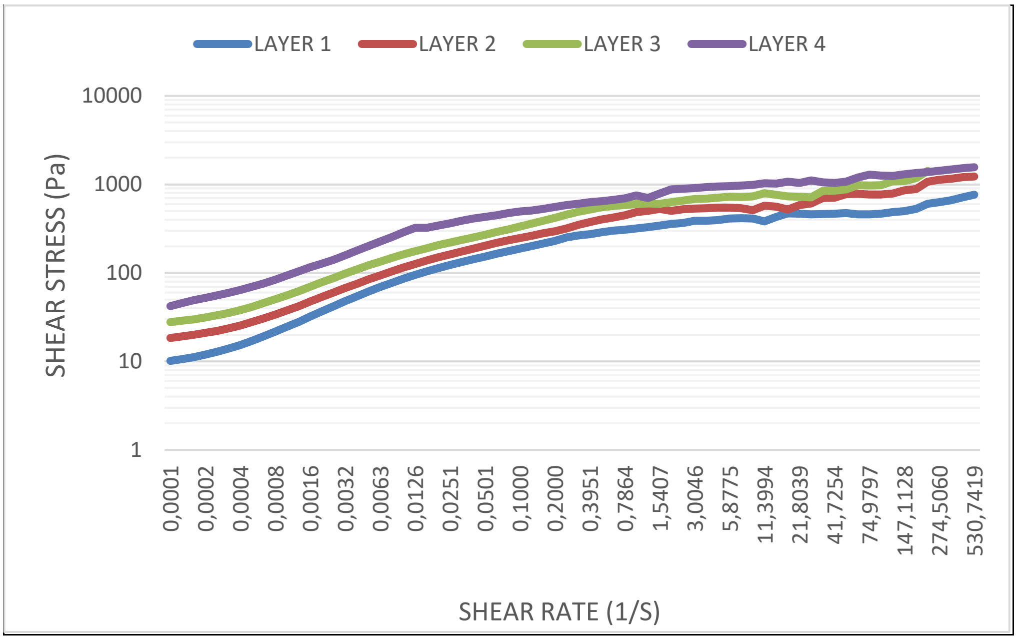


FIGURE 5-4: SHEAR STRESS VS SHEAR RATE CURVES FOR BROADHURST PITS AT VARIOUS DEPTHS

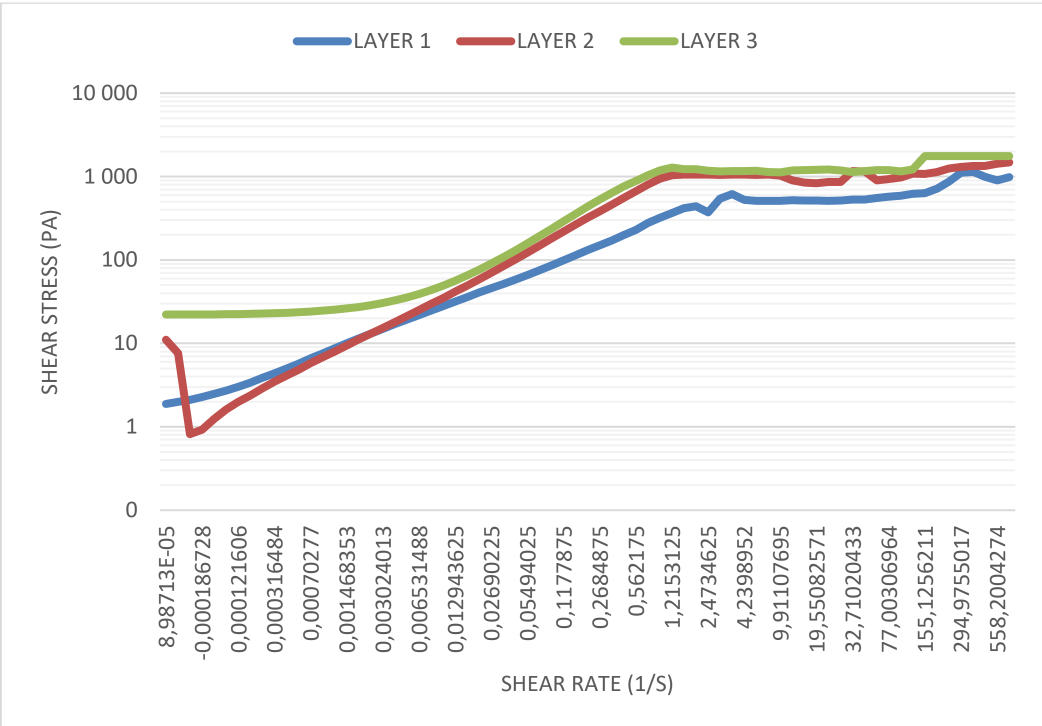


FIGURE 5-5: SHEAR STRESS VS SHEAR RATE CURVES FOR MOGODITSHANE PITS AT VARIOUS LEVELS (3 LAYERS)

Shear rates above 1 s^{-1} resulted in shear stresses that caused destruction of the faecal sample structure, changing the mechanical properties of the sample. Flow curve tests were performed by increasing the shear rate exponentially, in order to reduce the amount of time at which the sample was subject to shear rates above 1 s^{-1}, thus limiting any structural damage.

From the rheograms above, the presence of a yield stress is evident, which indicates the minimum stress required for the sludge to reach flow conditions. Yield stress (τ_0) is defined as the material property at which a material begins to deform plastically. The values of the yield stress (τ_0) observed in Figure 5-4 and Figure 5-5 correspond to the applied stress required to overcome the cohesion Van Der Waals forces and induce the flow of suspension (Seyssiecq et al., 2003). Therefore, it can be concluded that the faecal sludge displays viscoelastic behaviour (Seyssiecq et al., 2003).

6 Quality of faecal sludge from VIPs

6.1 Introduction

To increase arable farming around major settlements in Botswana, government funding has been availed for small horticultural projects around the Gaborone Wastewater Treatment Plant (GWWTP), in Gaborone. Since soils in semi-arid regions like Botswana are generally poor with regards to physical conditions such as water retention capacity and are characterized by low plant nutrient status, commercial fertilizers are required for agricultural production. These, however, tend to increase production costs. The use of sludge as a fertilizer is an efficient and sustainable alternative to return nutrients to agricultural soils. Sludge is a by-product of the wastewater treatment plant and consists of solid organic and inorganic matter originating from the incoming wastewater. It is produced through mechanical, biological and chemical processes at the wastewater treatment plant where solids in wastewater are separated from the liquid stream (Hammer & Hammer, 2014; Wang et al., 2006).

Sewage sludge may contain hazardous compounds such as heavy metals, micro pollutants and pathogens (Hashem, 2000). These compounds can harm the human health and/or the environment. Studies showed that increases in metal concentrations in the soil due to sludge application can produce significant increases in Cd, Ni, Cu and Zn concentrations in the edible portion of most of the crops grown (Hashem, 2000). These crops include: wheat, potato, lettuce, red beet, cabbage and ryegrass. However, lead (Pb) has been found in most cases to be relatively unavailable to crops from the soil. The availability of metals to crops is also reported to be less significant (lower) in soil treated with dried sludge compared to liquid sludge.

Faecal sludge (FS) from ventilated improved pit latrines (VIPs) has been suggested as a viable alternative fertilizer because of its rich nutrient content and value as a good soil conditioner (Diener et al., 2014). Although human faeces have been considered a valuable nutrient source in a number of countries such as China, Japan, Korea, and also in some countries of Africa and South-America (Malkki, 1999), the practice is not fully accepted in Botswana, except for a few city dwellers who use sludge for conditioning soils for landscaping and gardening. Faecal material is identified as a critical threat to human and animal health as well as ecosystem function (Alexander & Godrej, 2015).

Pit latrines are found globally and used by an estimated 1.77 billion people as their primary means of sanitation (Graham & Polizzotto, 2013). They are low cost, do not require extensive sewage infrastructure, require little maintenance, and use little to no water (Graham & Polizzoto, 2013), which is critical in water-stressed regions such as Botswana. Pit latrines have brought improvements in sanitation in developing countries during the last few decades, preventing infection of children and infants with parasitic and bacterial infections such as giardia (Jacks et al*.,* 1999). Because of the need to periodically empty the latrines, treatment and disposal of faecal sludge has become an important and complex problem.

According to Malkki (1999), the annual amount of sludge obtained from pit latrines is about 520 kg/person. This sludge mainly consists of urine and faeces and can therefore be used as fertilizer of high quality due to high content of the nutrients required by crops. Urine is known to be rich in nitrogen, while faeces have high contents of phosphorous and potassium (Jönsson et al., 2005). These nutrients are found in high amounts in excreta since the human body barely retains them. As a result, the amount of each nutrient which is excreted is essentially equal to that which has been consumed, which in turn is equal to that which had been taken up by the crops (Jönsson et al., 2005). Recycling this sludge will therefore return these nutrients to the soil, leading to the maintenance of the land's fertility.

An additional benefit of using faecal sludge as fertilizer is its low content of heavy metals. Various authors have reported very low amounts of heavy metals in faecal sludge (Jönsson et al., 2005; Nikiema et al., 2013). In contrast, inorganic fertilizers are known to contain high amounts of heavy metals (Gimeno-García et al., 1996; Macedo-Miranda et al., 2009; Nziguheba & Smolders, 2008) as a result of their origin and/or processing. An example is phosphate fertilizer, which is known to contain high amounts of As, Cd and Pb as part of the phosphate rock ore or other ingredients used in the phosphate fertilizer industry (Abdel-Haleem et al., 2001). Since heavy metals are usually found in commercial and industrial wastewater, faecal sludge obtained from pit latrines is bound to contain very small amounts of heavy metals if it is not mixed with industrial wastewater. Its application to the ground therefore like poses no threats with regards to heavy metal pollution.

However, faecal sludge does contain some heavy metals and microorganisms which could have negative ecological, biological and health impacts (Hashem, 2000). These include pathogenic organisms (Langergraber & Muellegger, 2005) such as *Ascaris lumbricoides*, which has been reported to be the most prolific soil-transmitted helminth (Navarro et al., 2008; Jimenez, 2007), with about 1.3 billion cases of Ascariasis globally. Ascariasis is endemic in Latin America, the Far East and Africa, with children under the age of fifteen years being greatly affected (Jimenez, 2007). The importance of *Ascaris* as an indicator organism lies with the fact that its inactivation or removal from faecal matter may indicate the inactivation of all other pathogens (Jimenez, 2007; Norup & Aberg, 2015).

Nonetheless, if properly managed, the hazards posed by faecal sludge can be averted. Proper FSM strategies can lead to proper and beneficial use of faecal sludge without the risks posed by the pathogens in the sludge. Hygienic behaviour varies according to the individuality, responsibility and practicality of the local population (Carr & Strauss, 2001). When designing FSM processes and treatment technologies, barrier efficiency (e.g. log reduction of pathogen achieved) must be considered as a measure of effectiveness.

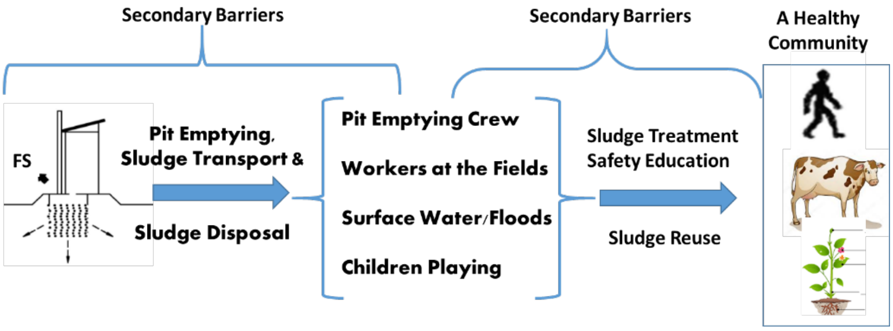


FIGURE 6-1: EXAMPLES OF FAECAL ORAL PATHOGEN TRANSMISSION ROUTS (ADAPTED FROM CARR & STRAUSS, 2001)

On-site sanitation management involves pit emptying; sludge transport; and final disposal, treatment or reuse of sludge. The main health issues of concern are therefore associated with occupational and environmental risks as observed in Figure 6-1. Applying untreated sludge to soils can lead to disease transmission to farm workers, farmers and consumers of crops.

The main objective of this chapter is to determine the biological and chemical quality of FS and assess the risks associated with possible reuse of VIP sludge for beneficial use. This includes determination of metal content and nutrient levels in sludge sampled from VIPs using ICP-OES and Ion Chromatography (IC), respectively. Three types of evaluations are used to assess health risks: microbial analysis, epidemiological studies and Quantitative Microbial Risk Assessment (QMRA). In this work, the assessment of the risks is based on the comparison of the chemical and viable helminth ova results with standards/limits for sludge handling and reuse.

6.2 Results and discussions

6.2.1 Nutrient content in FS

The effects of organic matter, nitrogen, phosphorus and toxic elements in sewage sludge applied to agricultural land have been reviewed extensively in the literature. However, studies on the impacts of faecal sludge from pit latrines are limited. FS is rich in organic matter and may improve the structure and water holding capacity of poor soils and also contains significant amounts of nitrogen and phosphorus, which give it value as a fertiliser (Sterritt & Lester, 1980).

Results in Figure 6-2 and Table 6-1 reveal that the amounts of NO_3^-, NO_2^- and PO_4^{3-} in faecal sludge sampled were very high. For example, in Mogoditshane, nitrate concentrations were as high as 4.47×10^4 mg/kg. These are important nutrients in crop production. The results show that in all pits investigated in Mogoditshane, average nitrite concentrations were higher than nitrate concentrations, but the opposite was true in samples collected from Broadhurst pits. The average phosphate concentrations in the two sampling areas were comparable, as high as 39000 mg/kg. In

Figure 6-2: Mean amounts of nitrate, nitrite and phosphate in various pit latrines as sampled in Mogoditshane village in Botswana, PL 1 to PL 20 denotes pit number. Means were calculated from replicates of extraction and analysis. Error bars represent standard deviation (computed from extraction and analysis standard deviations).

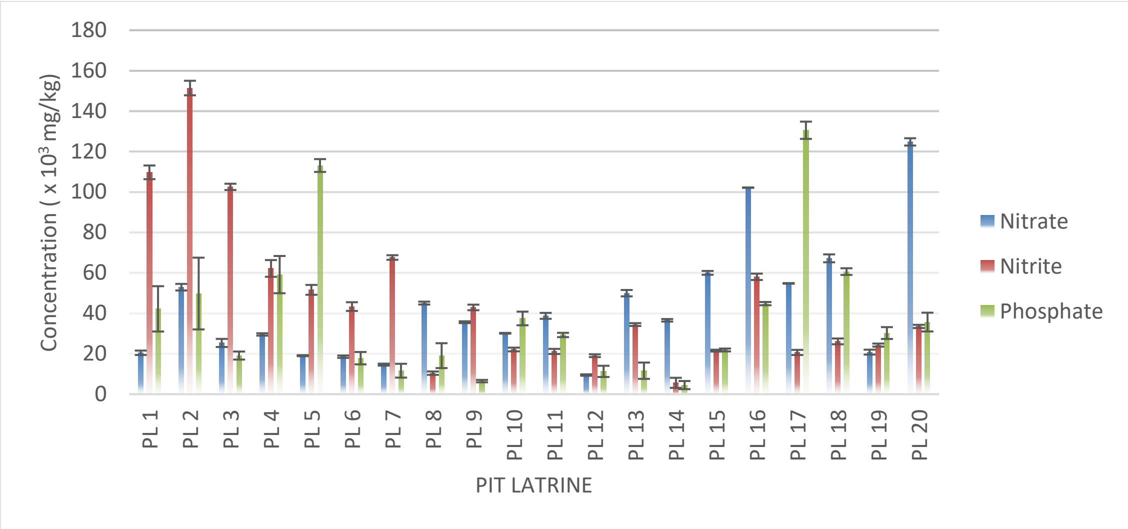


Figure 6-2: Mean amounts of nitrate, nitrite and phosphate in various pit latrines as sampled in Mogoditshane village in Botswana

Table 6-1: Minimum, maximum and average values of NO_3^-, NO_2^- and PO_4^{3-} in pit latrine sludges sampled from Mogoditshane and Broadhurst, analysed by Ion Chromatography

Analyte	Location	Minimum (mg/g)	Maximum (mg/g)	Mean ± SD
[NO_3^-]	Mogoditshane	9.93 ± 0.14	125.22 ± 1.14	42.47 ± 3.21
	Broadhurst	6.06 ± 0.19	92.87 ± 3.03	46.33 ± 1.31
[NO_2^-]	Mogoditshane	5.96 ± 0.21	159.01 ± 3.75	59.61 ± 2.62
	Broadhurst	9.77 ± 3.19	149.03 ± 7.16	33.73 ± 2.03
[PO_4^{3-}]	Mogoditshane	4.28 ± 0.79	134.22 ± 2.28	38.02 ± 1.13
	Broadhurst	5.56 ± 0.28	121.09 ± 6.59	39.52 ± 6.22

Following the principles of sustainable development, nutrients in faecal sludge should be used in plant production, instead of ending up in wastewater treatment plants. However, the most undesirable consequence of such high nutrient concentrations is the risk of pollution posed by pit latrines. Several researchers have found that pit-latrines are a source of nitrate contamination and therefore a hazard to groundwater due to their capacity to play a part in chemical and/or microbial pollution (Dzwairo et al., 2006; Jacks et al., 1999; Mafa, 2003; Odikamnoro et al., 2014; Vinger et al., 2012; Graham & Polizzoto, 2013; Zingoni et al., 2005). Earlier studies carried out by Mafa (2003) in the city of Francistown in Botswana showed that pit latrines had a high impact on groundwater quality, resulting in such groundwater being unsuitable for consumption. Nitrogen (in the form of nitrate) is the most dominant of all these and is therefore used as a key indicator of overall groundwater quality (Graham & Polizzoto, 2013; Vogel, 2002). Moreover, it has been shown that in Botswana, about 50% of nitrogen from pit latrines leaches to groundwater (Jacks et al., 1999).

The results from all the pits were pooled and averaged per sampling location. These results indicated high average concentrations of all the nutrients above recommended maximum level that could contaminate groundwater. In the area where sampling was carried out, there are boreholes near several pit latrines. Previous researches have shown that such close distances between groundwater sources and pit latrines always lead to chemical and/or microbiological contamination of groundwater (Graham & Polizzoto, 2013; Zingoni et al., 2005), leading to nutrient values above the Maximum Allowed Limit (MAL) of 50mg/ℓ set by WHO (Graham & Polizzoto, 2013; Jacks et al*.,* 1999; WHO, 2011). In addition to the fact that the soils in Botswana are permeable and thus allow for excessive bacterial and chemical pollution (Drangert, 2010), almost all the pits in the area that was sampled were not lined, thereby presenting little or no impediment to the mobility of bacteria and other faecal contaminants. The observed high variability (between minimum and maximum amount) observed could be due to poor mixing within layers as the faecal sludge was observed to be thick.

6.3 Carbon/nitrogen ratio

Digestion properties of organic substances depend on the organic component of the substance (Liu et. al., 2008). The accumulated sludge in pits undergoes anaerobic digestion. Therefore, it is expected that FS in the bottom lay is more digested that the top layers. The C/N ratio is an important parameter that impacts the quality of the end product and values of 25-30% are ideal. Results for C/N ratios for FS from different layers in the pits are presented in Figure 6-3.

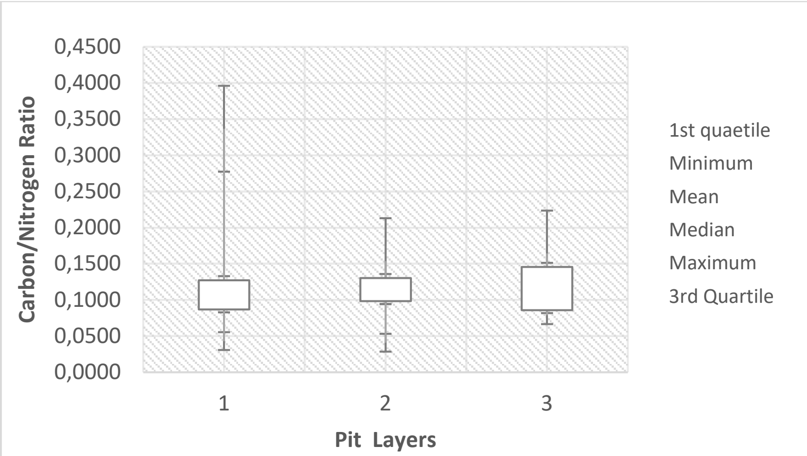


FIGURE 6-3: THE VARIATION OF C/N RATIO ACCORDING THE PIT LAYERS FOR MOGODITSHANE

6.4 COD: BOD ratio analyses

Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are commonly used to measure organic matter. Comparison of these values indicates the stability or biodegradability of faecal sludge (Still & Foxon, 2012). COD provides a measure of the carbonaceous or organic content of faecal sludge (Still & Foxon, 2012). The COD:BOD ratio is used to estimate the biodegradability of the faecal sludge. The average COD:BOD ratios for Mogoditshane and Broadhurst pits are shown in Figure 6-4.The ratios are highly variable, indicating that there is a greater percentage of slowly biodegradable and non-biodegradable material in sludge samples tested.

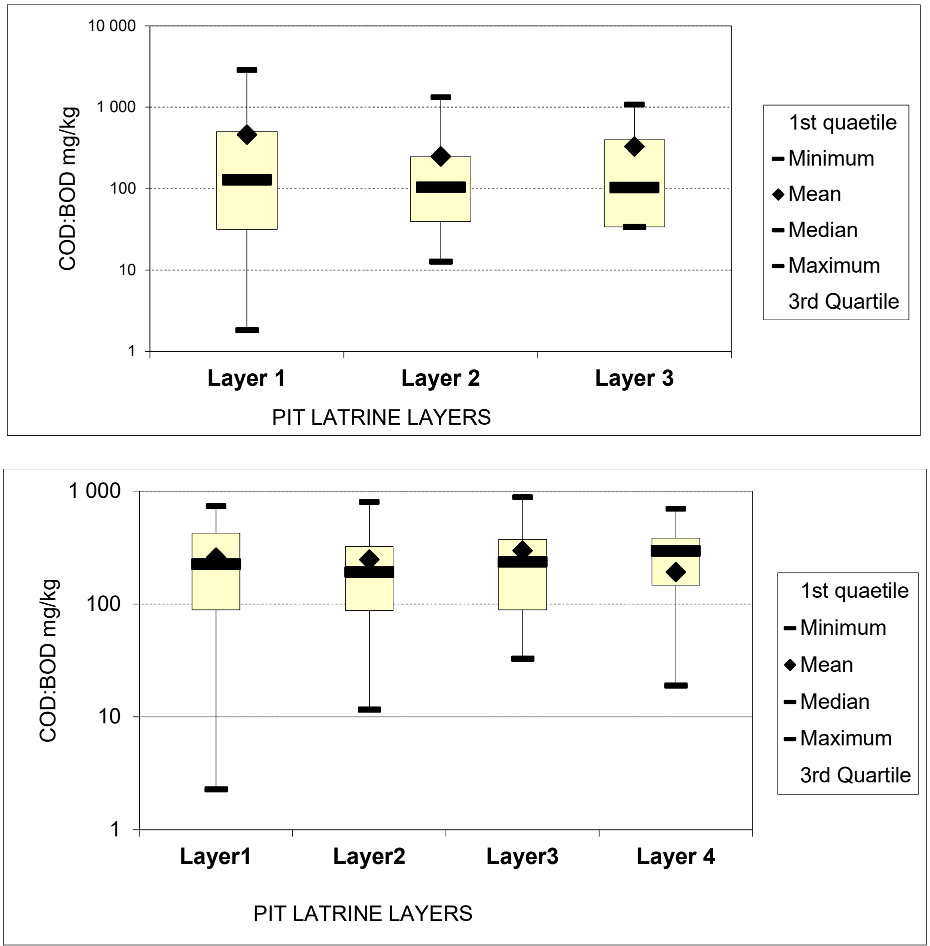


FIGURE 6-4: AVERAGE COD:BOD RATIOS OF FS IN GABORONE AT DIFFERENT DEPTHS FOR PITS IN MOGODITSHANE PITS (TOP) AND BROADHURST PITS (BOTTOM)

6.5 Risk of heavy metals in agricultural soils

Soils are regularly contaminated by heavy metals through emissions from industrial activities, mines, spillage of petrochemicals and paints, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, and atmospheric deposition (Khan et al., 2008; Zhang et al., 2010; Wuana & Okieimen, 2011). Heavy metals of concern that are commonly found at contaminated sites include lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), mercury (Hg), and nickel (Ni) (Wuana & Okieimen, 2011). Soils are the major sink for heavy metals released into the environment by anthropogenic activities and, unlike organic contaminants which are oxidized to carbon (IV) oxide by microbial action, most metals do not undergo microbial or chemical degradation.

The heavy metals in sludge that are most hazardous to humans are cadmium, mercury, and lead. In high concentrations, these metals are particularly poisonous to plants (Malkki, 1999). Table 6-2 and Table 6-3 show average heavy metal content of FS from Mogoditshane and Broadhurst, respectively. In general, FS has a low potential risk to humans and within acceptable levels for land application based on both South African and European Union standards. The results, however, show escalated amounts of copper in all sludge levels compared to the South African limits for application on fields. However, the South African limits for Cu are more stringent compared to the European Union (EU) limit for Cu.

TABLE 6-2: CONCENTRATIONS OF HEAVY METALS IN FAECAL SLUDGE FROM 25 MOGODITSHANE PITS

Metal	Layer 1 (mg/kg)				Layer 2 (mg/kg)				Limit for Spreading on field**	
	Mean	max	min	SD	Mean	max	min	SD	ZA	EU
Ni	8.62	15.84	0.32	0.33	9.33	11.32	6.70	0.31	200	300-400
Cr	28.72	55.41	12.15	2.07	39.63	69.45	13.16	1.91	1750	1000-1500
Pb	9.31	16.69	4.13	0.42	8.29	15.65	3.19	0.35	50.5	750-1200
Zn	390.59*	880.80	137.63	5.23	327.55	573.00	150.85	6.19	353.5	2500-4000
As	1.68	6.68	0.03	0.14	3.82	9.17	0.79	0.31	15	-
Cd	0.32	0.82	0.13	0.02	0.39	1.04	0.11	0.06	15.7	20-40
Ca	15278.11	40579.4	2.48	2.15	3254.28	21813.2	2.49	2.13	-	-
Cu	40.36	72.02*	22.04	0.35	43.03	62.35	29.36	0.38	50.5	1000-1750
Na	2114.77	5127.31	741.11	53.97	2254.72	3538.46	1296.9	115.0	-	-
Sn	1.79	2.69	1.25	0.14	2.15	5.87	1.08	0.46	-	-
Mg	3406.30	4157.74	2513.0	163.3	2831.97	3825.28	1896.0	137.4	-	-
K	3950.40	3950.40	3950.4	52.79	3863.72	3950.40	3343.7	74.50	-	-
Mn	199.83	255.86	150.69	7.01	204.07	301.01	151.06	8.77	-	-
Fe	8483.00	15294.7	3389.5	421.2	11854.7	20447.1	4058.1	557.8	-	-

*exceed the South African limits for spreading on fields. - No limits
**ZA = South Africa, EU = European Union

TABLE 6-3: CONCENTRATION OF HEAVY METALS IN FAECAL SLUDGE FROM 25 BROADHURST PITS

Metal	Layer 1 (mg/kg)				Layer 2 (mg/kg)				Layer 3 (mg/kg)				Layer 4 (mg/kg)				Limit for Spreading on field	
	Mean	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	ZA	EU
Ni	3.34	6.18	0.28	0.08	2.02	3.35	1.13	0.05	1.88	4.00	0.13	0.04	2.53	3.54	1.52	0.78	200	300-400
Cr	13.43	20.95	10.68	0.60	10.78	13.44	6.58	0.42	15.15	22.51	8.12	0.69	8.65	11.57	5.73	3.94	1750	1000-1500
As	0.83	1.88	0.33	0.14	6.32	27.22	0.45	0.30	0.87	1.72	-0.04	0.19	7.28	13.79	0.77	3.28	15	-
Cd	0.19	0.69	0.00	0.01	0.30	0.69	0.00	0.02	1.26	5.64	0.00	0.02	0.96	1.82	0.10	0.96	15.7	20-40
Cu*	591.6*	1101.0	242.0	37.72	672.15*	1031.4	397.18*	49.76	733.2*	1513.4	307.23	30.67	455.08*	562.50	347.65	26.21	50.5	1000-1750
Sn	0.64	1.34	0.35	0.11	1.47	3.94	0.18	0.43	1.03	2.71	0.36	0.24	11.69	22.70	0.67	4.76	-	-

*exceed the South African limits for spreading on fields. - No limits pH influences the behaviours of these metals. When pH exceeds 6.5 and/or soil contains high organic content, metals bind to soils. If neither of these are true, metals become mobile and can be absorbed by crops and contaminate water bodies (Wuana & Okieimen, 2011). The FS sample results in Figure 6-5 show that the sludge pH ranges from 7 to 8. This suggests that metals are likely to bind to soil if FS is applied for agriculture.

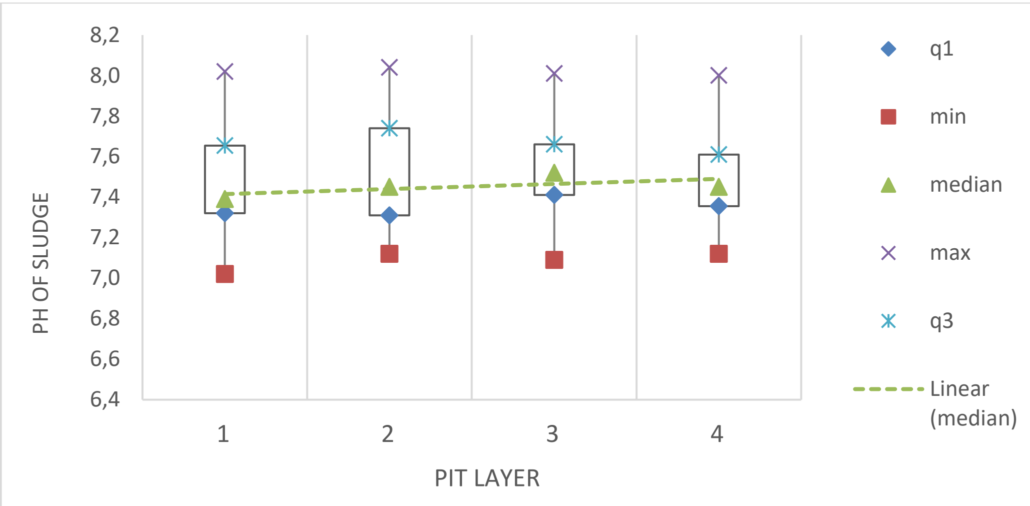


FIGURE 6-5: AVERAGE PH VALUES FOR PIT SLUDGE FOR ALL THE 50 PITS FROM THE STUDY AREAS

The primary consideration in the application of sludge to farm land is its possible addition of toxic elements, and any beneficial effects are secondary to this. This is because crops can accumulate toxic elements from sludge-amended soils, and where heavily-contaminated sludges and excessive rates of application are used, plants may accumulate toxic amounts. While cadmium and lead are particularly hazardous to humans, copper, zinc, chromium, and nickel in high concentrations are particularly poisonous to plants (Mäkelä-Kurtto, 1994).

Environmental concerns regarding land disposal are surface water and groundwater pollution, contamination of the soil and crops with toxic substances, and transmission of human and animal diseases. The presence of toxic metals in soil can severely inhibit the biodegradation of organic contaminants (Wuana & Okieimen, 2011). Heavy metal contamination of soil may pose risks and hazards to humans and the ecosystem through: direct ingestion or contact with contaminated soil, the food chain (soil-plant-human or soil-plant-animal-human), drinking of contaminated ground water, reduction in food quality (safety and marketability) via phyto-toxicity, reduction in land usability for agricultural production causing food insecurity, and land tenure problems (Wuana & Okieimen, 2011).

While soil characterization provides insight into heavy metal speciation and bioavailability, attempts to remediate soils contaminated with heavy metals requires knowledge of the source of contamination, basic chemistry, and environmental and health.

6.6 *Ascaris lumbricoides*

FS samples from 12 pits in Mogoditshane were analysed for the presence of *Ascaris lumbricoides* at the University of Botswana Biology laboratory. The results show an average value of 76.2 number per gram of FS, and this number decreases with increase in depth of sludge to an average of 7 per gram at 1.2 m depth. The recovery of *A lumbricoides* in raw faecal sludge is known to reflect on the health status of the local community (Sasakova et al., 2005; Appiah-Effah et al., 2015), and these results indicate that *A lumbricoides* is highly-prevalent in the population of Mogoditshane. Although *Ascaris lumbricoides* infection is often asymptomatic, it is known to affect child morbidity when associated with malnutrition, pneumonia, other enteric diseases and vitamin A deficiency. Therefore, carriage of this parasite may significantly contribute to the community's healthcare burden. Figure 6-7 shows the identified fertile egg in a wet mount of sludge as well as an infertile egg of *A. lumbricoides.*

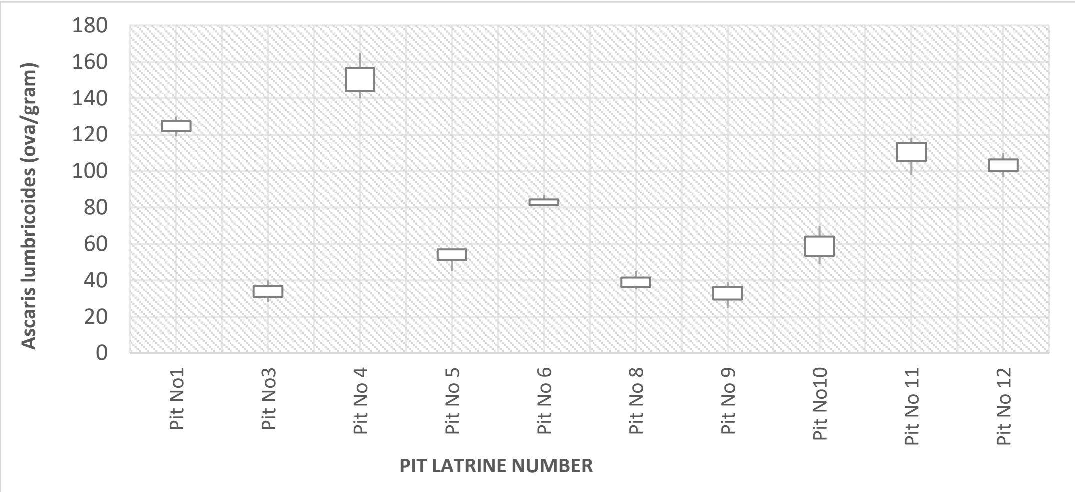


FIGURE 6-6: CONCENTRATIONS OF *A. LUMBRICOIDES* IN FAECAL SLUDGE SAMPLES OF SELECTED VIP LATRINE IN MOGODITSHANE

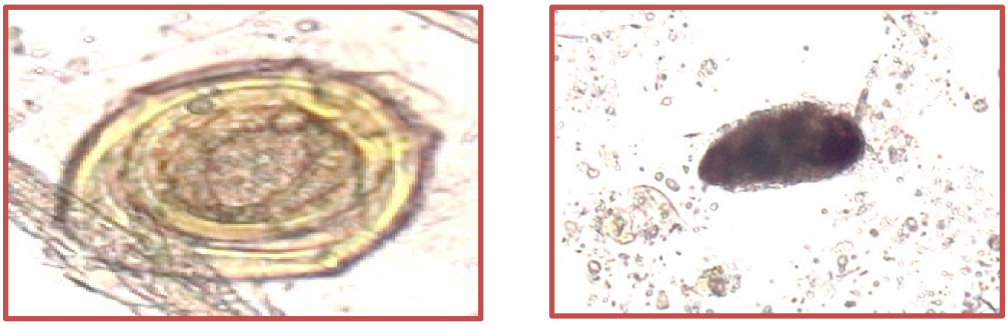


FIGURE 6-7: *A. LUMBRICOIDES* DECORTICATED, FERTILE EGG IN A WET MOUNT OF SLUDGE, 200X MAGNIFICATION (LEFT) AND UNFERTILIZED EGG OF *A. LUMBRICOIDES* IN A WET MOUNT OF STOOL, NOTE THIS SPECIMEN LACKS THE MAMMILLATED LAYER (DECORTICATED), 200X MAGNIFICATION (RIGHT)

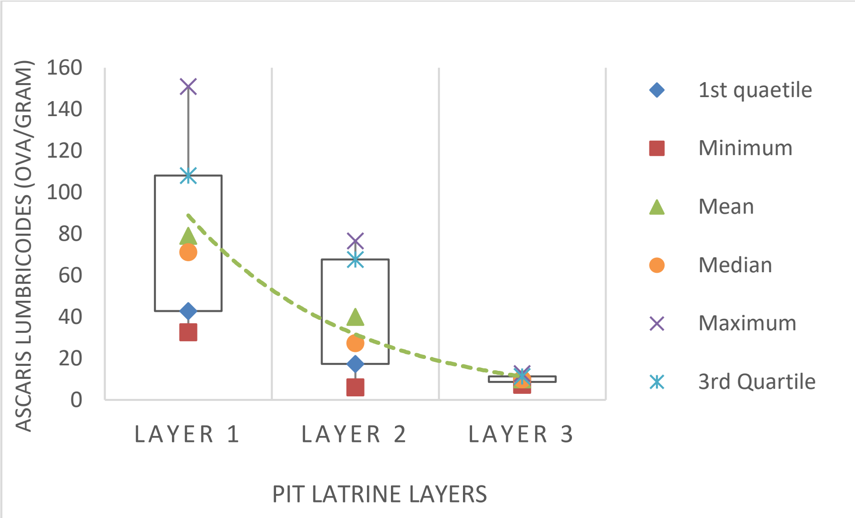


FIGURE 6-8: QUANTIFICATION OF *ASCARIS* IN VIPS ACCORDING DEPTH OF PIT CONTENTS

Land application provides a sustainable, beneficial alternative for the disposal of treated faecal sludge. However, it increases the threat of public exposure to disease. Because of their persistence, Nematode eggs are used as the indicators to determine hygienic quality and safety of faecal sludge in cases where FS is to be used as a soil conditioner and fertilizer. *A. lumbricoides* tends to be more persistent in the environment than viruses, bacteria and protozoa. As such, *A. lumbricoides*, is one of the nematode infections found to be highly prevalent among African countries and is believed to infect approximately 25% of the world's population annually (Crompton, 1988). The presence of *A. lumbricoides* in all samples analysed indicates that the depth and length of storage of VIP sludge does not effectively inhibit the viability of pathogenic helminths. The United States Environmental Protection Agency (US EPA) recommends that pathogens in sludge should be reduced to below detectable limits if it is to be applied on land (US EPA, 1992). Therefore, it is recommended that faecal sludge should be processed further to reduce the pathogens below detectable levels before being applied on land.

6.7 Recommended health protection measures

Several health protection measures have been documented in various sources in the literature. Some of the measures that are commonly adopted, including: core treatment with municipal wastewater at wastewater treatment plant; crop restrictions where sludge is applied to soils for agricultural purposes; human exposure control; and chemotherapeutic interventions. In practice these are usually used in combination, and not singly. The most commonly used combination is partial wastewater treatment plus crop restrictions, and this is reflected in the wastewater guidelines. Partial wastewater treatment can, however, be combined with one or more of the other measures. Co-treatment with municipal wastewater at a wastewater treatment plant is the current practice in Gaborone. However, this practice may influence the operations of the wastewater treatment plants and may affect the quality of the wastewater treatment plant sludge, which could result in high concentrations of heavy metals.

The use of sludge as a fertiliser may pose a threat to human and animal health as well as groundwater resources and plants due to pathogenic microorganisms present in the sludge. Faecal sludge stabilisation, with the aim of sterilisation, is therefore necessary before being utilised for any beneficial purpose including agriculture. The following model in Figure 6-9 is therefore suggested for farmers and small-scale businesses.

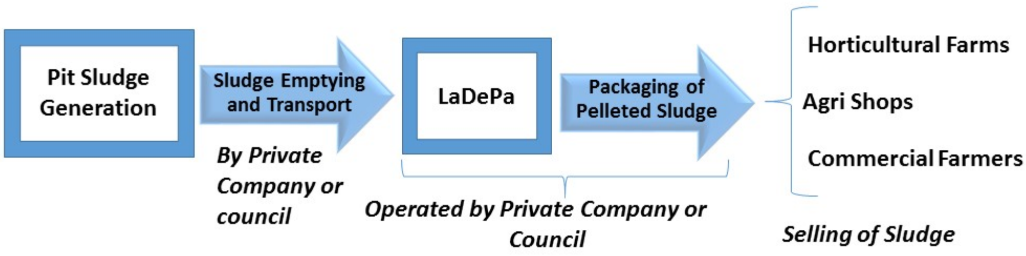


FIGURE 6-9: PROPOSED SLUDGE MANAGEMENT MODEL FOR GABORONE

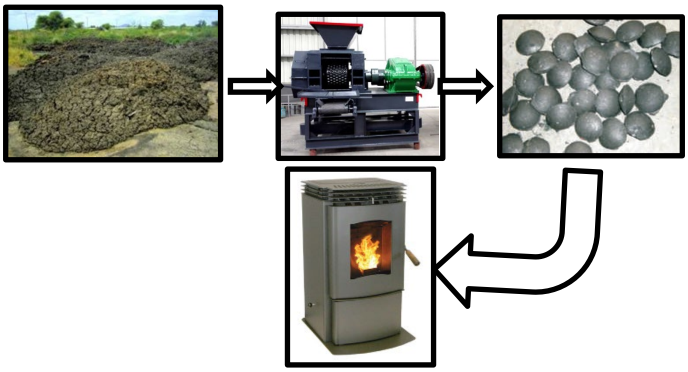


FIGURE 6-10: USE OF FAECAL SLUDGE AS A SOURCE OF ENERGY

6.7.1 Environmental protection measures

The analytical results indicate that sludge contains trace amounts of metals and pathogens. This indicates that their application could result in contamination of soils if not properly handled and if not well treated. Ultimately, contamination of the soils will end in contamination of water resources.

Odour control is the most important environmental dimension of sludge application to land. Enclosed tankers should be used for transporting treated sludge, which tends to be less odorous than raw sludge. Movement of sludge by tanker from sewage treatment plant to agricultural land can create traffic problems and give rise to noise and odour nuisance. Vehicles should be carefully selected for their local suitability and routes chosen to minimize inconvenience to the public. Discharge points for sludge from tankers or irrigators should be as near to the ground as is practicable and the liquid sludge trajectory should be kept low to minimize spray and visual impact. Untreated sludge should be injected under the soil surface using special vehicles or tankers fitted with injection equipment.

Great care is needed to prevent sludge running off onto roads or adjacent land, depending on topography, soil and weather conditions. On sloping land there is the risk of such runoff reaching watercourses and causing serious water pollution. Sludge application rates must be adjusted accordingly and, under certain circumstances, spreading might have to be discontinued. In addition to the problem of surface runoff, pollution may arise from the percolation of liquid sludge into drains, particularly when injection techniques are used, or liquid sludge is applied to dry fissured soils. In highly-sensitive water pollution areas, sludge should be used only in accordance with the requirements of the pollution control authority as well as of good farming practice. Sludge storage on farms can optimize the transport and application operations but every effort must be made to ensure that storage facilities are secure.

Care should always be taken when applying sewage sludge to land to prevent any adverse environmental impacts. The sludge must not contain non-degradable materials, such as plastics, which would make land disposal unsightly.

7 Key findings

The following key findings have come out of this study:

- Faeces and urine are health hazards but also have potential for reuse if handled and treated in the right way. However, negative perceptions on faecal sludge are a hindrance to companies and individuals realising this potential. This is caused by lack of knowledge about FSM by the community and the private sector.
- In Botswana, the main cause of poor FSM is the introduction of the water sector reforms, which have resulted in on-site sanitation hanging in the balance despite the government having a good history of improved sanitation provision.
- Lack of capacity and inexperience with on-site sanitation issues has led to the WUC abandoning pit emptying services. The WUC is not able to cope with the demand for pit emptying services, leading to inadequate service provision.
- There is currently no clear working relationship between the WUC and the private companies. Although there are policies related to sanitation, there is no clear strategy specifically speaking to FSM, particularly to address issues of pit emptying. Proper and coordinated FSM strategies have the potential to improve agricultural productivity and public health and dignity.

Attempts have been made to improve this situation by enhancing the quality of sewage sludge and finding new treatment methods and functions for it. Reuse of sludge in agriculture requires efforts in marketing and commercialisation but bears the advantages of generating revenues. However, without shared understanding among the community of the value of FSM, reuse cannot be fully achieved.

7.1 Conclusions

There is no working relationship among stakeholders to adequately manage faecal sludge. Although there are policies related to sanitation, there is no clear strategy addressing FSM and, in particular, pit emptying. Without the community understanding the value of FSM, reuse FS cannot be fully achieved. For better understanding of the behaviour of FS in VIP latrines, a thorough characterisation of pit latrine sludge should be done in order to improve pit emptying devices and technologies. FSM goals can only be adequately achieved if the community and the private sector are educated thoroughly. At the same time, government must develop a more specific sludge management policy or strategy that emphasises pit emptying and transportation with treatment facilities in mind. New technologies for sludge treatment and processing must be considered and introduced as part of the FSM strategy to add value to the FSM process.

Poor coordination among stakeholders renders the sanitation sector difficult to manage. The WUC should involve and engage stakeholders, such as households as well as representatives from the communities and key faecal sludge management stakeholders (such as local authorities, emptying companies, transporters (Small and Medium Enterprises – SME), relevant government authorities and sanitation experts). While BPWSM acknowledges cost recovery in sanitation matters, very little is done to realise this principle. In order to consider resource recovery during FSM, a new FSM model is needed in Botswana to turn around the sanitation sector. Promotion of resource recovery and reuse (RRR) of FS can go a long way in avoiding long-distance travel by vacuum tankers to the WWTP. Decentralisation of services may be achieved by construction of planted drying beds (PDBs), also sometimes referred to as planted dewatering beds and sludge drying reed beds. To manage FS in a more sustainable manner, the WUC must start viewing FS as a resource rather than waste and keep cost recovery in mind.

7.2 Recommendations

Based on the observations and discussions made in this work, it is evident that while sanitation is taken seriously in terms of provision, FSM management is still lagging. Therefore, the authors give the following recommendations and suggestions for better FSM:

1. For better understanding of the behaviour of faecal sludge in VIPs, a thorough characterisation of pit latrine sludge must be done. This will allow for improved design of emptying devices as well as treatment techniques for FS. At the same time, government must develop a more specific sludge management policy that emphasises pit emptying, transportation, and treatment.
2. New technologies for sludge treatment and processing must be considered and introduced as part of the FSM strategy. eThekwini Municipality in Durban developed the LaDePa machine and promoted for value addition to the FSM process. The use of this technology will add direct economic benefits of improved FS management to the private sector and ensure a healthy environment the community.
3. Fragmentation of stakeholders renders the sanitation sector very complicated to manage. The WUC should involve and engage stakeholders, including households and community representatives as well as key faecal sludge management parties (e.g. local authorities, emptiers, transporters (SME), relevant government authorities and experts).
4. To avoid long distance travel by vacuum tankers to wastewater treatment plants, decentralisation of services may be achieved by constructing planted drying beds (PDBs), also sometimes referred to as planted dewatering beds, and sludge drying reed beds.

7.3 Summary

In the past, sanitation was the responsibility of local authorities or councils with the DWMPC. Pollution of groundwater in Botswana is currently forcing the GoB to abandon the I,of pit latrine construction and VIP emptying services in peri-urban areas and instead advocate for the expensive and unsustainable construction of sewer systems. This approach would require the peri-urban community to pay for connection fees. Most rural communities cannot afford these fees, and since Botswana is a water-scarce country, sewer connection may cost the country much more than finances. With proper management of faecal sludge, environmental and health risks could be eliminated. This work discussed the current practices and policies and recommended rigorous sludge management strategies that include reuse and value addition strategies to the sludge management framework. It suggested new policies that specifically target faecal sludge management in order to set a new norm for FSM.

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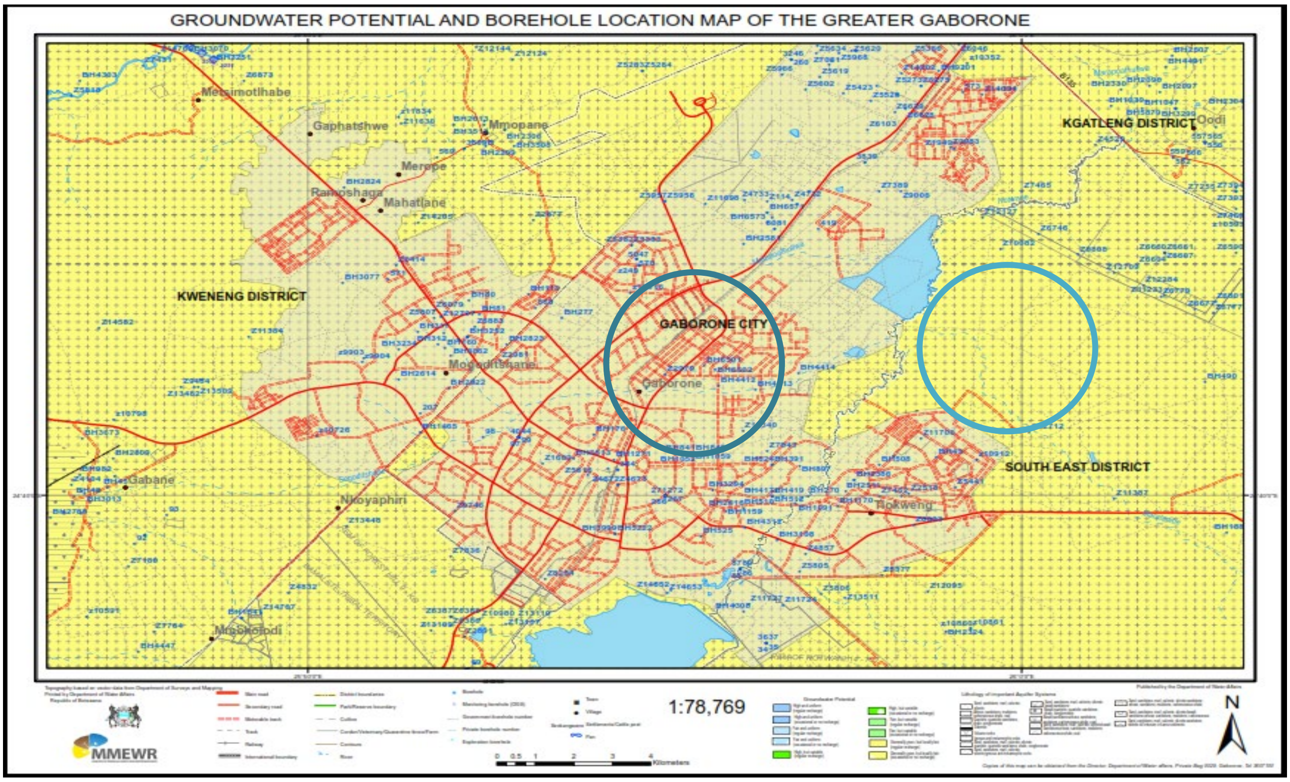
APPENDIX A: Groundwater potential and borehole location map relative to study site


GROUNDWATER POTENTIAL AND BOREHOLE LOCATION MAP OF THE GREATER GABORONE
KWENENG DISTRICT
GABORONE CITY
KGATLENG DISTRICT
SOUTH EAST DISTRICT
Metsimotlhabe
Gaphatshwe
Mmopane
Mahatlane
Mogoditshane
Gaborone
Gabane
Nkoyaphiri
Tlokweng
Oodi
1:78,769
Kilometers
N
MMEWR

APPENDIX B: T-test Results

TABLE A1-0: LIQUID LIMIT T-TEST OF MOGODITSHANE AND BROADHURST SLUDGE PIT PER LAYER

LIQUID LIMIT TTEST			
LAYER 1	BRODHURST	MOGODITSHANE	T-TEST
STDEV	12.1	8.0	-2.841
AVAR	42.4	58.2	
NO. OF SAMPLES	6.0	10.0	
VAR	146.9	64.7	
LAYER 2	BRODHURST	MOGODITSHANE	T-TEST
STDEV	11.49	7.92	-2.165
AVAR	45.78	54.96	
NO. OF SAMPLES	12.00	9.00	
VAR	132.00	62.70	
LAYER 3	BRODHURST	MOGODITSHANE	T-TEST
STDEV	7.73	5.34	-1.338
AVAR	48.91	53.65	
NO. OF SAMPLES	11.00	4.00	
VAR	59.74	28.47	

TABLE A1-1: DENSITY T-TEST OF MOGODITSHANE AND BROADHURST SLUDGE PIT PER LAYER

DENSITY TTEST			
LAYER 1	BRODHURST	MOGODITSHANE	T-TEST
STDEV	0.151	0.144	-1.489
AVAR	1.000	1.106	
NO. OF SAMPLES	14	6	
VAR	0.023	0.021	
LAYER 2	BRODHURST	MOGODITSHANE	T-TEST
STDEV	0.165	0.158	-0.668
AVAR	1.058	1.110	
NO. OF SAMPLES	15	6	
VAR	0.027	0.025	
LAYER 3	BRODHURST	MOGODITSHANE	T-TEST
STDEV	0.2291	0.1779	0.552
AVAR	1.1811	1.1294	
NO. OF SAMPLES	15	6	
VAR	0.0525	0.0317	

Table A1-2: Viscosity t-test of Mogoditshane and Broadhurst sludge pit per layer

Viscosity TTEST			
LAYER 1	BRODHURST	MOGODITSHANE	T-TEST
STDEV	31220338.12	6779391.585	
AVAR	4374477.52	3464255.439	
NO. OF SAMPLES	70	70	
VAR	9.88836E+14	4.66262E+13	0.237
LAYER 2	BRODHURST	MOGODITSHANE	T-TEST
STDEV	43480438.88	248093.9947	
AVAR	-6356205.31	62442668333	
NO. OF SAMPLES	70	70	
VAR	1.91795E+15	4.66262E+13	1.242
LAYER 3	BRODHURST	MOGODITSHANE	T-TEST
STDEV	40161548.96	17496546.75	
AVAR	-8845267.25	4609118.905	
NO. OF SAMPLES	69	70	
VAR	1.63667E+15	3.10566E+14	2.536

Table A1-3: BOD t-test of Mogoditshane and Broadhurst sludge pit per layer

BOD TTEST Values			
LAYER 1	BRODHURST	MOGODITSHANE	T-TEST Values
STDEV	30783.26	10294.78	4.107
AVAR	43511.11	9742.36	
NO. OF SAMPLES	15	24	
VAR	947608994.7	105982413	
LAYER 2	BRODHURST	MOGODITSHANE	3.217
STDEV	35473.38	9495.82	
AVAR	45.78	54.96	
NO. OF SAMPLES	15	14	
VAR	1258360582	90170521.21	
LAYER 3	BRODHURST	MOGODITSHANE	2.677
STDEV	32508.72	12490.65	
AVAR	48.91	53.65	
NO. OF SAMPLES	15	4	
VAR	1056816931	156016373.7	