USE OF ANAEROBIC TECHNOLOGY TO TREAT PIT LATRINE SLUDGE FOR BENEFICIATION

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Executive Summary

Zimbabwe has made tremendous strides in improving access to safe water, sanitation and hygiene; but in recent years there has been massive growth of peri-urban settlements as the majority of citizens make efforts to secure urban dwellings. These settlements are informal in most cases and are not supported by local governments in terms of provision of sanitation, until such a time when they are formalised, if at all. The residents of such settlements largely rely on pit latrines, which occasionally fill up and are associated with various other management problems. However, little consideration has been given to the management and disposal of faecal sludge, which raises health, safety and environmental concerns. This report details the findings of an investigation on the uses and management practices of pit latrines and pit latrine faecal sludge (FS) in selected peri-urban settlements of Zimbabwe. The study was commissioned by the Water Research Commission (WRC) of South Africa with funding received from the Bill & Melinda Gates Foundation (BMGF, Grant ID: OPP1044943). The terms of reference of the study were to review the Faecal Sludge Management (FSM) policies, characterise the nature and composition of the faecal sludge, develop solutions for safe disposal and reuse on land applications, evaluate the potential for biogas generation from the sludge and develop a model for value addition of faecal sludge that could sustainably benefit communities.

In order to review the local Faecal Sludge Management (FSM) and emptying policies, practices and perceptions in Zimbabwe, a survey was conducted within the 32 urban local authorities comprising the cities, municipalities, town councils and town boards under the ten administrative provinces of Zimbabwe. The data included the social, legal, institutional and socio-economic factors surrounding the practices, policies and perceptions. It was observed that there was no comprehensive national policy to clearly outline the rules governing the provision of sanitation services to communities in general and the roles and responsibilities of different agencies in informal settlements. It appeared that there was no policy in place on the emptying of pit latrine toilets and that most of the public were not aware of the potential benefits of faecal sludge for agricultural beneficiation and biogas generation. Water, sanitation and hygiene policies are coordinated by various institutions in Zimbabwe but most tended not to entertain the existence, adoption or use of pit latrine facilities. For these reasons, the authorities felt they did not have any obligation to be involved in the management of faecal sludge from pit latrines, as that would promote their proliferation. Furthermore, such practices were not deemed socially acceptable, except in communities that had been educated by NGOs on such practices. However, a few individuals were aware of the use of treated municipal waste for agricultural beneficiation. It was concluded that there is a need for harmonised legislation and policy on FSM and pit latrine emptying in Zimbabwe.

In order to characterise the pit latrine contents from Zimbabwean peri-urban areas, sludge was collected from sites located in the distinct geological and socioeconomic zones of Harare (Hatcliff and Hopley) and Chinhoyi (Shackelton). The physico-chemical and microbiological properties were analysed. Sampling was conducted using a graduated tool that was developed specifically for this project and laboratory analyses were conducted in order to characterise the sludge. It was established that the characteristics of the fresh sludge varied by pit latrine and "no two pits were alike". Socioeconomic factors, individual differences and pit construction and management practices were found to be the main determinants of pit content variability. In addition, the characteristics of the

sludge within each pit varied with depth (and therefore, residence time). Coliforms and *E. coli* were present in high counts, and helminth ova and cysts were detected in some pits. The faecal sludge from all the study sites contained relatively high concentrations of nutrients (N, P, K, Ca, Mg, K) suitable for plant growth.

Laboratory experiments were carried out to anaerobically digest the fresh sludge using mesophilic batch reactors. The experiments assessed the potential for bioenergy (biogas) production and the improvement of sludge quality for safe environmental disposal on land and its use as a soil amendment and/or fertiliser for agricultural beneficiation. The changes in the physico-chemical and microbiological properties of the sludge were used for the assessment. The initial COD values ranged from 14 403 ± 638.7 mg/ℓ to 25 647 ± 638.7 mg/ℓ, with a mean of 20 025 mg/ℓ, and anaerobic digestion reduced the values to between 11 011 ± 231 mg/ℓ and 16 670 ± 399 mg/ℓ, with a mean average of 13840.5 mg/ℓ. Similarly, the BOD average values were reduced from the range of 11 421 ± 258.5 mg/ℓ to 14 680 ± 300 mg/ℓ to a range of 9 868 ± 900 to 8 530 ± 690 mg/ℓ. Anaerobic digestion significantly reduced the mean faecal coliform (FC) counts from the range of between 7.66×10^5 and 2.8×10^6 MPN/100 mℓ to 9.0×10^5 and 1.5×10^6. Similarly, the total coliform (TC) counts were significantly reduced from the range of between 1.8×10^6 and 3.4×10^6 MPN/100 mℓ to 1.1×10^6 and 1.6×10^6.

Anaerobic digestion produced sufficient amounts of biogas that could be useful for household energy applications. Digestion also significantly transformed the quality of the sludge. The daily methane production from anaerobic digestion averaged 0.012 m^3/kg VS_A for sludge from the Hatcliff Extension sites and 0.05223 m^3/kg VS_A for the Shackelton sites. The overall range of daily methane production in all samples was between 0.0085 and 0.0894 m^3/kg VS_A. However, the total nutrient composition was slightly altered. In addition, there was notable transformation of microbial populations with the elimination of most coliforms and *E. coli.* However, the counts of *E. coli* still remained above the WHO (2006) standards for land application and the faecal coliform counts also exceeded the limits for use in agriculture and aquaculture.

Since the results demonstrated the potential of anaerobically digested faecal sludge to produce methane for household use, and improved the nutrient quality and safety to human health, the study findings were used to design large-scale biodigestors for on-site treatment of faecal sludge and subsequent generation of biogas for household use. Therefore, three full scale digesters were constructed in Hatcliffe, Hopley (Harare) and Shackleton (Chinhoyi) and commissioned for use by the communities. The digesters were successfully used for faecal sludge disposal and sustainable biogas generation for household cooking and lighting by beneficiary members of these communities.

The anaerobically digested sludge from laboratory digester experiments was used for potted plant experiments in the open field and greenhouse trials. The trials generally indicated that anaerobically digested faecal sludge improves plant growth and can be comparable to commercial inorganic fertilisers at 2% (w/w) dry sludge application rate. The research team provides scientific research and technical back-up support services to these communities in order to ensure improved and optimum performance that can produce digested sludge of acceptable levels for land application and agricultural beneficiation with no restrictions, especially considering the longer residence time before emptying the digesters.

This project supported two MPhil students and all the objectives and milestones were successfully completed. The project also raised awareness about the use and management of pit latrines and faecal sludge. The project also resulted in the transfer of knowledge to the Zimbabwean peri-urban communities on the potential benefits of sustainable use of faecal sludge for bioenergy production and agricultural beneficiation. In conclusion, the project showed that faecal sludge is a resource that can be beneficiated to provide energy for household use and for use as fertiliser/soil amendment.

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We would also like to thank the various organisations who worked closely with the project team during the execution of this project. We are grateful to The City of Harare and Chinhoyi Municipality for allowing access to the study sites. Special thanks go to Dialogue on Housing and Shelter who introduced us to the communities in the study areas, especially Mr Masimba Nyama. We would also like to thank the Federation for Homeless People and the communities in Hatcliffe, Hopley and Dzivarasekwa Extension in Harare; and in Shackleton (Chinhoyi).

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Table of Contents

List of Tables

List of Figures

List of symbols and abbreviations

AGRITEX	Agricultural Technical and Extension Services
BMGF	Bill & Melinda Gates Foundation
BNR	Biological nutrient Removal
BOD	Biochemical Oxygen Demand
BVIP	Blair ventilated improved pit latrine
COD	Chemical Oxygen Demand
CSO	Central Statistical Office
CUT	Chinhoyi University of Technology
DDF	District Development Fund
EMA	Environmental Management Agency
FSM	Faecal Sludge Management
GoZ	Government of Zimbabwe
IRWSS	Integrated Rural Water Supply and Sanitation
IWSD	Institute of Water and Sanitation Development
MENR	Ministry of Environment and Natural Resources
MLGRUD	Ministry of Local Government, Rural and Urban Development
MoA	Ministry of Agriculture
MoEN	Ministry of Energy
MoHCW	Ministry of Health and Child Welfare
MoTCID	Ministry of Transport Communication and Infrastructure Development
NAC	National action committee
NCU	National coordinating unit
NGO	Non-governmental organization
RBC	Rotating Biological Contactor
TF	Tricking filter
UNICEF	United Nations Children's Emergency Fund
VIP	Ventilated improved Pit Latrine
WASH	Water sanitation and hygiene
WWTW	Wastewater Treatment Works
ZIMSTAT	Zimbabwe National Statistics Agency
ZINWA	Zimbabwe National Water Authority

1 Policies, practices and perceptions in faecal sludge management (FSM) in Zimbabwe

1.1 Country background: Zimbabwe

1.1.1 Study area: Location and population

Zimbabwe lies in the southern hemisphere (latitude 19°S and longitude 30°E) and is bordered by Mozambique on the east, Botswana on the west, South Africa on the south, and Zambia on the north and northwest (Figure 1-1). It is part of a great plateau, which constitutes the major feature of the geology of southern Africa. The altitude ranges from 162 to 2592 m, with high relief areas being largely located in the eastern part of the country. It experiences cool, dry winters and warm, wet summers. Zimbabwe has an area of 390 757 km^2 and population of approximately 13 million (ZIMSTAT, 2012) with an average population density of about 33 persons per square kilometre. Harare is the most populated city (Figure 1-2).

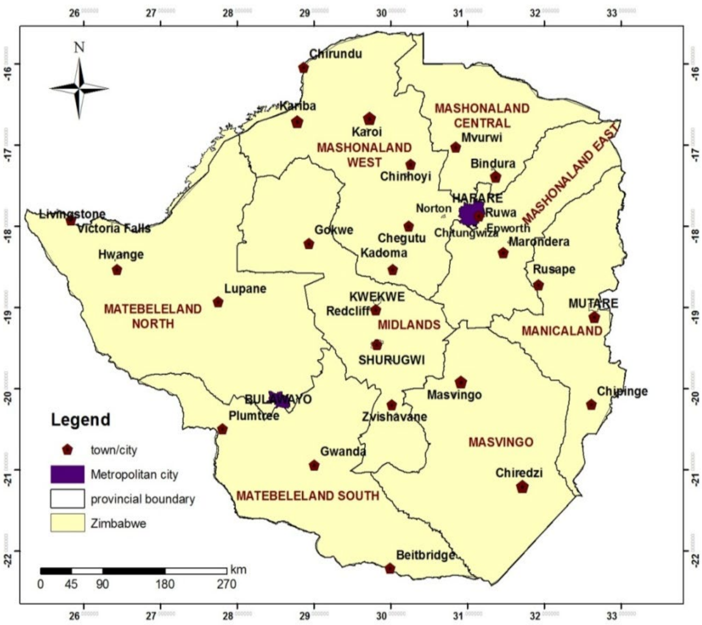

FIGURE 1-1: MAP OF ZIMBABWE SHOWING URBAN CENTRES

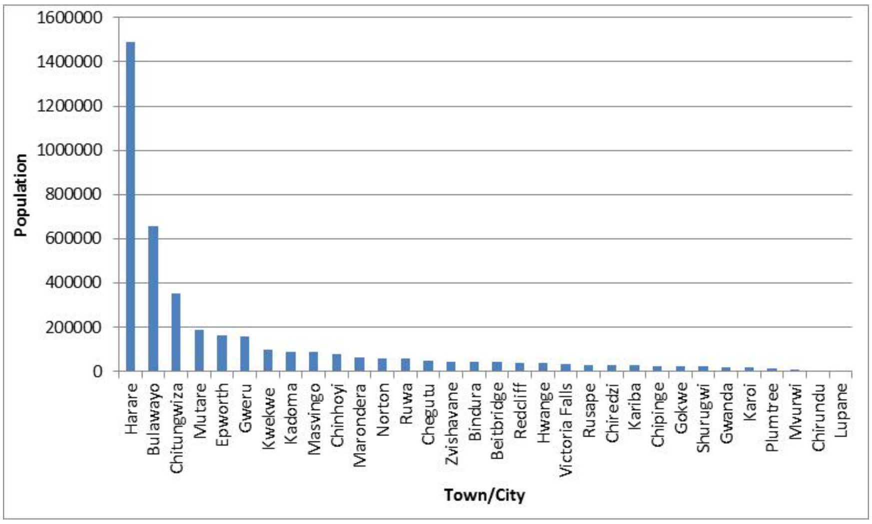

FIGURE 1-2: POPULATIONS OF TOWNS AND CITIES IN ZIMBABWE (ADAPTED FROM ZIMSTAT, 2012)

There are ten administrative provinces and 32 urban local authorities comprised of cities, municipalities, town councils and town boards (Table 1-1). Local authorities are classified and ranked according to their size and levels of development as cities, municipalities, towns and local boards (Government of Zimbabwe [GoZ], 2013).These local authorities are autonomous bodies that are responsible for the administration of their areas of jurisdiction and for the provision of services and infrastructure to ratepayers (Table 1-1). They have authority to levy rates and charges on rate payers in order to raise revenue to cover the cost of council activities (GoZ, 2013).

TABLE 1-1: CLASSIFICATION OF SELECTED URBAN COUNCILS IN ZIMBABWE.

City Council	Municipality	Town Council	Local Board
Harare	Chinhoyi	Karoi	Ruwa
Bulawayo	Chitungwiza	Norton	Epworth
Mutare	Marondera		
Masvingo			
Gweru			

1.1.2 Sanitation facilities

An estimated 36% of urban households in Zimbabwe have improved toilet facilities that are independent of other households (ZIMSTAT, 2012). Of these facilities, about 43% are connected to a sewer system or a septic tank. Other sanitation facilities used in Zimbabwe are flush to piped sewer system (85%), flush to septic tank (6%), pit latrine (5%), VIP (2%) and open defecation (2%) (ZIMSTAT, 2009).

1.1.3 Social aspects

Since independence in 1980, the Zimbabwean economy experienced a period of gradual growth and relative stability. A diverse economy, dominated by agricultural production, was complemented by a strong manufacturing base. This economic boom resulted in rural-urban migration by economically active age groups in search of jobs. However, since the 1990s, years of drought and political, economic, and social upheaval brought economic challenges that led to unemployment remaining at 80%. This pushed people into the informal economy, and migration from rural to urban areas increased (Sigauke, 2002). In addition, following the National Land Reform Programme in 2000, there has been a rise in peri-urban and informal settlements in and around major towns and cities. Traditionally, the two major such settlements were Epworth (established well before 1980) and Hatcliffe (established post 1980) in Harare. However, Harare now has several such settlements, established legally or otherwise by neighbouring rural local authorities such as Zvimba and Goromonzi or by private land developers and cooperatives. These settlements now include Hopley, Caledonia, Whyte Cliff and Southley Park. Government has also started the Garikai/Hlalani Kuhle Housing initiative.

The increase in urban population was not accompanied by the provision of infrastructure and sanitation services. Urban poverty increased and was often characterised by large families with a high proportion of tenants and semi-literate household heads. Sanitation is often not a priority among the many problems faced, which affects the effectiveness of health and hygiene education by non-governmental agencies (Manase, 2000). Other constraints include absence of effective communication channels between policy makers and the urban poor, little civic education and lack of social cohesion and heterogeneity. The neglect of sanitation and hygiene is arguably the major factor that contributed to the unprecedented cholera outbreak of 2008/2009. Among the reasons for the spread of these diseases are poor hygiene practices, lack of sanitation facilities and contaminated drinking water as a result of the rampant open defecation practices among the population.

1.1.4 Water and sanitation in peri-urban areas of Zimbabwe

Complex socio-economic and political factors such as rapid urbanisation, high unemployment, retrenchment, and either shortage or prohibitive costs of formal accommodation has led to the formation of informal settlements in peri-urban areas. In Harare, for example, high density (averaging 150 m^2) settlements such as Hatcliffe, Southley Park, Hopely, White Cliff and Caledonia have been established since the late 1990s. Sanitation and water services are not provided in informal settlements. In cases where these services are provided, they are in the form of public facilities (e.g. latrines which are over utilized and subjected to immense pressure). For example, a study revealed that in the poor community of Mbare, Newlines, a toilet with six squatting holes was shared by 1300 people (Manase, 2000). These settlements are also generally characterised by poor drainage and solid waste management, poor housing, overcrowding and high incidence of water and sanitation related diseases. Most local authorities evict residents rather than upgrading informal settlements. This approach makes it difficult for other organisations to make meaningful investments in these areas.

1.2 Sanitation technologies in use in Zimbabwe

Historically, Zimbabwe has pursued a dual system in terms of sanitation provision, with the urban sector relying on waterborne sewerage networks designed to the highest international standards, where sewage collected is conveyed to highly advanced and mechanised systems such as activated sludge/biological nutrient removal (BNR) and trickling filters (TF) and to the less technically complex waste stabilisation pond (WSP) systems. There are isolated cases of the use of other less common technologies (e.g. the rotating biological contactor (RBC) for Maphisa in Matobo, Matabeleland South Province).

On the other hand, the rural sector is dominated by the use of the pit latrines, of which the Blair Ventilated Pit Latrine (BVIP) has been the main technology. Other technologies include the Ecosan toilet.

1.2.1 Activated sludge and BNR systems

Most major cities in Zimbabwe have BNR systems, but most of them are currently either non-functional or partially functional (Figure 1-3). The major sources of sludge from these plants are screenings, primary and secondary sludges and slurry from the anaerobic digesters. While some sewage treatment works were designed to dry the sludge, most drying beds are no longer functional or are not in use (Figure 1-4).

FIGURE 1-3: NON FUNCTIONAL BNR TREATMENT WORKS

FIGURE 1-4: DRYING BEDS FOR SEWAGE SLUDGE (NOT IN USE)

1.2.2 Trickling filters

Trickling filters (TF) have been a popular wastewater treatment technology in most urban centres in Zimbabwe. The sources of sludge from these systems include the screenings, primary sludge and humus. Where digesters are installed, slurry is also another biosolids by-product of this process.

1.2.3 Waste stabilisation ponds

Waste stabilisation ponds (WSPs) are generally used in smaller urban settlements in Zimbabwe, as they require large surface areas. However, their simplicity of design, construction and operation and the non-requirement of electricity have ensured their recent revival, even in the larger urban settlements as power outages are frequent and prevalent in Zimbabwe.

The main sources of sludge from this technology are the screenings and sludge emanating from the desludging of the anaerobic pond, which must be de-sludged about once every 3-5 years. However, currently, most WSP systems in Zimbabwe are not being de-sludged as often as is required.

1.2.4 General comments on urban sludge

Solids from the screening process (generally larger than 1 mm), primary and secondary solids, oils and fats are generally classified together as "sludge" from wastewater treatment works. Sludge usually also contains grit (mainly sand), grease, floatable fats and oils. Primary settlement solids are finer, while the secondary (biological) solids (formed when specialised bacteria feed on nutrients in wastewater) may appear as flocs. Slurries from digesters generally have the consistency of thick porridge. Sludge is generally high in COD/BOD and contains nutrients and other elements. However, the main disadvantage is that, for highly industrialized cities, the sewage may contain substantial proportions of industrial wastewater, which may be rich in undesirable ions such as chloride, sulphate and/or heavy metals such as copper, lead, cadmium and other pollutants.

It is generally known that improving the efficiency of wastewater treatment systems results in the production of more biosolids. Thus, the current situation in Zimbabwe, where most wastewater treatment works (WWTW) are not fully functional, means that relatively small volumes of sludge are currently being produced. Where screens are installed and are not worn out, screenings are currently the major biosolids being produced, and most STW currently deal with them simply by burying on site.

Ideally, sludge is processed using a combination of stabilisation (to reduce their potential to decay), disinfection (to kill pathogens in sludge), dewatering/drying (to reduce volumes and enable easy handling), and/or anaerobic digestion. Stabilised sludge is finally either disposed of in a landfill or applied to land.

The current practice of simply burying screenings is known to result in serious contamination of the groundwater resources. Additionally, while the land application of sludge is known to result in the longer retention of soil moisture, improve soil structure and add some nutrients to the soil, the biosolids are not a high grade fertiliser. Excessive application of sludge to land can also result in the pollution of surface waters and may damage the soil permanently.

1.3 Rural and peri-urban technologies

1.3.1 Ventilated improved pit latrine

The sanitation technology of choice in rural Zimbabwe has been the Blair Ventilated Improved Pit latrine (BVIP) (Figure 1-5). The design is standardised and has been approved by the Ministry of Health (Figure 1-6). While this design has been useful over the years, the main disadvantages now seems to be the high costs and that the design makes emptying of pits difficult when full.

FIGURE 1-5: STANDARD BVIP TOILET

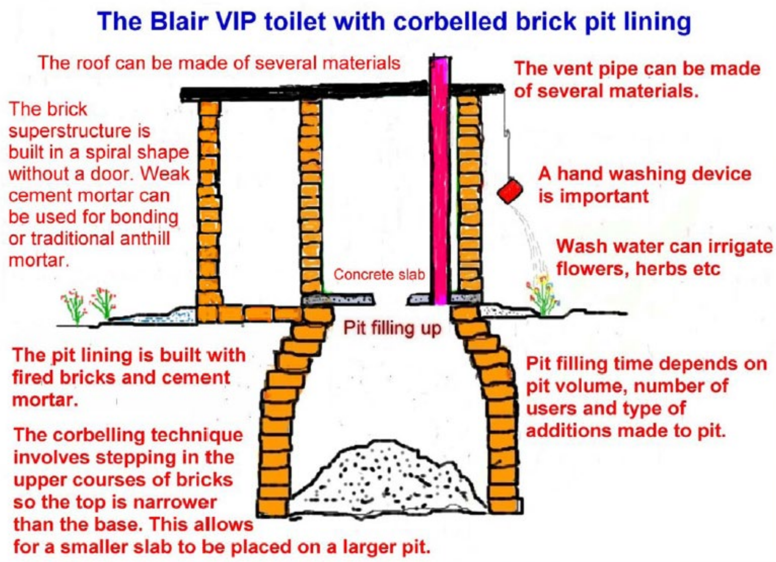

FIGURE 1-6: SECTION THROUGH A STANDARD BVIP

1.3.2 Other technologies used in rural and peri-urban sanitation

The latrines and sludge management practices promoted in peri-urban communities are based on designs and experiments conducted and promoted by Peter Morgan, the 2013 Stockholm Water Price Laureate. He put forward the following ideas for ecological sanitation (Morgan, 2007):

- Shallow pit latrines where trees are planted on top after latrine use is discontinued (*Arbor loo*)
- Humus-making twin-pit latrines where additional material is put in for humus production (*Fossa alterna*)
- Fertility pits or trenches (organic pits or eco-pits) for making humus or planting vegetable trees
- Bags for storage and humus production
- Buckets for storage and humus production
- Collection of urine and direct application onto or into soil

NGOs in Zimbabwe have worked extensively to promote and construct the various forms of pit latrines in Zimbabwe. One example is the work of Mvuramanzi Trust in the peri-urban informal settlements of Hatcliffe, Dzivarasekwa extension and Porta Farm since 1999. By 2002, about 1650 pit latrines had been built with the intention that the pit contents would be used as a soil conditioner after adequate storage. The Mvuramanzi Trust built pit latrines of the Arbor loo (shallow pit toilets), Fossa alterna and Sky loo (urine diversion toilets) types at individual homesteads and some urine diversion toilets at institutional premises.

The Fossa alterna uses a method of changing pits on a 6-month to one year cycle. Soil and ash are added in generous amounts to the faeces after each toilet visit. The ash is meant to raise the pH in an attempt to prevent multiplication of pathogenic bacteria within the faecal material. Occasionally, vegetable matter (sawdust, grass, leaves, etc.) must be added along with the soil and ash. As a result, a kind of compost is generated. When the pit is almost full to within 30 cm of the top, it is filled up with topsoil, and the owners are encouraged to plant either vegetables or flowers on top. The subsequent watering of the plants provides moisture for further composting of the pit contents, while the plant roots make their way down into the faecal matter and draw on the nutrients.

Although still limited in terms of number of households who have adopted it, a urine diversion eco-san toilet (Sky loo) is being promoted in some informal settlements such as Epworth (Figure 1-7 & Figure 1-8). Ecological sanitation is a system that makes use of the human waste and turns it into something useful and valuable, without polluting the environment or misusing any other natural resource. Thus, water closets, most composting toilets and pit latrines are not ecological. With respect to the widespread adoption of ecosan technologies, the main challenges have been raising public awareness, improving hygiene, marketing the recovered nutrients and applying nutrients safely in agriculture. Though the current acceptability of ecosan is still low, those who have adopted this technology use the sludge and urine for fertilizing crops and vegetables.

FIGURE 1-7: URINE DIVERSION TOILET IN EPWORTH

FIGURE 1-8: SOLIDS FROM URINE DIVERSION

1.4 Sanitation sector in Zimbabwe: A historical perspective

Up to about the year 2000, Zimbabwe had a robust water and sanitation sector in urban areas, with modern, highly mechanised, and well-designed and functional sewer networks and sewage treatment works. The latter consisted mainly of biological nutrient removal (BNR) systems, trickling filters (TF) and waste stabilisation ponds (WSP). However, very few of these systems are currently operational, and the sector faces numerous challenges.

The rural water, sanitation and hygiene (WASH) sector had an impressive record of researching and implementing rural sanitation programmes, with the Zimbabwean-designed Blair Ventilated Improved Pit (BVIP) toilets being built in large numbers, mainly through donor-assisted funding mechanisms. The considerable donor support (up to 5 bags of cement per family) had to be matched by a large contribution from the family (bricks, labour, paying an artisan). Very few self-financed BVIP toilets were ever built, as the Blair VIP typically served the better off who could afford the community contribution. The thrust of this design was not on the reuse of sludge or on the emptying of pits, as one would have had to physically dismantle the toilet to easily access the pit contents.

Half a million units were built serving an estimated 3 million people. The program was promoted vigorously by the Environmental Health Department of the Ministry of Health. The Blair toilet was built in households and as multi-compartment units at schools, clinics and other institutions (Figure 1-9). No consideration was given of the issue of pit emptying, as a new set of toilets would be built when the pits filled up.

FIGURE 1-9: MULTI-COMPARTMENT BVIP AT A SCHOOL

However, the programme only served about 33% of households, and the remaining 66% depended on standard pit toilets or open defecation. When donor support declined, the number of units built rapidly declined. The standardised Blair VIP was too expensive for most families to build themselves.

Each Blair VIP has a limited life span of 10-15 years. Thus, most are now full and not used at all. When donor support declined, the program almost collapsed. Thus, the program was not sustainable. Had the technology been simpler, more affordable and easier to build, more families would have benefited and many more self-financed toilets would have been built.

Experts in the WASH sector now say that a new approach must be adopted. This must be based on a policy which accepts greater flexibility in design of toilets and upgradability of toilets. Toilet designs should be simpler, more cost effective and thus more easily copied. They should use a higher content of traditional materials and should be designed in an upgradeable series so that Blair VIPs can still be eventually built. Additionally, more emphasis should now be placed on resource recovery and pit content beneficiation. Some important milestones in the development of the WASH sector in Zimbabwe post-independence in 1980 are shown in Table 1-2.

TABLE 1-2: MILESTONES IN THE WATER AND SANITATION SECTOR IN ZIMBABWE

Date	Event
1980	National Independence
1985	National Master Plan for rural water supply and sanitation (NMWP)
1987	National Action Committee (NAC) established
1987	Integrated Rural Water supply and sanitation (IRWSS) programme launched
1999	Water Act
1999	Zimbabwe national water authority established
2004	Draft Water and sanitation Policy
2008	Cholera outbreak kills more than 4000 people
2010	NAC re-launched
2011	National Sanitation and Hygiene strategy
2013	National Water Policy

(Adapted from Government of Zambia, 2011)

1.5 Current challenges in FSM in Zimbabwe

The current faecal management policies and practices in Zimbabwe can only be understood in the context of the current challenges in the WASH sector, discussed below.

- Lack of proper pit emptying technologies when VIP latrines have filled up: VIP latrines constructed in some settlements (e.g. Dzivarasekwa Extension) filled up and residents were reliant on NGO assistance for emptying.
- Lack of political will is also a key factor resulting in lack of sanitation and sludge management policies in poor urban settlements.
- There is inadequate wastewater treatment capacity to meet demand, leading to overloading.
- Water supplies are unreliable, compromising wastewater collection and treatment.
- Local authorities are struggling to operate and maintain the highly mechanised and technically complex energy-demanding sanitation systems, such as BNF and TF. Frequent power outages also affect the operation of sewerage treatment plants, especially BNR plants.
- Infrastructure has suffered through many years of low or no investment, leading to frequent breakdowns of equipment due to poor maintenance.
- The highly subsidised and high technology sanitation technologies (waterborne sewerage in urban areas and BVIPs in rural areas), which Zimbabwe has promoted in the past, are no longer affordable at a large scale. While other sanitation alternatives have been developed, government approval of these technologies has been slow**.**
- The informal and peri-urban areas present a special challenge. Sanitation services are very sparse or non-existent in these areas. Generally, national access to water and sanitation services is dropping both in terms of reliability of supply, quality and adequacy.
- Sanitation is not represented at high enough levels in the Ministry of Health. The highest official is the Director of Public Health in the Ministry of Health. As such, WASH has only recently received prominence in the last five years, following the 2008 cholera outbreak, which killed about 4300 people.
- Too many different government Departments are involved in different aspects of sanitation (e.g. Department of Health, Department of Water, urban councils, EMA), and thus, coordination and apportionment of responsibilities is often a challenge.
- Roles in sanitation management and provision are unclear between rural and urban local authorities and government departments, especially with respect to peri urban areas.
- Enforcement of environmental and public health regulations relating to sanitation is often weak and ineffective. Political interference has also been an issue.
- Poor engagement of the private sectors is a barrier.
- Insufficient tariffs have led to the unavailability of sufficient funds for normal operation, repair and maintenance. Additionally, for most local authorities, WASH revenue is not ring-fenced to benefit the sector. Revenue collection and reinvestment mechanisms are largely unclear.
- There is a serious lack of human and institutional capacity in the whole sector (government, NGO institutions and service providers) due to the flight of skills. There is very low to manage peri-urban settlements.

- Poor hygiene promotion is a serious issue in both urban and rural areas. There has not been much attempt to promote the beneficiation of faecal products (e.g. the use of faecal sludge in biogas production).
- Currently, even the installed conventional sewage treatment systems in most urban areas are not fully functional, especially the BNR plants. The sewage is not being treated to acceptable standards and water bodies are polluted, which causes harm to the environment.

1.6 Policy framework: sanitation policies with a bearing on FSM in Zimbabwe

The WASH sector has undergone numerous changes during the last 30 years. Currently, sanitation responsibilities are defined in several Acts of Parliament, including:

i. Rural District Councils Act
ii. Urban Councils Act (which makes it mandatory to have water and sewerage access before a house is built)
iii. Town Planning Act, whose custodian is the Ministry of Local Government, Rural and Urban Development (MLGRUD)
iv. Housing Standards Act (Ministry of Local Government, Rural and Urban Development (MLGRUD)
v. The Public Health Act (Ministry of Health and Child Welfare; MOHCW) which stipulates that every household should be provided with a toilet and gives powers to act on any forms of public nuisance through prosecution
vi. Water Act (Ministry of Water)
vii. Environmental Management Act, which deals with prosecution of those who discharge raw sewage into water bodies. The treatment and discharge of wastewater is regulated by the Pollution Control Regulations; however this has not always been enforced, leading to discharge of partially treated effluent into the environment.
viii. The model building bylaws for each urban local authority are set as good standards of practice with respect to all facilities, including sanitation facilities, such as drainage provisions. Local bylaws prohibit BVIP latrines in urban areas. Other bylaws target specific issues such as open defecation, safe sanitation and lack of cleanliness and hygiene.

However, currently there is no harmonised WASH Act. A draft National Sanitation policy document was produced in 2004 but was not ratified, and a National Sanitation and Hygiene strategy document was produced in 2011. A National Water Policy (2013) is now in place but does not mention sewage or faecal sludge explicitly.

Currently, there is no clear policy/legislation for peri-urban settlements. It is also not clear whose responsibility specific settlements are, although ultimately, it is envisaged that they will be incorporated into the structures of the nearest urban local authority.

The sanitation services afforded to the urban population of Zimbabwe is primarily flush toilets. Bucket (pour flush) systems used to be permissible in urban areas but have now been phased out over the last few decades. Urban sanitation standards in Zimbabwe are set and controlled through a variety of legislative mechanisms. Legislation with a bearing on sanitation and pit latrines (and by implication sludge management) includes: the Zimbabwe National Water Authority (ZINWA) Act, the District Development Fund (DDF) Act, Mining Health and Sanitation Regulations, the Provincial Council and Administration Act, and the Traditional Leadership Act.

In terms of these regulations, local authorities are compelled to provide waterborne sanitation in all urban areas. Any attention given to wastewater treatment and sludge management is indirect and related to effects of discharges on water quality in the Water Act and the EMA Act. The water must be approved by the MOHCW, who must also be satisfied with the standard of sanitation provided. Consequently, urban areas classified as towns or cities are not permitted to have pit latrines of any kind as a sanitation option for housing.

Under the Public Health Act, government has the power to rectify an illegal health-threatening situation and recover costs from the offender. Under the cited legislation, pit latrines in urban areas qualify as illegal health-threatening structures. If government systems are not functioning well, the MOHCW can advise; prosecute; rectify; or close the premises, with the latter reaction being deemed the most persuasive. There have been many examples, including hospitals and other institutions where the MOHCW has applied this regulation to temporarily close premises which had violated this Act. Chitungwiza town council is on record as having sought permission from the MOHCW to deviate from the Housing Standards Act and use pit latrines in urban areas but was refused permission and compelled to install waterborne sewerage for all new housing developments (IWSD, 1997). This aversion to pit latrines is prevalent although Zimbabwe has in the past spearheaded WASH technology development and innovations through public and private partnerships. Rather than abandon pit latrines altogether, the sector should build on these historical achievements.

Waterborne sanitation advocated for by Zimbabwean legislation is very reliant on water. Current experiences point towards a pressing challenge related to reliability of water supply and the efficiency of operation of wastewater collection systems. Waterborne sewerage has inadvertently failed due to inadequate water supply, old facilities, low investment into wastewater treatment, overloading and intermittent power outages.

The Blair Ventilated Improved Pit Latrine (BVIP) is arguably the most widely-promoted both at home and abroad. It is a Zimbabwean-developed latrine, developed by the Blair Research Institute, now called the National Institute of Health Research.

While local authorities must still follow the appropriate legislation and by-laws, they are given responsibility for service provision to the legislated standards in the face of serious challenges. However, they do not have any technical agency, policy guidelines or other technical support for issues pertaining to sanitation. However, responsibility for sanitation management does not fall clearly within any government agency (IWSD, 1997). Larger urban councils usually have better capacity and technical knowledge while smaller local authorities generally lack the technical capacity to make informed decisions.

1.6.1 Institutional framework in WASH sector

The structure of the WASH subsector consists of the Ministerial Committee, National Action Group (NAC) and National Coordinating Unit (NCU) (Figure 1-10). The lead implementing agencies are the

Ministry of Health and Child Welfare (MOHCW), Ministry of Water Resources Development and Management (MWRDM), Ministry of Transport Communications and infrastructure Development (MoTCID), Ministry of Agriculture (MoA) and Ministry of Local Government, Rural and Urban Development (MLGRUB). The chair of these agencies is a member of the NAC. In lower hierarchal administrative units (i.e. provincial, district and sub-district levels), the NAC structure is replicated through WASH sub-committees responsible for planning, implementation and coordination. However, there is no legal instrument to back up the NAC structure. In urban areas, sanitation provision is the responsibility of local authorities. There is no clear specific policy on peri-urban areas that addresses their long-term institutional, financial and service level challenges.

1.6.2 Institutional framework in informal settlements

Institutional issues directly affect the provision of sanitation and subsequent sludge management in informal settlements. Because informal settlements are considered illegal and non-permanent, they are given low or no priority in local authority and government programs. There is no comprehensive national policy that clearly outlines the rules governing the provision of sanitation services and the roles and responsibilities of different agencies in informal settlements.

Government's interaction with informal settlements sends mixed signals due to unclear policy. Although settlements are illegal, councils normally adopt a "hear no evil, see no evil" approach to what is in their backyard. Some of these settlements are actually created as temporary holding camps by the government, and administrative policy and structure of service provision is unclear. Dzivarasekwa Extension, Porta Farm and Hatcliffe are examples of settlements established by the government to house people relocated from squatter camps. In addition, although these settlements are just at the edge of cities and towns, administratively most of them fall under rural district councils.

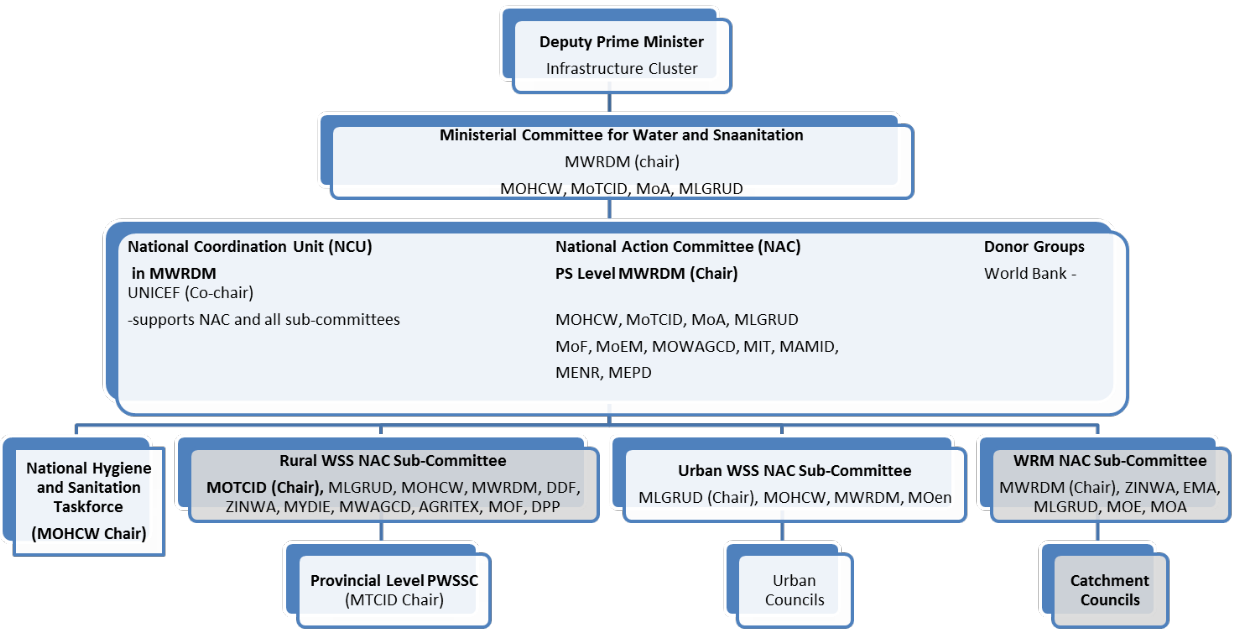

Figure 1-10: Institutional framework in the WASH sector (2010-2013)

1.6.3 Towards reform in the sanitation sector

With respect to latrine technology, the BVIP latrine has remained the technology of choice with policy makers, although this is relegated to rural areas. This has effectively blocked any other forms of innovation, thereby curtailing incremental sanitation improvements at the national policy level. This has also led to unwillingness and lack of openness to new innovative technologies by the policy makers (IWSD, 2010). However, non-governmental agencies have repeatedly turned a blind eye to legislation and introduced various pit latrine technologies in poor urban and peri-urban areas.

1.7 Perceptions on the use of pit latrine/sewage sludge

1.7.1 Household survey on use of human waste

Previous studies suggest that smallholder farmers have accepted the use of composted human manure and sewage sludge in crop production (Guzha, 2004). This is corroborated by intensive vegetable production in and around sewage treatment works in the urban areas (e.g. Crowborough Treatment Works in Harare; Gimboki Sewage Works in Mutare). Surveys on awareness of biogas technology in the suburbs of Hatcliffe, Whitecliffe and Epworth have shown that there are fewer (<20% of the respondents) who are aware of the biogas technology (Sibanda et al., 2013). It was established that the majority of the respondents (82%) would not have any problems with the use of human waste for generating fuel for cooking. In these suburbs, most respondents had been informed about the importance of faecal matter for fertilizer and energy production by non-governmental organisations. Those who indicated problems related to use of human waste for generating fuel and in crop production were concerned about the spread of diseases that could affect their health.

1.7.2 Socio-economic characteristics of the households in suburbs without sewer systems

Studies by Sibanda et al. (2013) have shown that households without sewer systems have low income of less than USD200 per month. The reason for the low levels of income is that most of the respondents are self-employed (i.e. they were mainly informal sector traders). Household size is between two to four persons. This agrees with Harare's average household size of four persons from the 2002 population census (CSO, 2002). This implies that most households are composed of spouses and their children. Most of the children are below the age of 15 years. This may have implications for involving schools in waste management and energy production.

1.8 Sanitation and FSM practices in selected towns and cities in Zimbabwe

1.8.1 Harare

Harare City has a population of about 1.4 million. Until the year 2000, almost all the city's residential and industrial properties were served by waterborne sewerage. The sewage from larger stands (generally 2000 m^2 and above) is treated on site in septic tanks, while small and medium density stands are discharged into sewers. Sewers transport the sewage to five WWTWs, namely Crowborough (BNR and TF), Firle (mainly BNR), Hatcliffe (BNR), Marlborough waste stabilisation ponds (WSP), and Donnybrook WSP.

Traditionally, the WWTWs have treated wastewater to very high standards. However, the economic challenges of the last decade have resulted in poor maintenance of the infrastructure, resulting in poorly treated wastes being discharged into the receiving rivers. Within the city itself, the aged sewerage infrastructure often breaks down due to overloading and blockages (Figure 1-11), and this is often made worse by an erratic water supply system and lack of reliable electricity (where the sewage must be pumped).

Figure 1-11: Overflowing manhole in Harare

Figure 1-12: Children play with stagnant raw sewage in Harare's Machipisa

1.8.1.1 Disposal of treated sludge

It is common practice at Harare's WWTWs to collect and bury screenings. Biodegradable screenings have also been mixed with primary and secondary sludge and digested in huge on-site digesters. However, some digesters have not worked for some time, resulting in screenings being simply buried on site. Primary and secondary sludge from the BNR and TF processes along with treated sludge from digesters have often been pumped to the so-called sewage farms and used for the irrigation of cattle pastures. This has been the practice at Firle and Crowborough WWTWs. However, the current challenges have arisen from the fact that some sewage farms have now been converted to housing estates, thus limiting the land available for sludge disposal. Currently, there are no functional drying sludge beds at Harare's WWTWs; thus, no dried sludge is available.

1.8.1.2 Disposal of WWTW effluent

Site visits indicated that some effluent from WWTW in Harare is used extensively for growing agricultural and horticultural crops at small scale plots around the sewage works, such as Firle and Crowborough. Here, crops and vegetables such as tomatoes, onions, rape, cabbage and maize are grown throughout the year. The produce is sold in leading supermarkets in the city, although this origin of the crops is not often publicised by the retail outlets for fear of scaring away customers. The safety of this partially-treated wastewater in terms of its potential for transmission of waterborne diseases to the vegetable farmers and the ultimate consumers of the produce has not been studied in depth. In addition, the long-term effects of heavy metals and other materials originating from industrial sources have often not been established. While overflowing sewers within Harare have caused headaches to city engineers, some residents have opted to use both the untreated and treated wastewater for urban farming (Figure 1-13).

FIGURE 1-13: VEGETABLE PRODUCTION IN SANDY SOILS USING SEWAGE SLUDGE IN MASVINGO. BRASICCAS (*LEFT PHOTO*) AND PUMPKINS (*RIGHT PHOTO*) ARE THE MAIN CROPS GROWN AT THIS SEWAGE TREATMENT WORKS SITE.

Most of the new settlements in Harare (e.g. Hopley, Caledonia, Whyte Cliff and Southley Park and Government's Garikai/Hlalani Kuhle Housing initiatives) are not connected to the city's sewerage and water network. The lack of simple authorised appropriate technologies to collect and treat wastewater in new developments in the peri-urban areas has resulted in low coverage by conventional sewerage systems in informal settlements, mainly because the technologies adopted for Zimbabwe are expensive to install and maintain. This has led residents to resort to other methods such as pit latrines, ventilated pit latrines and open defecation, which may expose the residents to health hazards if not properly managed. These sanitation facilities are not recommended in urban areas according to the Urban Councils Act. In addition, parallel development, a mechanism put in place to allow residents to construct their dwelling units while they stay on the properties before servicing, has led to the use of sanitation facilities such as pit latrines and ventilated pit latrines. Moreover, some residents have installed septic tanks on stands as small as 200 m^2, which is against the urban building bylaws of most cities in Zimbabwe.

In Dzivarasekwa Extension, communal Blair latrines, which were constructed in 1992, filled up due to the increase in population, which led to the residents to use the bush for defecation (Mvuramanzi Trust, 2002). Urine diversion toilets were then constructed, which diverted the urine to irrigate sugar cane plants while the faecal matter was deposited in a container at the base of the toilet. In order to reduce odour and accelerate decomposition, soil and ash were added to the faecal matter with each deposit and then this was either further composted in plastic bags or in pits. The decomposed faecal matter could be used to grow plants. Most families, however, preferred to bury the faecal matter and ash (Mvuramanzi Trust, 2002).

Site visits to the informal and peri-urban settlements in and around Harare such as Epworth, Hatcliff and Hopley showed that the distinguishing feature of these settlements is lack of land use planning and water and sewer reticulation systems. In these areas, the great majority of residents rely on pit latrines for sanitation. The latrines consist of a 1.5 to 3-metre-deep pit dug behind the house, with brick, corrugated sheet or plastic material walls built around it for privacy (Figure 1-14). The pit latrines do not have the features necessary for eliminating odours and flies. The structure is often not roofed and frequently when in use, users' heads and torsos can be seen, especially if they are relatively tall.

Figure 1-14: Makeshift pit latrine

Currently, there is no policy in place on the emptying of pit latrines. Most of the settlements are not more than five years old and the pits have not yet filled up, but a crisis is looming as the pits may fill up soon. The current practice is that when a pit is full, the latrine is simply abandoned, and a new one is constructed adjacent to it. However, challenges due to space have been encountered given the small stand sizes.

1.8.2 Bulawayo

Sewage treatment is done mainly by the conventional (tricking filter) sewage treatment, modified activated sludge (MAS), and biological nutrient removal (BNR) methods, with plants located at different sites in the city. Sewage is treated through coagulation, flocculation, filtration and chlorination, and effluent from the plants is stored in ponds before being used for flood and sprays irrigation or discharged into various rivers. Effluent is also used for pasture and cereal irrigation at Umguza Plots, Luveve Gum Plantations, Khami prison Farm, Aisleby and Good Hope farms and for irrigation of eucalyptus tree plantations.

Treated solid sludge generates revenue, as it is sold to farmers at a price of USD6.71/ton. Average flows of sludge at treatment plant per month are approximately 406 000 m^3, yielding sludge production per month of 40 000 m^3 with all systems working. The annual estimate of this sludge is around 360 00 m^3.

Presently, the plants are 50% functional. This means most sludge is disposed of without adequate treatment. All high-density suburbs are connected to the sewer line except for some parts of Cowdry Park, which have onsite sanitation in the form of pit latrines. Low density areas and surrounding plots have septic tanks which are emptied when need arises.

1.8.3 Gweru

All high-density suburbs in Gweru are connected to sewer lines which empty to a hybrid sewage treatment plant consisting of inlet works, primary and secondary anaerobic ponds and biological tricking filters.

The output from the plant consists of liquid effluent and solid sludge. The liquid effluent is used to irrigate grazing farms and eucalyptus plantations. The solid sludge settles in digesters, where biogas is produced and allowed to escape into the air. The remaining solid matter is used as manure in gardens. Neither effluent nor solid sludge are sold to the public. At present, the sewage treatment plant operates below capacity because the infrastructure is dilapidated. This means the sewage does not get adequate treatment before being used for irrigation purposes.

In low density areas and surrounding plots, septic tanks are used to collect toilet waste and are emptied when they get filled up. There are no suburbs which use pit latrines within the Gweru municipality areas, which means there is high sanitation coverage in Gweru urban. There are no flow measurements of sewage and thus, sludge production cannot be quantified.

Sludge management policies are not known by city engineers. Desludging of sewers is done under excerpt the Urban Councils Act Chapter 29.15 and the regional Town and Country Planning Act Chapter 29.6, which compel all households to comply with accessible sanitation before an occupation certificate is issued. Other instruments used include the Public Health (effluent) and the Environment Management (Effluent and Solid Waste Disposal) regulations.

1.8.4 Chinhoyi

In the town of Chinhoyi, 115 km from Harare, there is a community which has been assisted by the NGO “Homeless People’s Federation” to build Sky loo and Fossa alterna latrines. These are dry composting toilets which are built to cater for a family of five. The Sky loo is urine diverting, while the fossa alterna is not. The Sky loo is constructed above the ground on top of a vault. Inside, it is fitted with a urine diverting pedestal consisting of two chambers; the smaller chamber collects the urine and the bigger chamber provides an entry for the faecal material to be deposited into the chamber below the latrine superstructure. The urine is drained from the small chamber by a pipe either into a container or into an underground drainage zone outside the toilet. Users add ash, soil or lime into the faecal chamber after each use. The ash is assumed to absorb moisture and also raise the pH of the latrine contents, to inhibit bacterial multiplication, fly breeding and odour generation. The soil also introduces flora and fauna which activate aerobic decomposition. When the faecal chamber is full, the humanure is removed using a spade and it is assumed that most of the pathogenic bacteria has died off. It is then applied to gardens or field plots.

A household of six can use each vault (roughly 1 square meter volume) for 1 year and 6 months, after which a layer of topsoil is put on top, the vault is sealed and left to compost for a further 6 months before the contents are extracted. The community is organised into a club, which attends to the management of these latrines, disseminates educational material and assists others with no latrines to set up their own.

1.8.5 Masvingo

Masvingo Municipality has a reticulated sewer system which uses the conventional (trickling filter) and biological nutrient removal (BNR) systems. In the conventional filter system, sludge (both domestic and industrial) is anaerobically digested and then passed through filters to remove the solids, which are then placed on drying beds. Effluent from the filter system is used to irrigate Eucalyptus plantations. Dried sludge is sold at USD 10/ton and USD15/ton (2012-13 prices) for the crushed and uncrushed, respectively. Most people who buy and collect sludge indicated that they use it for garden vegetables, lawn and field crop production. Sludge is sometimes re-sold to the farmers. At the sewage treatment works site, anaerobically treated sludge is applied to gardens for vegetable production. Gases generated from anaerobic digestion escape into the atmosphere.

1.8.6 Mutare

In Mutare, both the conventional (trickling filter) and BNR methods are used to treat sewage sludge at Gimboki Sewage Treatment works (Figure 1-15). An average of 236 mℓ/day of slurry is processed each day. Most of the infrastructure at the sewage works in Mutare and Masvingo has broken down, resulting in direct discharge of sewage sludge in the nearby streams and land. At Gimboki, slurry is used to irrigate and fertilise maize and bananas. No routine microbiological and nutritional assays for the sludge are being performed. Dried sludge is sold to farmers at USD 5/50 kg and USD 4/ton.

FIGURE 1-15: SEWAGE TREATMENT WORKS IN MUTARE – EFFLUENT IS USED TO IRRIGATE MAIZE CROPS AND BANANAS IN NEARBY FIELDS.

All urban areas visited in Zimbabwe do not have their own policies on sludge use and disposal. However, advice on crops which can be grown is usually given to farmers who use sludge for crop production. Farmers are discouraged from growing salad crops or any crops eaten raw or partially cooked in the fields where sewage sludge was applied. In Mutare, the demand for sewage sludge by farmers and traders has grown in recent years as evidenced by daily enquiries about this product. Informal interviews with farmers by some personnel at the Municipality of Mutare also revealed that dried sludge is mainly used as a fertilizer during the production of Brassicas (mainly covo). Due to the breakdown of some equipment at the sewage processing works, raw sludge is sometimes directly applied to the nearby fields.

1.8.7 Marondera

In Marondera, both on-site and off-site sewage treatment services are in use. On-site services involve emptying septic tanks in low to medium density areas, which is done at the request of the client. Off-site treatment uses the conventional and BNR methods. However, sewage treatment plants have not been working for the past ten (10) years. Sludge and effluent management involve the discharge of raw sewerage into streams at various points, relying on natural treatment by the stream and polluting the environment. Use of pit latrines is considered illegal, and where they do exist, they are temporary structures that would be demolished once proper structures have been erected. For this reason, the local authority does not have a policy document on the use of pit latrines. In Marondera, they were aware of the eco-san pit latrine but had not adopted the technology.

The aerobically treated effluent is used to irrigate pastures for livestock grazing at the municipal farm (Elmswood farm) but is not used for agricultural crops. Sludge collected in the process is then sent to drying beds where it is naturally dried into a cake under the sun. The dried sludge is sold at USD 5 per cubic metre and used for maize farming on small-scale farms.

1.8.8 Chitungwiza

In Chitungwiza, the bulk of the faecal sludge treatment is off-site at sewage treatment plants. However, the municipality has not been treating sewage for the past thirteen (13) years and relies on discharging raw sewage into the streams. When the system was working, the effluent was used to irrigate pastures at the municipal farm (Imbwa farm, Beatrice).

Most of the sludge that they manage has accumulated over the years in the ponds or drying beds. Disposal of sludge appears to be a challenge, as very few people appreciate how it can be used. Occasionally, dried sludge is buried because the municipality is sceptical about using it for agricultural purposes since it is untreated. However, when the plant was operating properly, the public (including fertiliser companies) were permitted to collect the dried sludge. There were also indications of lack of awareness or marketing plans to sell the sludge as manure.

Local authorities explained that allowing or promoting the use of pit latrines would result in unwelcome odours and the proliferation of flies and other disease vectors. In general, the municipalities do not have policy documents of their own but refer to the policies and standards of the Environmental Management Agency (EMA) of Zimbabwe. Routine characterisation of sewage is conducted by the municipality to monitor the presence of cholera, cysts and pathogens. The Town Engineer indicated that there were developments to invest in a biogas plant with the private sector and mentioned that they welcome any organizations willing to partner in such collaborations but certainly at no cost to the municipality.

2 Physico-chemical characterisation of faecal sludge in Harare and Chinhoyi

2.1 Introduction

The physical and chemical properties of faecal sludge are influenced by geographic location and user habits. These properties may affect the potential use of faecal sludge in agriculture and biogas generation applications. This study investigated the effects of geological distribution and socioeconomic factors on the quality of faecal sludge.

2.2 Objective

The objective of this study was to determine the physico-chemical properties of faecal sludge in peri-urban Harare and Chinhoyi.

2.3 Methods and materials

2.3.1 Study Sites

The study sites are located in Harare (Hatcliffe and Hopley) and Chinhoyi (Shackelton) (Figure 2-1) and differ in climate and geology. Hatcliff (31.114^{o}E and 17.67^{o}S) and Hopley (31^{o}E and 17.95^{o}S) have warm and wet summers and cool, dry winters. Average temperature and annual rainfall are 18^{o}C and 800 mm, respectively. Hatcliffe is at an average altitude of about 1560 m and Hopley at 1430 m. Although both sites in Harare have similar climates, they differ in geology. Hatcliffe lies on the Greenstone Belt, which consists of mainly mafic rocks, while Hopley is on the granitic rocks. The weathering of mafic rocks has resulted in the formation of dark reddish-brown clay soils, while granitic rocks have produced coarse grained sandy soils. Boulders and outcrops are common at both sites.

At Shackelton (30.03^o E and 17.30^o S) in Chinhoyi, average annual temperature and rainfall are 20^{o}C and 800 mm, respectively. The geology consists of dolomitic limestone, which overlies light brown clayey soils. The average altitude is about 1160 m.

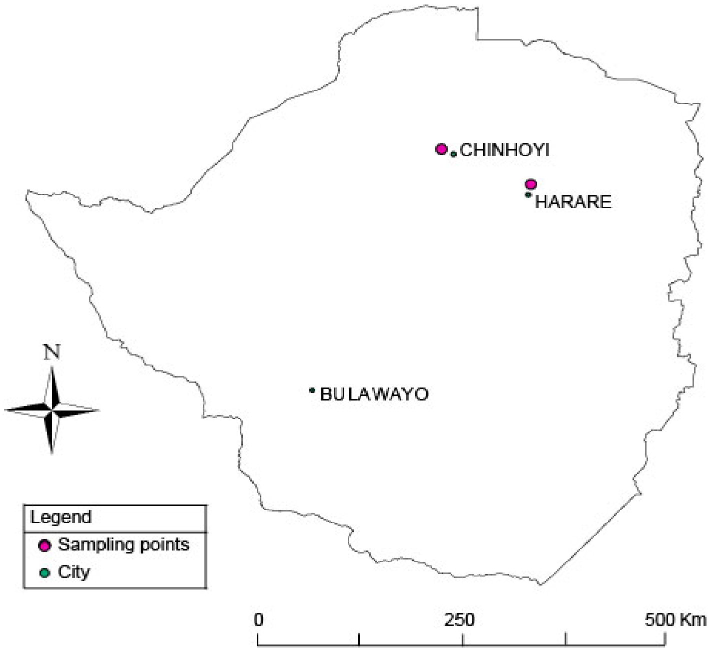

Figure 2-1: Location of study sites in Zimbabwe

2.3.2 Sampling procedures

At each location, pit latrines of similar age and depth were randomly selected for sampling. Household data (e.g. number of pit latrine users, diet, etc.) was also collected. Sampling was conducted using tools (Figure 2-2) designed by The Department of Agricultural Engineering, Chinhoyi University of Technology. After determining the depth of each pit latrine, triplicate faecal samples were taken at each of the top, middle and bottom depths of the pit. Samples were placed in 300-mℓ clear polythene vials (for chemical analysis) and 30-mℓ sterilized glass vials (for microbiological assays) and immediately sealed. The samples were then immediately placed in a cooler box and covered with ice. At the end of each sampling session, faecal samples were taken to the laboratory for analyses. A total of 24 samples was analysed for each of the physico-chemical and microbiological properties.

FIGURE 2-2: FIELD SAMPLING *(LEFT)* USING SPECIALLY DESIGNED PIT LATRINE SAMPLERS (*RIGHT*)

2.3.3 Laboratory analyses

The following analyses were performed: moisture content, total volatile solids, pH, electrical conductivity, total alkalinity, total coliforms, faecal coliforms, helminths, cysts, chemical oxygen demand (COD), biochemical oxygen demand (BOD), NO_3-N, total P, total cations and trace metals (Cu, Fe, Mn and Zn).

Moisture content was determined by oven drying at 105°C for 24 hours. Total volatile solids were determined by heating the oven dried (105°C) samples to 550°C for 1 hr. pH was determined using a glass electrode in a solid:water at ratio of 1:2.5 (weight: volume). Electrical conductivity (EC) was determined using a conductivity meter and the same solution ratio as in pH. Total alkalinity was determined by titration with dilute sulphuric acid.

For total coliforms, the most probable number (MPN) count and the multiple tube MacConkey broth methods were used. The spread plate method using MacConkey agar was used to enumerate faecal coliforms per millilitre. Eosin methylene blue agar was used to confirm the presence of faecal coliforms. The fermentation tube method gives the MPN, and if all dilutions are positive the MPN is greater than 1500/100 mℓ. The sludge was diluted to 10^{-4} and then used to inoculate the MacConkey broth and the spread plates. Where the dilution solution produced no growth on the plate, a lower dilution was used. Helminth eggs were isolated by flotation in concentrated sodium chloride (specific gravity of 1.19). The eggs were stained with grams iodine for better visibility and counted at **x**400 magnification using a Neuber counting chamber.

BOD was determined by incubation for 5 days at 25°C. Faecal samples were diluted in water, and dissolved oxygen measured using a dissolved oxygen meter. COD was determined using the potassium dichromate and silver sulphate catalyst procedure. Absorbance was read using a data logging spectrophotometer at 435 nm. Cations were determined by the atomic absorption spectrometer after digestion of the faecal sample with aqua-regia solution.

2.3.4 Statistical analysis

Means, standard error (SE) and percentage reduction for each parameter were computed for each digester using Microsoft Office Excel (2007).

2.4 Results and discussion

2.4.1 Household diet

Most residents (97%) who were interviewed at both study sites took at least two meals per day (i.e. breakfast and supper). Breakfast was usually served with porridge, sadza, tea and/or bread, and was taken at about mid-morning (9-11 am). Some respondents indicated that no lunch was taken and the time for breakfast was designed to cover lunch. Most residents could not afford milk, butter or bread due to low incomes. Supper was commonly served with sadza and green vegetables, dried fish or soya meal. Although no quantitative data was obtained about how much was consumed at each of the meals, it was assumed that inadequate food was taken each day due to low incomes.

2.4.2 Pit latrine dimensions

The dimensions of pit latrines sampled at all the study sites varied from 1.5-2.0 m long by 1-1.5 m wide by 1-1.5 m deep. These pits had been used for about 1 to 1.5 years, and the contents depth ranged from about 0.1 to 0.6 m below ground level. Some residents applied wood ash in the pit latrines to reduce odour and household flies.

2.4.3 Pit latrine contents

Apart from faecal sludge, there were a variety of items found in the pits, including sticks, newspapers, maize cobs, plastics and cloths (Figure 2-3). The majority of residents used newspapers for anal cleansing material. In some households without access to newspapers, sticks and shelled maize cobs are also used as cleansing material. About 10% of the residents in the study sites use pit latrines as dumping sites for any material.

Figure 2-3: Typical composition of extraneous material found in pit latrines in Hatcliffe, Hopley and Shackelton

The top layers were also characterised by the abundance of maggots, indicating the intense reproduction of the common housefly (Figure 2-4).

Figure 2-4: Pit latrine top layer showing characteristically high presence of maggots

2.4.4 Physico-chemical properties

At all study sites, the COD and BOD values were generally higher for the top layers than the middle and bottom layers (Table 2-2 and Table 2-6). These results indicated that the top layer still contained relatively higher percentage of undecomposed faeces than the bottom layers, as expected. These results showed that the substrate in general would be very suitable for anaerobic digestion and biogas production, even using material from the bottom layers. In addition, the results show that anaerobic treatment, which occurs at lower depths in the pit latrine, has an effect of reducing the COD and BOD of the sludge. Similar trends were observed for pH, which, in pits that had no ash applied, increased from the top layer to the bottom layers, possibly due to the presence of recently formed organic acids in the fresh faeces (top layer), and the raising of pH in the bottom layers as this acid was depleted due to anaerobic composition. Ammonification would also tend to increase the pH in the bottom layers. However, since wood ash is alkaline, it would be expected that its use in some pit latrines would increase the pH of the top layers. The geology and soils of the area likely also impacts the pH and other chemical properties. Except for relatively high levels of potassium in pit latrines for both sites, there was no apparent trend in concentrations of basic cations and trace metals (Table 2-3). Although total alkalinity was generally low, it would possibly still be sufficient to initiate and maintain satisfactory anaerobic digestion of the substrate.

Faecal sludge from all the study sites contained relatively high concentrations of plant nutrients (N, P, K, Ca, Mg, K) and high moisture holding properties, which can be harnessed for crop production (Table 2-3 and Table 2-4). In addition, the alkaline pH of the faecal sludge would neutralize acidic pH in sandy soils. Based on these properties alone, application of this sludge to the soil will potentially result in increased crop yield and the reduction of input costs by decreasing the quantity of inorganic fertilisers and lime.

TABLE 2-1: SELECTED PHYSICO-CHEMICAL PROPERTIES OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND HOPLEY

SAMPLE REF.	MOISTURE CONTENT (w/w)	TOTAL VOLATILE SOLIDS (w/w)	pH	TOTAL ALKALINITY (mg/ℓ)	EC (mS/cm)	COD (mg/ℓ)	BOD (mg/ℓ)	NO_3-N (mg/ℓ)	TP-P (mg/ℓ)
H1T*	1.47	0.85	8.02	444	16.4	12990	2435	84.0	37.3
H1M**	1.30	0.76	8.24	567	15.7	7740	1775	116.0	75.5
H1B***	1.34	0.91	8.54	465	19.3	8670	1525	72.0	71.5
H2T	3.05	0.54	6.05	420	14.8	16710	2755	140.0	112.5
H2M	3.16	0.61	7.18	510	21.2	8730	2660	40.0	41.5
H2B	1.65	0.54	7.76	264	15.4	7740	2750	100.0	73.8
H3T	12.6	0.75	7.01	148	12.3	22650	2585	88.0	6.65
H3M	10.2	0.35	7.09	264	11.6	23370	2495	88.0	5.71
H3B	3.72	0.27	6.08	270	17.2	10050	2460	100.0	10.2
H4T	3.87	0.40	7.33	270	16.3	21180	1480	96.0	105.9
H4M	3.71	0.46	7.02	300	20.9	8730	2535	280.0	52.4
H4B	4.45	0.49	7.69	270	10.9	5880	2745	92.0	80.6
P1T	1.26	0.22	6.83	426	11.1	10130	2350	76.0	13.2
P1M	0.93	0.21	6.67	375	10.4	9540	2210	94.0	14.8
P1B	0.81	0.24	6.57	284	4.2	9430	2090	45.0	15.4

SAMPLE REF.	MOISTURE CONTENT (w/w)	TOTAL VOLATILE SOLIDS (w/w)	pH	TOTAL ALKALINITY (mg/ℓ)	EC (mS/cm)	COD (mg/ℓ)	BOD (mg/ℓ)	NO_3-N (mg/ℓ)	TP-P (mg/ℓ)
P2T	0.91	0.81	7.43	550	16.2	12110	2540	36.0	11.1
P2M	0.87	0.56	7.30	544	14.7	10220	2365	58.0	15.6
P2B	0.89	0.36	7.33	387	13.8	11300	2020	42.0	22.4
P3T†	0.79	0.32	6.76	394	18.4	12870	2945	42.0	38.4
P3M††	0.68	0.26	7.95	237	12.1	11260	2990	28.0	70.2
P3B†††	0.69	0.21	7.43	129	14.1	8220	1040	18.0	89.3
P4T	0.76	0.52	7.65	880	20.1	9830	3125	55.0	32.6
P4M	0.67	0.41	7.40	605	21.6	9050	2770	64.0	28.2
P4B	0.81	0.17	6.91	340	22.4	9250	2845	42.0	29.2

HIT* - **Hatcliffe** site, pit **1**, **T**op layer HIM** - **Hatcliffe** site, pit **1**, **M**iddle layer HIB*** - **Hatcliffe** site, pit **1**, **B**ottom layer

P3T† - **Hopley** site, pit **3**, **T**op layer P3M†† - **Hopley** site, pit **3**, **M**iddle layer P3B††† - **Hopley** site, pit **3**, **B**ottom layer

TABLE 2-2: SELECTED PHYSICO-CHEMICAL PROPERTIES OF PIT LATRINE FAECAL SLUDGE FROM SHACKLETON, CHINHOYI

SAMPLE REF.	MOISTURE CONTENT (w/w)	TOTAL VOLATILE SOLIDS (w/w)	pH	TOTAL ALKALINITY (mg/ℓ)	EC (mS/cm)	COD (mg/ℓ)	BOD (mg/ℓ)	NO_3-N (mg/ℓ)	TP-P (mg/ℓ)
S1T	3.86	0.27	7.63	465	14.2	9330	2780	56.0	22.8
S1M	2.74	0.25	7.37	465	12.5	8340	2730	64.0	104.8
S1B	4.61	0.28	7.07	294	5.2	11430	2770	60.0	25.2
S2T	3.22	0.80	7.13	1350	15.1	10110	2840	48.0	107.1
S2M	2.81	0.54	7.70	540	16.8	10680	2965	76.0	34.6
S2B	2.95	0.34	7.81	375	16.8	13200	3020	60.0	32.5
S3T†	5.29	0.32	6.76	420	2.4	10980	2935	52.0	28.7
S3M††	1.08	0.34	7.95	180	11.1	10200	2900	56.0	92.3
S3B†††	1.01	0.30	7.43	1200	14.1	8220	1040	48.0	99.9
S4T	1.49	0.57	7.35	480	21.8	10830	3015	60.0	22.4
S4M	2.39	0.49	7.50	465	21.6	9030	2795	52.0	18.2
S4B	1.98	0.10	6.84	180	21.8	14250	2955	52.0	27.6

S3T† - **Shackelton** site, pit **3**, **T**op layer S3M†† - **Shackelton** site, pit **3**, **M**iddle layer S3B††† - **Shackelton** site, pit **3**, **B**ottom layer

TABLE 2-3: SELECTED CHEMICAL PROPERTIES OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND HOPLEY, HARARE

Sample REF.	Ca (mg/kg)	Mg (mg/kg)	K (%)	Na (mg/kg)	Fe (%)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
H1T*	3866	375	0.93	2201	0.39	1394	63	270
H1M**	6630	676	1.21	1825	0.73	1025	62	400
H1B***	3565	409	1.22	2966	0.40	12534	75	554
H2T	26252	3819	5.85	26028	3.79	4250	258	1917
H2M	15100	1718	4.41	9159	1.79	3390	151	695
H2B	4974	5789	1.29	2746	0.65	2595	114	401
H3T	17853	3668	5.65	89235	3.86	2618	126	353
H3M	6854	1141	3.25	27707	1.32	2379	116	276
H3B	521	90	0.43	2784	0.10	626	41	101
H4T	7570	991	2.88	7066	0.89	1309	79	678
H4M	5542	655	2.72	6758	0.55	865	59	443
H4B	1401	174	0.59	1063	0.18	695	24	179
PIT	4825	3498	0.92	3416	0.42	360	122	82
P1M	3144	3324	1.06	3048	0.36	296	136	62
P1B	3266	3088	1.12	3264	0.54	198	128	66
P2T	6654	1542	1.24	1335	0.48	320	118	98
P2M	7740	1584	1.10	1422	0.62	446	120	108
P2B	6882	1508	1.22	1390	0.53	490	140	104
P3T†	4296	1632	2.48	2200	0.56	263	250	118
P3M††	3934	1326	1.64	2137	0.62	233	230	93
P3B†††	3845	1208	1.44	1824	0.49	194	292	114
P4T	5248	864	1.36	3165	0.63	383	182	182
P4M	6601	992	0.95	2785	0.82	338	194	112
P4B	7416	1036	1.20	2595	0.72	424	166	116

HIT*- **Hatcliffe** site, pit **1**, **T**oplayer HIM** - **Hatcliffe** site, pit **1**, **M**iddle layer HIB*** - **Hatcliffe** site, pit **1**, **B**ottom layer

P3T†- **Hopley** site, pit 3, **T**op layer, P3M††- **Hopley site**, pit **3**, **M**iddle layer H3B†††- **Hopley** site, pit **3**, **B**ottom layer

P4T†- **Hopley** site, pit 4, **T**op layer, P4M††- **Hopley site**, pit 4, **M**iddle layer H4B†††- **Hopley** site, pit 4, **B**ottom layer

TABLE 2-4: SELECTED CHEMICAL PROPERTIES OF PIT LATRINE FAECAL SLUDGE FROM SHACKLETON, CHINHOYI

Sample REF.	Ca (mg/kg)	Mg (mg/kg)	K (%)	Na (mg/kg)	Fe (%)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
SIT	5004	1198	1.92	5813	0.53	250	49	429
S1M	3077	771	1.26	4088	0.58	186	36	423
S1B	24941	6091	6.00	39864	3.24	1909	291	2636
S2T	3674	576	0.42	1335	0.67	130	19	145
S2M	8760	1949	6.00	15257	1.30	586	120	1086

Sample REF.	Ca (mg/kg)	Mg (mg/kg)	K (%)	Na (mg/kg)	Fe (%)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
S2B	2852	508	1.82	6370	0.43	209	46	404
S3T†	5286	1755	3.56	5200	0.49	263	70	538
S3M††	1141	356	0.64	937	0.33	133	23	93
S3B†††	1945	268	0.77	1624	0.21	194	29	167
S4T	5461	668	1.67	4165	0.53	483	49	287
S4M	8601	990	2.50	5795	0.82	493	59	370
S4B	11713	1586	4.30	12065	1.12	815	99	696

S3T†- **Shackelton** site, pit 3, **T**op layer, S3M††- **Shackelton** site, pit **3**, **M**iddle layer S3B†††- **Shackelton** site, pit **3**, **B**ottom layer

S4T†- **Shackelton** site, pit 4, **T**op layer, S4M††- **Shackelton** site, pit **4**, **M**iddle layer S4B†††- **Shackelton** site, pit 4, **B**ottom layer

2.4.5 Microbiological properties

Selected microbial properties showed that all the faecal sludge samples, irrespective of depth, had high levels of faecal coliforms (Table 2-6). In general, the concentrations of total coliforms decreased from the top to the bottom layers. These trends suggest the death of total coliforms with depth, possibly due to the relatively reduced oxygen concentrations (anaerobic conditions) towards the bottoms of the pits and the depletion of substrate. The former observation suggests that anaerobic treatment has an effect of reducing these coliforms in faecal sludge. At all study sites, helminths were present in all samples (Figure 2-5), and their concentrations varied from pit to pit. However, cysts were not detected in Hatcliffe but were significantly high in Hopley and Shackelton (Table 2-5 & Table 2-6), which requires further investigation.

TABLE 2-5: SELECTED MICROBIOLOGICAL PARAMETERS FOR PIT LATRINE FAECAL SLUDGE (HATCLIFFE & HOPLEY, HARARE)

SAMPLE CODE	Total coliforms MPN/100 mℓ	Faecal coliforms/mℓ	Helminth ova/g	Cysts/g
HIT*	4.5×10^6	7.0×10^5	0	0
HIM**	2.0×10^4	1.6×10^3	1.06×10^4	0
HIB***	7.3×10^4	2.4×10^3	0	0
H2T	$>1.5 \times 10^9$	3.9×10^7	1.77×10^4	0
H2M	$>1.5 \times 10^9$	8.28×10^7	7.07×10^3	0
H2B	$>1.5 \times 10^7$	3.2×10^5	3.5×10^3	0
H3T	$>1.5 \times 10^9$	6.84×10^7	3.18×10^4	0
H3M	$>1.5 \times 10^7$	$1.2 \text{ X } 10^5$	1.2×10^4	0
H3B	$>1.5 \times 10^8$	1.38×10^6	1.77×10^4	0
H4T	$>1.5 \times 10^9$	2.46×10^7	0	0
H4M	$>1.5 \times 10^9$	2.32×10^7	3.53×10^3	0
H4B	$>1.5 \times 10^8$	2.8×10^6	0	0
P1T	$>1,5 \times 10^8$	1.7×10^6	0	0
P1M	$>1.5 \times 10^7$	1.8×10^5	0	0
P1B	$>1.5 \times 10^6$	2.0×10^5	0	0
P2T	$>1.5 \times 10^8$	2.24×10^7	1.0×10^3	0.2×10^2
P2M	$>1.5 \times 10^7$	5.2×10^4	1.1×10^2	0.5×10^2
P2B	$>1.5 \times 10^6$	5.0×10^5	0.8×10^2	0.4×10^2

SAMPLE CODE	Total coliforms MPN/100 mℓ	Faecal coliforms/mℓ	Helminth ova/g	Cysts/g
P3T†	>1.5 X 10^7	8.2 X 10^5	1.2 x 10^2	1.06 x 10^5
P3M††	>1.5 x 10^6	6.0 x 10^5	0	0
P3B†††	>1.5 X 10^6	3.6 X 10^5	0	0
P4T	>1.5 x 10^7	5.0 x 10^6	56	48
P4M	>1.5 x 10^5	3.2 x 10^5	32	3
P4B	>1.5 x 10^5	1.6 x 10^6	0	0

HIT*- **Hatcliffe** site, pit **1**, **T**op layer HIM** - **Hatcliffe** site, pit **1**, **M**iddle layer HIB*** - **Hatcliffe** site, pit **1**, **B**ottom layer

P3T†- **Hopley** site, pit 3, **T**op layer P3M††- **Hopley site**, pit **3**, **M**iddle layer P3B†††- **Hopley site**, pit **3**, **B**ottom layer

TABLE 2-6: SELECTED MICROBIOLOGICAL PARAMETERS FOR PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND SHACKLETON

SAMPLE CODE	Total coliforms MPN/100 mℓ	Faecal coliforms/mℓ	Helminth ova/g	Cysts/g
S1T	>1,5 x 10^7	1.14 x 10^6	3.53 x 10^3	2.47 x 10^5
S1M	>1.5 x 10^7	1.9 x 10^5	1.41 x 10^4	1.06 x 10^5
S1B	>1.5 x 10^7	2.0 x 10^5	1.06 x 10^4	0
S2T	>1.5 x 10^9	2.46 x 10^7	1.0 x 10^4	9.9 x 10^5
S2M	>1.5 x 10^7	4.8 x 10^4	1.41 x 10^4	3.53 x 10^4
S2B	>1.5 x 10^6	5.0 x 10^5	6.0 x 10^5	1.41 x 10^5
S3T†	>1.5 X 10^7	8.2 X 10^5	2.47 X 10^4	1.06 x 10^5
S3M††	>1.5 x 10^5	3.0 x 10^4	7.07 x 10^3	0
S3B†††	>1.5 X 10^6	2.8 X 10^5	0	7.07 x 10^4
S4T	>1.5 x 10^7	4.0 x 10^6	1.77 x 10^4	7.77 x 10^5
S4M	>1.5 x 10^5	2.0 x 10^4	3.53 x 10^5	3.53 x 10^4
S4B	>1.5 x 10^7	1.76 x 10^6	0	1.41 x 10^5

HIT*- **Hatcliffe** site, pit **1**, **T**op layer HIM** - **Hatcliffe** site, pit **1**, **M**iddle layer HIB*** - **Hatcliffe** site, pit **1**, **B**ottom layer

S3T†- **Shackelton** site, pit 3, **T**op layer S3M††- **Shackelton** site, pit **3**, **M**iddle layer S3B†††- Shackelton site, pit **3**, **B**ottom layer

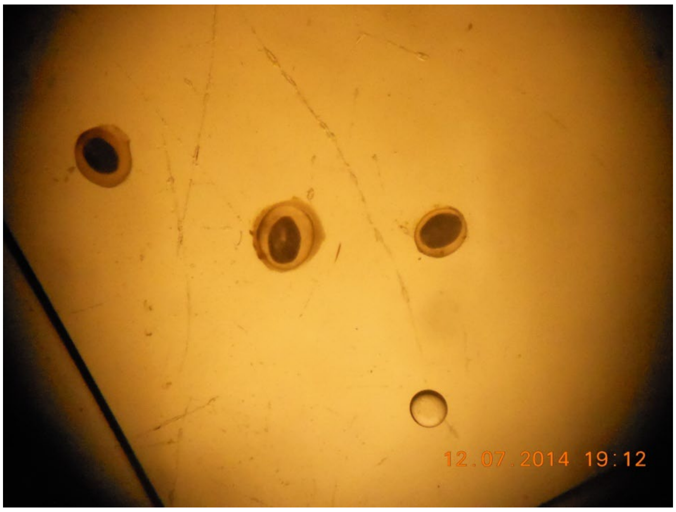

FIGURE 2-5: SLIDE OF HELMINTH EGGS ISOLATED FROM FAECAL SLUDGE IN HATCLIFFE. THE EGGS SEEN WERE TYPICAL OF CESTODES AND NEMATODES. PROTOZOAN CYSTS WERE ALSO ENUMERATED.

3 Developing solutions that result in beneficiation of sludge through reuse and application

3.1 Introduction

Pit latrines have been promoted as sanitation facilities in rural and peri-urban areas of Zimbabwe. Over the last 30 years, VIPs were the standard pit latrine promoted. Anaerobic digestion has been used to treat sewage sludge in numerous urban cities worldwide. The anaerobic digestion process occurs in the absence of oxygen and is mediated by a consortium of microorganisms, which perform different functions. During this process, biogas, consisting mainly of methane and carbon dioxide, is produced.

Besides its use in sophisticated sewage treatment works in urban centres, anaerobic digestion also has the potential to generate biogas from faecal sludge from simple pit latrines, which constitute the main form of sanitation in rural areas and peri-urban areas in developing countries. The biogas can be used as a fuel for cooking and for other household uses. Additionally, the sludge produced from the digestion process can be used as a fertiliser or soil conditioner. The quantity of biogas that is generated by anaerobic digestion depends on the physico-chemical properties of the feedstock. The users' diet and the presence of other pit contents could impact on the quantity and quality of biogas produced.

In addition to biogas generation, some pathogenic organisms are killed during digestion. For example, a large percentage of pathogenic organisms found in human faeces, such as *Escherichia coli* and helminths, are destroyed. This aspect is critical, as the digested sludge can then be handled safely during its use in agriculture. The efficiency of pathogen die-off depends on the environmental conditions (temperature, pH, time, etc.) at which the anaerobic digestion process occurs.

3.2 Objectives

The objectives of this study were as follows:

- To investigate the use of anaerobic technology to treat faecal sludge for biogas generation
- To investigate the potential of anaerobically digested faecal sludge as a soil amendment

3.3 Methodology

3.3.1 Sampling of faecal sludge

Samples were collected from pit latrines located in Hatcliffe and Shackelton from April to July 2015. Typical pit latrines in the study sites were made of brick or thatch grass with or without roof. Only top faecal samples in the pits were selected for use in anaerobic digestion, as they were fresh and showed relatively higher amounts of faecal coliforms, COD and BOD than the underlying layers. After sampling, the equipment used for sampling was sterilised by heat and sodium hypochlorite solution. Samples were immediately placed in cool boxes containing ice. The collected faecal sludge samples were stored in a refrigerator at 4^oC overnight until use in laboratory experiments for biogas production. The pit latrine faecal sludge was then homogenised before digestion using an electric blender to prevent separation as described by Badger et al. (1979). A 3.5 kg moist faecal sample was weighed and placed into each bioreactor. A 350 mℓ (10%) volume of rumen fluid inoculum (Ojolo et al., 2007) obtained from a nearby abattoir (The Cold Storage Commission, Chinhoyi) was added to each digester and thoroughly mixed by gently shaking.

3.3.2 Laboratory set-up of anaerobic digesters

The experiment was carried out in nine batch reactors at room temperature. The experimental set-up is shown below (Figure 3-1 and Figure 3-2). Plastic (HDPE) containers of 5-ℓ volume were used as bioreactors for the study. The experiment used a completely randomised design with three replications per pit latrine. A total of nine (9) digesters were used for each study site. Each digester bioreactor was fitted with gas delivery pipes (Figure 3-2) and jacketed with cotton wool to insulate the internal working temperature from ambient fluctuations. An airtight seal was then used to maintain anaerobic conditions. The reactors were shaken by hand at least two times a day for 2 to 3 minutes to even out the temperature, pH and microbial distribution.

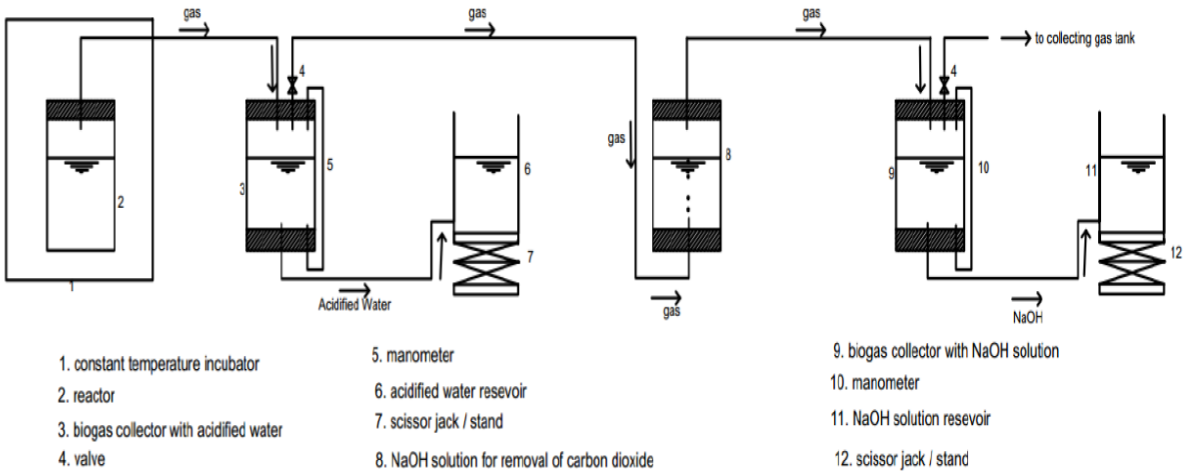

FIGURE 3-1: SCHEMATIC REPRESENTATION OF THE LABORATORY EXPERIMENTAL SET-UP FOR THE ANAEROBIC DIGESTION OF TOP-LAYER FAECAL SLUDGE.

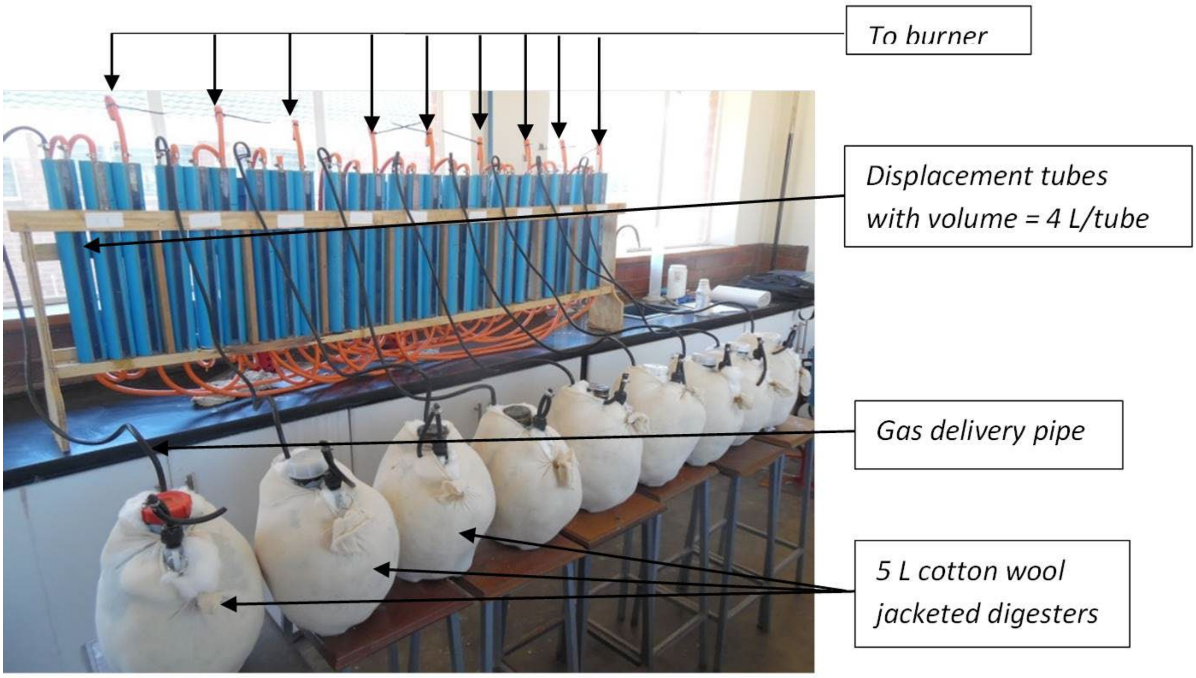

FIGURE 3-2: LABORATORY SET-UP OF THE ANAEROBIC DIGESTION EXPERIMENT - DISPLACEMENT TUBES ON EACH BIOREACTOR ARE (FROM *LEFT TO RIGHT*): ACIDIFIED (PH 2) WATER AND 0.05M NAOH

3.3.3 Gas measurement

Biogas production was measured by the downward displacement of acidified water (pH 2). The biogas was collected into the first displacement tube. This displacement tube was connected to the acidified water reservoir, which was maintained at pH 2. This lower pH reduced the solubility of CO_2 in water. When biogas bubbles entered the first tube (acidified water), they displaced water of an equivalent volume. The volume of the gas produced was calculated using Equation 1, under ambient temperature conditions.

$$V_{gas} = A_{tube} \times (L1 - L2) \quad \text{.........................} \quad \textbf{Equation 1}$$

where:

V_{gas} = volume of gas collected at the ambient temperature (m^3)

A_{tube} = cross-sectional area of the gas-collecting tube (m^2)

L1 = initial level of the water (m)

L2 = final level of the water after displacement (m)

The gas was further passed through 0.05M NaOH solution to measure the quantity of methane produced. The 0.05M NaOH was used in a subsequent container to absorb the carbon dioxide. Biogas was further passed through the second and third displacement tubes, each containing 0.05M NaOH solution to ensure that all the CO_2 was absorbed.

The volume of methane produced was equivalent to the volume of 0.05M NaOH displaced (Veeken & Hamelers, 1999). The pressure of the gas in the first and third displacement tubes was adjusted by raising or lowering the respective reservoirs. The gas volume reading was taken at zero-gauge pressure, that is, with the level of the liquid in the reservoir held at the same level as the water in the displacement tube. The gas pressure was determined using Equation 2.

$P_{gas} = P_{atm} - P_{vapour}$.......................... **Equation 2**

where:

P_{gas} = pressure of the gas (Pa)

P_{atm} = atmospheric pressure (Pa)

P_{vapour} = vapour pressure (Pa)

The quality of methane produced by the anaerobic digestion process was determined by comparing the volume of acidified water and 0.05M NaOH displaced. Equation 3 (Mahmoud, 2002) was used to calculate the percentage of methane in the biogas.

$$\% \text{ Methane} = \frac{\text{Displaced NaOH}}{\text{Displaced acidified Water}} x100 \quad \ldots \quad \textbf{Equation 3}$$

The gas volume measured during the experiment was corrected to standard temperature and pressure (STP) conditions using Equation 4. The ambient pressure was measured using a barometer mounted on a Geographical Positioning System device (GPS) and the ambient temperature was measured using a laboratory thermometer in accordance with Gastavson & Ahring (2000).

$$V_{STP} = Vm \frac{T_S \times P_M}{T_M \times P_S} \quad \ldots\ldots\ldots\ldots\ldots \quad \textbf{Equation 4}$$

where:

V_{STP} = volume of gas at standard temperature and pressure conditions (m^3)

V_m = volume of gas collected at ambient temperature (m^3)

P_s = gas pressure at STP (1 atm = 1.01325×10^5 Pa)

P_m = measured pressure of the gas (Pa)

T_m = measured ambient temperature (Kelvins)

T_s = temperature at STP (273.15 Kelvins)

3.3.4 Physico-chemical properties

3.3.4.1 pH, temperature, moisture content and total solids

The pH of raw faecal sludge was measured using a pH electrode in 1:5 solution (w/v) ratio after correction of moisture content. Temperature was measured using an infrared reflector thermometer. Moisture content and total solids were determined by gravimetric methods as outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

3.3.4.2 Total volatile solids

The total volatile solids (TVS) content was determined by heating the samples in a muffle furnace for three hours as outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

3.3.4.3 Total alkalinity and volatile acid alkalinity

Total alkalinity (TA) was determined by titration with 0.1M NaOH for acidic samples and titration with 0.1M HCl for alkaline samples. Volatile acid alkalinity (VAA) was determined by titration with 0.1M NaOH for acidic samples and titration with 0.1M HCl for alkaline samples. The volatile acid concentration was then determined by multiplying volatile acids alkalinity by 1.0 if the volatile acids alkalinity was less than 180 mg/ℓ and by 1.5 if the volatile acids alkalinity was greater than 180 mg/ℓ.

3.3.4.4 Biochemical oxygen demand

The biochemical oxygen demand (BOD_5) was determined by diluting samples of faecal sludge and then measuring initial dissolved oxygen. The samples were incubated for five days and then final dissolved oxygen was measured. Dissolved oxygen was measured using a dissolved oxygen probe.

3.3.4.5 Chemical oxygen demand

Chemical oxygen demand (COD) was determined by the oxidation of organic matter using potassium dichromate ($K_2Cr_2O_7$) in a strong sulphuric acid solution (H_2SO_4) and back titrating with ferrous ammonium sulphate.

3.3.5 Microbiological analysis

3.3.5.1 Total coliforms, faecal coliforms and *E. coli*

Total coliforms, faecal coliforms and *E. coli* were determined using a most probable number assay (MPN) method 8001A according to the USEPA (2000).

3.3.5.2 Helminth eggs

Helminth eggs were determined according to a modified Bailenger (1979) method. The number of eggs per litre was calculated using Equation 5 (Rachel et al., 1996):

$$N = AX/PV$$ **Equation 5**

Where:

N = number of eggs per litre of sample

A = number of eggs counted in the McMaster slide or the mean of counts from two or three slides

X = volume of the final product (mℓ)

P = volume of the McMaster slide (0.3 mℓ)

V = original sample volume (ℓ)

3.3.6 Statistical analysis

Mean, standard error (SE) and percentage reduction for each parameter were computed for each digester using Microsoft Office Excel (2007).

3.4 Results and discussion

3.4.1 Household diet

Most residents (97%) who were interviewed at both study sites took at least two meals per day (i.e. breakfast and supper). Breakfast was usually served with porridge, sadza, tea and/or bread, and was taken at about mid-morning (9-11am). In some cases, respondents indicated that no lunch was taken and the time for breakfast was designed to cover lunch. Most residents could not afford milk, butter or bread due to low incomes. Supper was commonly served with sadza and green vegetables, dried fish or soya meal. Although no quantitative data were obtained about how much was consumed at each of the meals, it was assumed that inadequate food was taken each day due to low incomes.

3.4.2 Physico-chemical properties

The physical and chemical characteristics of pit latrine faecal sludge before and after anaerobic digestion exhibited extreme variations (Table 3-2). These variations are attributed to the fact that no two individuals are alike in terms of their gut microflora and digestion efficiencies and likewise, no two pit latrines can contain similar sludge. This has also been observed in a number of earlier studies (Prescod, 1971; Um & Kim, 1986; Strauss & Heinss, 1997; Bakare et al., 2012). The differences in faecal sludge quality have largely been attributed to factors such as age of the sludge, user habits, geology, season, climatic conditions and the architecture of the on-site sanitation structure. In this study, for example, some pit latrines had no roof and were exposed to rain and atmospheric deposition, which impacts on the properties of sludge. Also, some residents added ash to the pit to control flies. Addition of ash to pit latrine faecal sludge normally increases the pH of contents to above 7.

There was a gradual decrease in the moisture content of the sludge during the 35-day anaerobic digestion. Moisture content (MC) is a measure of the amount of water in the pit latrine faecal sludge and greatly influences the anaerobic digestion process (Rees, 1980). Moisture is important both as a nutrient and/or for the facilitation of the exchange of nutrients, buffers and dilutes the inhibitors and spreads bacteria in niche areas (Christensen & Kjeldsen, 1989). The % MC values of the sludge used in this study were lower than the values (50-60%) recommended by Ham (1979) and Buvid, (1980) for efficient anaerobic digestion.

TABLE 3-1: SELECTED PHYSICO-CHEMICAL PROPERTIES OF PIT LATRINE FAECAL SLUDGE FROM THE STUDY SITES BEFORE AND AFTER (IN PARENTHESIS) DIGESTION

PARAMETER	HATCLIFFE PITS			SHACKELTON PITS		
	1	2	3	4	5	6
% Moisture	62.2±2.25	63.3±1.96	59.3±2.05	90.7±1.71	83.3±1.038	82.97±1.843
	(78.16±1.30)	*(78.4±2.02)*	*(76.7±0.99)*	*(69.8±0.28)*	*(77.0±0.31)*	*(79.0±0.09)*
%TS	37.8±2.24	36.7±1.97	40.7±2.05	9.3±1.71	16.7±1.04	17±0.310
	34.36±1.43	32.87±1.26	28.75±0.68	*30.3±0.266)*	*(22.7±0.301)*	*(20.7±0.085)*
%VS	34.4 ± 1.4	32.9 ± 1.3	28.8±0.68	54.5±0.503	32.5±0.611	44.4±0.361
	(28.9±1.53)	*(27±1.64)*	*(24.87±2.5)*	*(50.1±0.0265)*	*(30.2±0.04)*	*(41.1±0.11)*
TA (mg/ℓ)	4549±531.9	4649±411.6	6563±420.3	6649±631.9	6645±511.7	6563±520.3
	(4185±171.2)	*(4171±165.3)*	*4158±165.9*	*(6385±171.1)*	*(6371±164.9)*	*(6358±165.8)*
pH	7.5±004	8.1±006	6.3±0.49	7.49±0.12	8.67±0.03	6.79±0.15
	6.90±0.02	*7.3±009*	*6.1±007*	*(7.12±0.32)*	*(8.3±0.19)*	*(6.57±0.09)*
VAA (mg/ℓ)	1845±102.3	1886 ±176	980±103.6	1945±103	1986±178	1000±103.5
	(1020±102.5)	*(4006±189)*	*(8005±106)*	*(2020±103.6)*	*(5006±188.6)*	*(10005±106.7)*
COD (mg/ℓ)	23643±238.4	19689±175.6	14403±430	25647±4638.9	18403±4 621.6	15413±4 638.7
	13600±800.46	*13745±500.74*	*13627±302.89*	*(16670.6±4698.6)*	*(11961±4672.3)*	*(10011.95±4631.4)*
BOD (mg/ℓ)	12560±602.3	13580.9±350	11421.7±118.9	14680±1098	13721±1 086.1	13460±1 085.5
	8700.2±115.28	*7800±111.35*	*6926.47±260*	*(9 868±902.4)*	*(8 946±907.6)*	*(8 530±898.6)*

3.4.3 Anaerobic digestion of pit latrine faecal sludge

3.4.3.1 Methane production

The volume of methane produced in each digester was monitored daily over a 35-day period. Gas production in all the digesters started on the third day of the digestion process (Figure 3-3). This lag was attributed to the time required for the re-establishment and adaptation of the sludge degrading microorganisms, especially those pitched from the cow rumen to the environment. Gas production increased steadily with an increase in temperature up to day 15, when it reached peak levels and thereafter gradually decreased during the whole course of anaerobic digestion (Figure 3-3). The values were different depending on the sludge used. The decrease in gas production was attributed to the exhaustion of the substrate. It was also noted that peak biogas production coincided with a decrease in pH. This trend suggests the formation of acids (e.g. acetic acid), which were then used for the synthesis of acetate, a substrate for methane production by the acetotrophic methanogens.

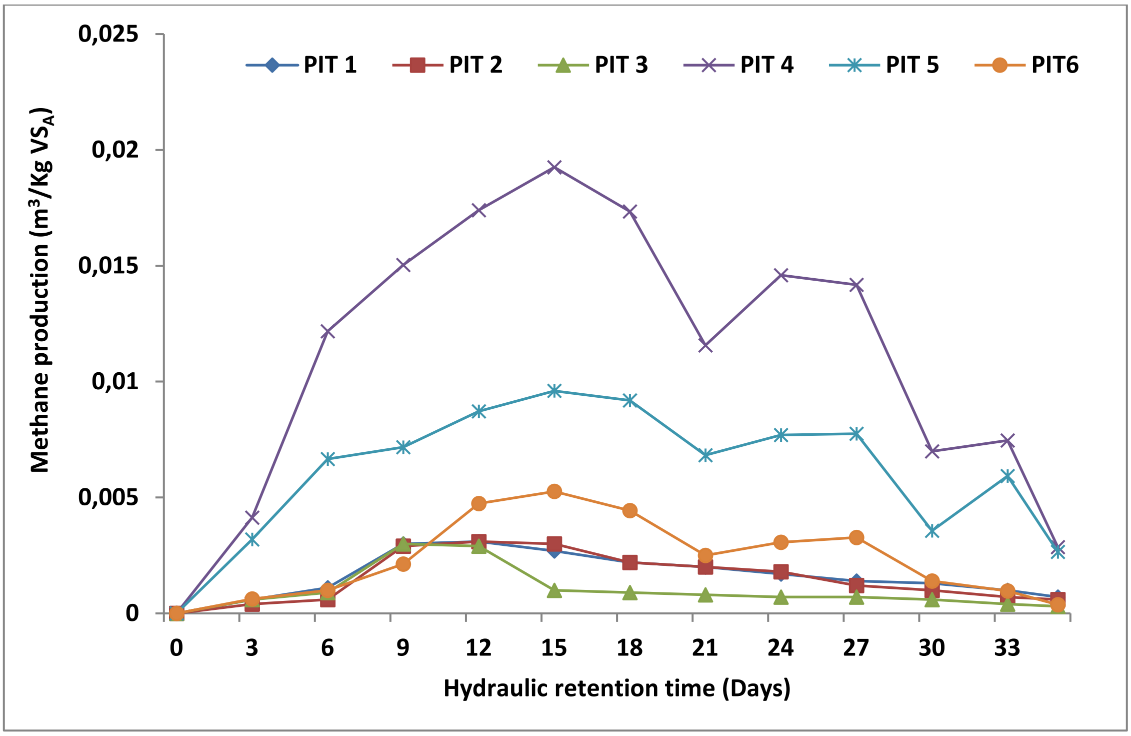

FIGURE 3-3: DAILY METHANE PRODUCTION FROM ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFF EXTENSION AND SHACKELTON

Relatively larger volumes of methane were generated with pit latrine faecal sludge from Shackelton (pits 5, 6 and 7) than those from Hatcliffe (pits 1, 2 and 3). These differences could be due to relatively higher COD and BOD for Shackelton than Hatcliffe (Table 3-1).

Cumulative gas produced by the pit latrine faecal sludge ranged from 0.013 to 0.021 m^3 methane and 0.029 to 0.134 m^3 for Hatcliffe and Shackleton, respectively (Table 3-2). The wide variation of methane produced within the same location reflects the varying diet of households, pit latrine contents, and climatic conditions. The results of the current study are comparable to the findings by Nagamani and Ramasamy (2002), who reported that human waste produces 0.028 m^3/kg VS_a. The amount of methane (m^3/kg VS_a) produced in this study was also comparable to that produced from chicken manure (0.011 m^3/kg VS_a), but lower than that produced from cow (0.36 m^3/kg VS_a) and pig (0.18 m^3kg VS_a) manure (Nagamani & Ramasamy, 2002). The quality of the sludge was also affected by maggots and decomposing thatch grass that was mixed with soil, which completely changed the purity of the sludge and the course of decomposition.

TABLE 3-2: METHANE PRODUCTION BY ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE DURING A 35-DAY PERIOD

Location	Pit Reference	Cumulative methane production (m^3)	Daily methane production (m^3/Kg VS_a)
Hatcliffe	Pit 1	0.021±0.00301	0.014
	Pit 2	0.0195±0.0059	0.013
	Pit 3	0.0128±0.0090	0.0085
Shackelton	Pit 4	0.1342±0.0098	0.0894
	Pit 5	0.0725±0.0011	0.0483
	Pit 6	0.0286±0.0012	0.0190

3.4.3.2 Trends in physico-chemical properties during anaerobic digestion

3.4.3.2.1 pH

The pH of the digesting samples affects the activity of methanogenic bacteria (Augenstein et al., 1976). The pH of the raw faecal sludge ranged from 6.3-7.5 and 6.8-8.7 for Hatcliffe and Shackelton, respectively (Table 3-1). These values are conducive for the production of methane from biodegradable organic matter (Deublin & Steinhauser, 2008). The addition of wood ash in pit 5 likely caused the influent pH to be higher as compared to pits 4 and 6 found in the same location. At Shackelton, in addition to the influence of ash, the near neutral to alkaline pH values were attributed to the dolomitic parent material, which increases pH.

During anaerobic digestion, there was a general trend of decreasing pH from the beginning of the digestion due to accumulation of volatile fatty acids formed by the hydrolysis process (Figure 3-4). The lowest pH values, which coincided with the lowest daily methane production, were observed between days 14 and 17 of digestion for all the pits in both locations. The pH range, however, still remained within the optimum range for methane production. A rise in pH of the digesting samples after day 17 can be explained by the ammonification process, which compromises methane production. The highest methane production was from pit 4, which had the lowest pH profile during the course of the digestion.

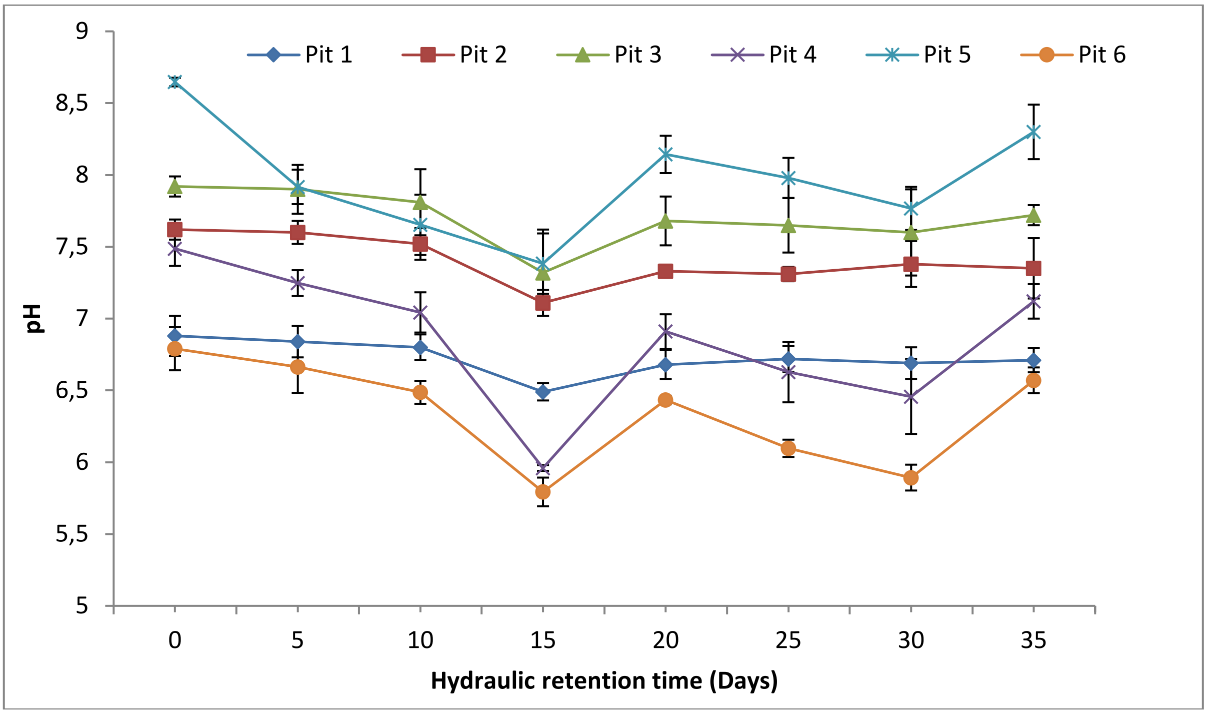

FIGURE 3-4: pH CHANGES DURING ANAEROBIC DIGESTION OF FAECAL SLUDGE FROM HATCLIFFE AND SHACKELTON

3.4.3.2.2 Temperature

Unlike trends for pH, there was a rapid increase in temperature from the onset of the digestion process (Figure 3-5). The maximum production of methane occurred at between 28-30°C, and the trends are similar to those reported in previous studies, that a rise in sludge in sludge temperature results in a corresponding increase in anaerobic digestion in the mesophilic range (Adrianus et al., 1994; Speece, 1996).

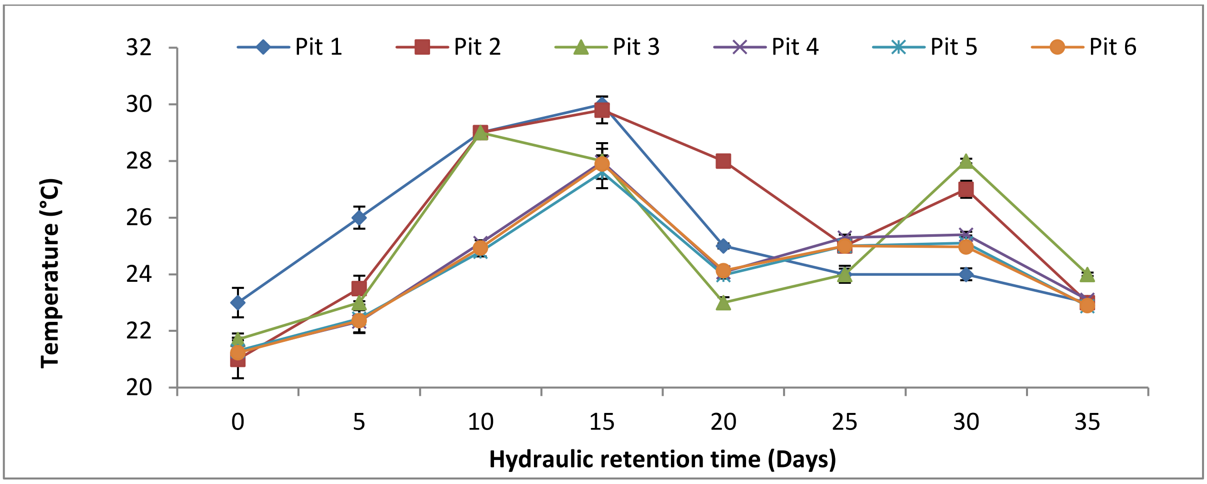

FIGURE 3-5: TEMPERATURE CHANGES DURING ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND SHACKELTON

3.4.3.2.3 Volatile solids

The volatile solids content was measured to determine the organic fraction of total solids, which was useful in the determination of the biodegradability of the pit latrine faecal sludge. It was calculated in terms of TS. The initial %VS content ranged from 28.8±0.68% to 54.5±0.503%, with a mean of 41.7%. The final %VS ranged from 24.9±2.5 to 50.1±0.027%, with a mean of 37.5%. The %VS decreased with anaerobic digestion (Figure 3-6). This supports the hypothesis by Buckley et al. (2008) that faecal sludge undergoes a certain degree of stabilisation over time as the chemical potential in the sludge is unlocked into renewable energy. There was a significant variation ($p < 0.05$) in %VS in all the pits over the entire 35-day retention period (Figure 3-6). The results generally show low levels of %VS compared to 62% VS observed by Tilley et al. (2008). This was an indication of contamination, and when the sludge is discharged improperly or into water bodies untreated, it could cause oxygen depletion, leading to fish kill and the extinction of other aquatic life.

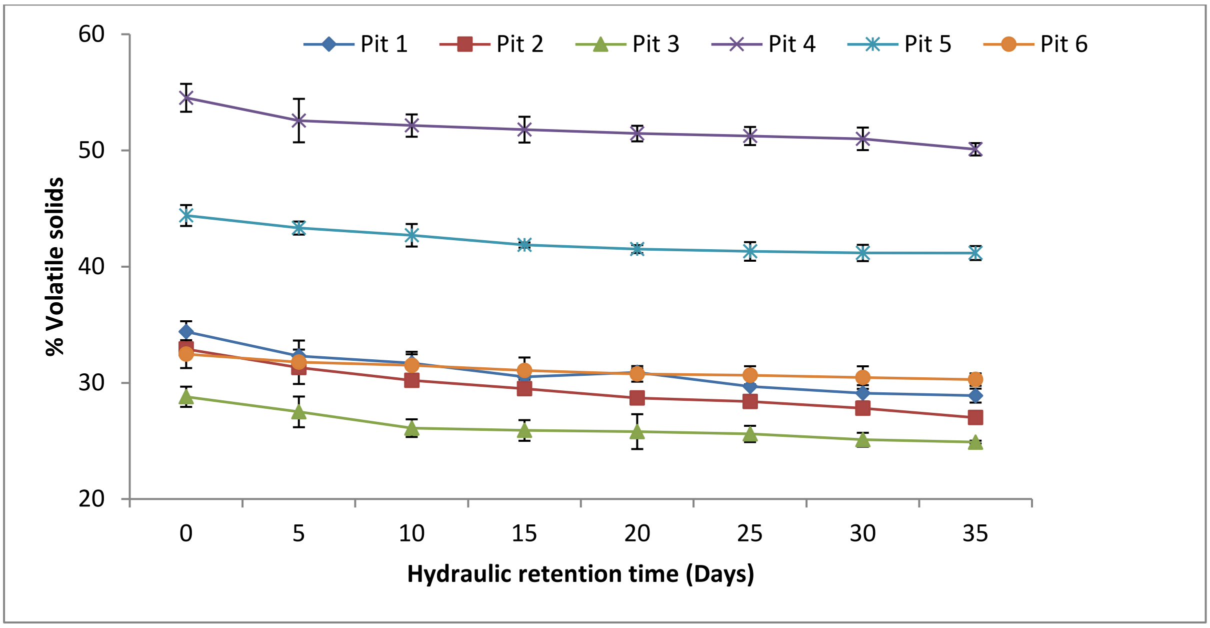

FIGURE 3-6: TRENDS IN VOLATILE SOLIDS CONTENT DURING ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND SHACKELTON

3.4.3.2.4 Chemical oxygen demand

The chemical oxygen demand (COD) was a measure of the oxygen equivalent of a fraction of organic matter in the sludge sample that could be readily oxidised. The COD was measured over the entire 35-day hydraulic retention period. The initial COD concentration ranged from 14 403 ± 638.7 mg/ℓ to 25 647 ± 638.7 mg/ℓ, with a mean of 20 025 mg/ℓ. The final COD concentration ranged from 11 011 ± 231 mg/ℓ to 16 670 ± 399 mg/ℓ, with a mean of 13 840.5 mg/ℓ. There was a gradual decrease in the COD values as the AD process progressed, and this indicated that the substrate got exhausted with anaerobic digestion process (Figure 3-7). The most significant decrease for pits 1, 2, 4, 5 and 6 were between days 15-20, and this period coincided with the peak production of biogas (Figure 3-3). The gradual decrease in COD in all the pits from days 25-35 after digestion was attributed to the stabilisation of the organic material as hypothesized by Buckley et al. (2008). Pit 3 showed the least decrease in COD, which was attributed to high contents of extraneous material.

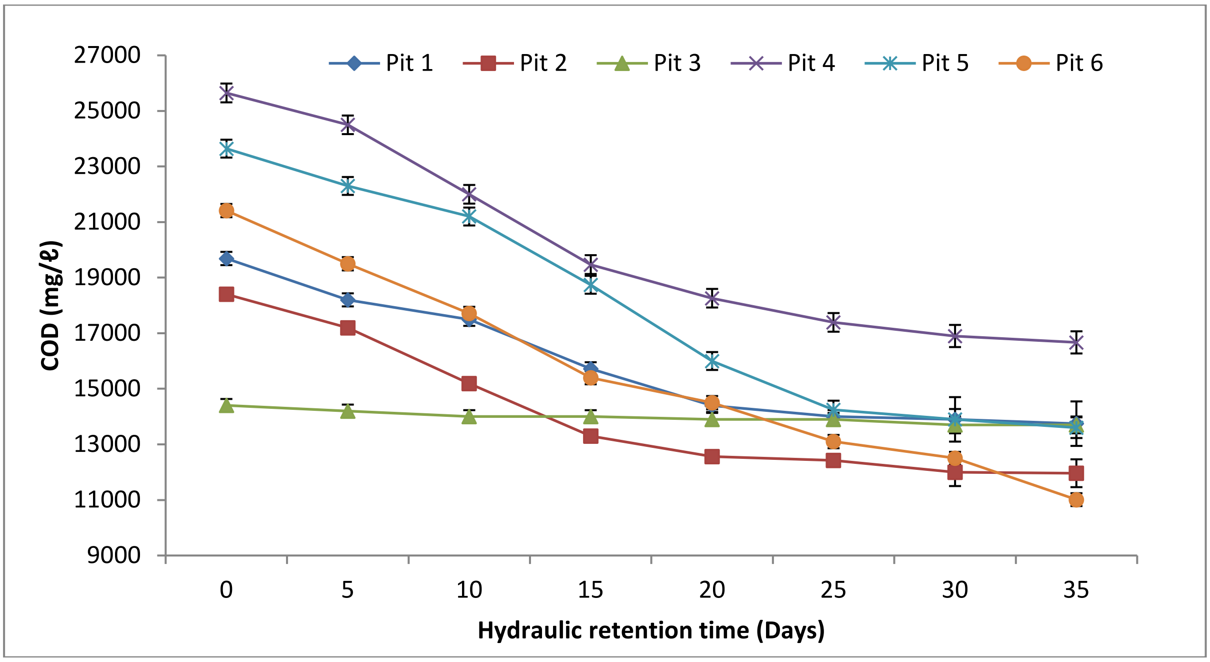

FIGURE 3-7: VARIATION IN COD DURING ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE FROM HATCLIFFE AND SHACKELTON

3.5 Microbiological properties

3.5.1 Total coliforms

The enumerated raw faecal sludge total coliforms (TC) ranged from 1.8×10^6 to 3.9×10^6 MPN/100 mℓ, with pits 4, 5 and 6 having the highest total coliforms (Figure 3-8). The AD process significantly reduced ($p<0.05$) total coliforms in each pit at both study sites. The significant reduction in total coliforms was attributed to an increase in temperature, changes in pH, microbial exo-enzymes and virucidal bacteria as previously reported by Dumontent et al. (1999). Generally, the percentage reduction in all the pits was low compared to previous studies, which recorded a 50-70% pathogen reduction (Saunders & Harrison, 2013; Issah et al., 2012) in mesophilic digesters. The numbers of TC in the digested pit latrine faecal sludge in all the pits still exceeded the WHO (2006) guidelines for restricted and unrestricted land application.

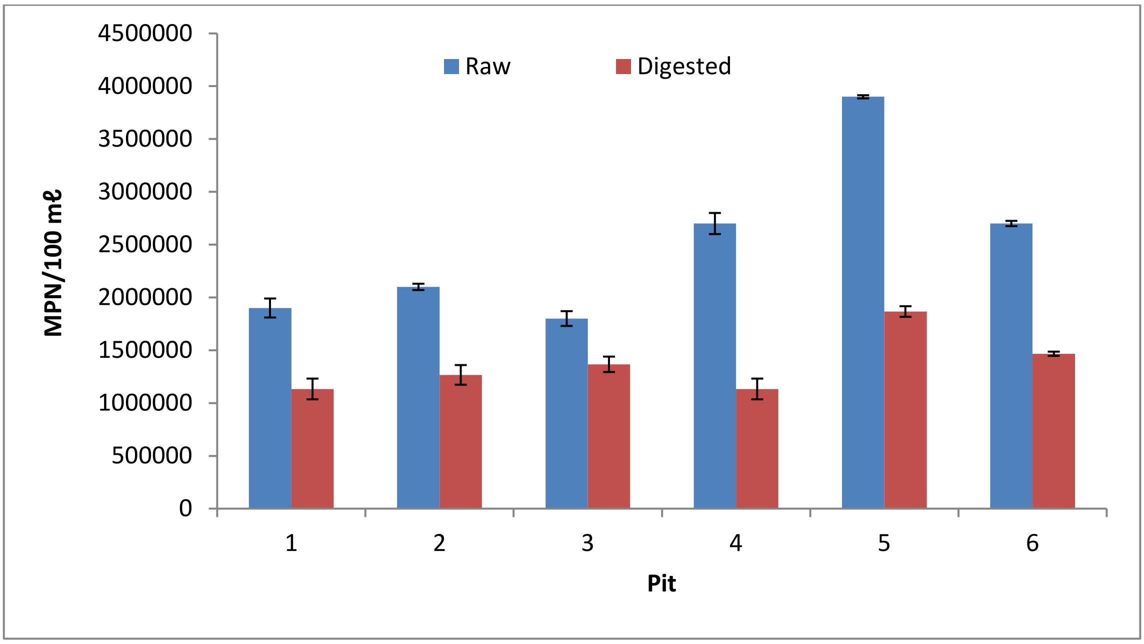

FIGURE 3-8: EFFECT OF ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE ON TOTAL COLIFORMS FROM HATCLIFFE AND SHACKELTON

3.5.2 Faecal coliforms

The mean faecal coliforms (FC) enumerated in the raw faecal sludge ranged from 7.66 x 10^5 to 2.8 x 10^6 MPN/100 mℓ (Figure 3-9). After the AD process, there was a significant reduction in FC in each pit at both study sites.

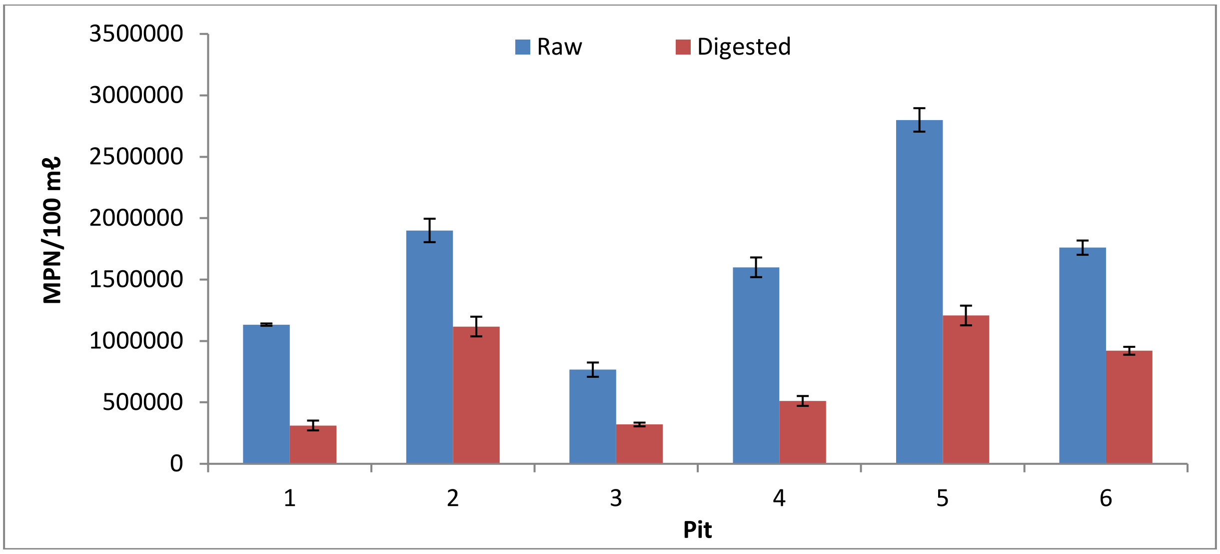

FIGURE 3-9: EFFECT OF ANAEROBIC DIGESTION OF PIT LATRINE FAECAL SLUDGE ON FAECAL COLIFORMS FROM HATCLIFFE AND SHACKELTON

The percentage reduction of FC in the effluent was comparable to findings by Saunders and Harrison (2013), who reported a 50- 70% pathogen reduction in mesophilic digesters at 50-70%. Although significant reduction of FC occurred in each digester during digestion, the number of FC still exceeded the acceptable standards of 10^3 CFU/100 mℓ (WHO, 2006) for use in agriculture and aquaculture.

3.5.3 *E. coli*

Human faeces naturally contain *E. coli,* and the presence of these bacteria in food and water gives an indication of faecal contamination. As expected, there were relatively large numbers of *E. coli* in the raw faecal sludge in each pit at both study sites (Figure 3-10). However, variations of *E. coli* numbers between pits within the same site could be attributed to user habits, such as the addition of ash and use of detergents. The AD process significantly reduced the number of *E. coli* (Figure 3-10). However, the number of *E. coli* in the digested faecal sludge was still above the WHO (2006) standards for land application.

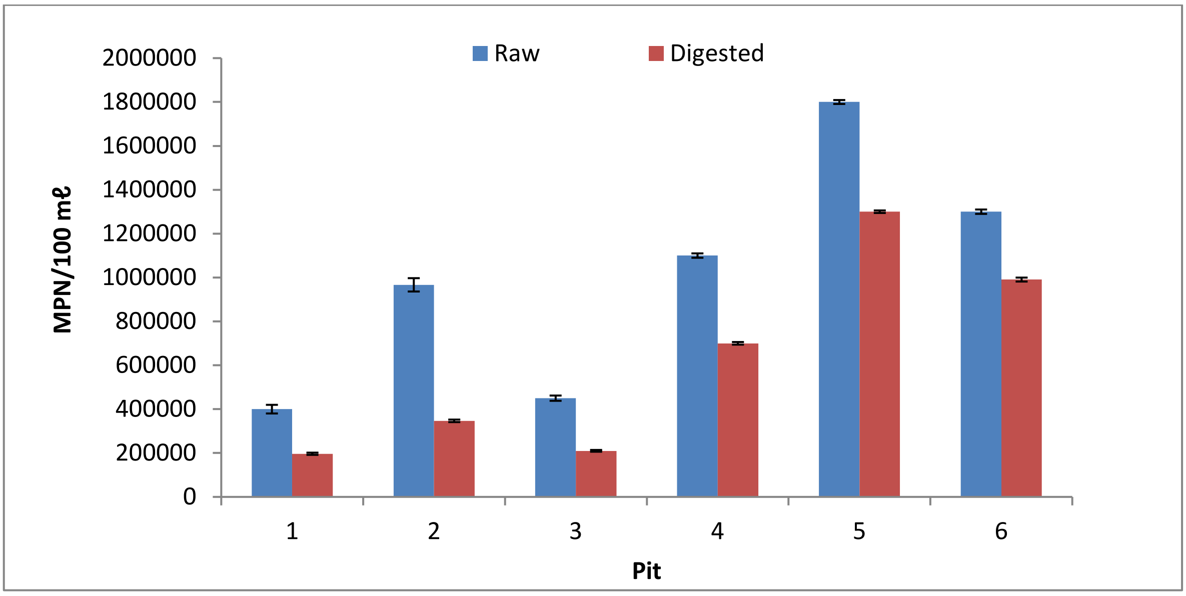

FIGURE 3-10: EFFECT OF ANAEROBIC DIGESTION OF PIT FAECAL SLUDGE ON *E. COLI* FROM HATCLIFFE AND SHACKLETON

3.5.4 Helminths

No helminths were detected in all the pit latrine faecal samples used in this anaerobic digestion process.

3.5.5 Microbial reduction

Generally, the mesophilic digesters temperature range of 20-30°C reduced the microbial load in faecal sludge. However, the reduction did not meet all the WHO recommended standards for disposal into the environment. The poor reduction may be due to the short retention time of 35 days and the mesophilic temperature in the digesters (20-30°C) failing to reach the optimum temperature of 35°C.

According to Côté et al. (2006), temperature and retention time are decisive factors for indictor organisms and pathogens survival during AD of effluents. Kumar et al. (1999) observed a fast elimination of *E. coli* at 35°C compared to AD of cattle slurry at room temperature. It appears that under the conditions of this experiment, a retention time of 35 days at a temperature of 20-30°C was not sufficient enough to ensure sufficient inactivation of pathogens in faecal sludge.

3.6 Conclusion

Residents of Hatcliffe and Shackelton often take an average of two meals per day and have similar diets. The faecal sludge samples from Shackelton had higher BOD and COD than those from Hatcliffe, which resulted in the production of larger quantities of biogas during anaerobic digestion. The results suggest that there is potential to produce methane for household use from anaerobic digestion of pit latrine faecal sludge.

The anaerobically digested pit latrine faecal sludge under the mesophilic temperature range could not reduce the levels of pathogenic indicator organisms below those prescribed by the WHO (2006) guidelines for land application. Helminths were not detected in the pit latrine faecal sludge samples, and thus, it was impossible to ascertain the effect of anaerobic digestion on their population. The findings from this study suggest that there is need to further pre-treat the anaerobically digested sludge before use in agriculture or at least optimize the fermentation of the sludge.

4 Pilot study of anaerobic digestion of faecal sludge for biogas generation

4.1 Introduction

This chapter provides a summary of the pilot study of anaerobic digestion of faecal sludge for biogas generation in Harare (Hopley) and Chinhoyi (Shackleton).

4.2 Objectives

The objectives of the current study were to assess the potential of on-site faecal sludge treatment using anaerobic digestion for sustainable biogas production in the communities of Shackelton, Chinhoyi and Hopley, Harare.

4.3 Methods and materials

4.3.1 Household selection

Hopley and Shackelton are peri-urban settlements located about 15 km south of Harare and 25 km west of Chinhoyi, respectively. These residential areas have no reticulated water and sewerage systems and use pit latrines for sanitation purposes. As a pilot study, two households from Hopley and one from Shackleton were targeted for the study. The communities in each study site were tasked to identify pit latrines for this pilot study. The selection criteria included:

- The existence of a pit latrine
- Willingness of the house owner/tenant to participate in the programme
- Households with at least four inhabitants
- At least two other neighbouring households with the same number of people
- Acceptance by the tenant/household to allow other members of the community to use the toilet and/or biogas

After setting the selection criteria, members of the community cast votes to select the most suitable candidate based on the highest number of votes. The geographical positions of the selected sites are shown in Table 4-1.

TABLE 4-1: LOCATION OF BIO-DIGESTERS FOR THE PILOT STUDY IN ZIMBABWE

Study site	Geographic position
Hopley	E 31° 0′13″ S 17° 56′22″
	E 31° 0′23″ S 17° 56′34
Hatcliffe	E 31° 0′13″ S 17° 56′22″
Shackleton	E 31° 0′13″ S 17° 56′22″

4.3.2 Bio-digester design

The installed bio-digester is a Chinese dome-shaped design and has a maximum capacity of 4 m^3 (Figure 4-1). This capacity was designed for three households, each with a minimum of four people. A pour flush toilet directs the faecal matter into the digester through a 110-mm PVC pipe. This digester is also fitted with a pre-treatment tank, “W” (Figure 4-3 B and E), for incorporation of kitchen waste for co-digestion with the faecal sludge. The movement of faecal matter from the toilet pan to the digestion chamber is facilitated by flushing the waste with the minimum amount of water. Gas formed in the bio-digester is delivered into the kitchen via an 8 mm PVC gas pipe with a regulating valve switch (Figure 4-3F). Impurities in the gas are removed using a de-sulphuriser (Figure 4-3G). An expansion manhole was constructed to relieve the build-up of pressure in the main digester. Gas produced in the digestion chamber is monitored by the rise in slurry level into the removal chamber, which is connected to an overspill chamber through the outlet. The accumulation of biogas in the digester was monitored using a pressure gauge.

4.3.3 Bio-digester priming/seeding

The digester chamber was initially filled with cow dung slurry, which was formed by mixing 2 m^3 of water with 2000 kg of cow dung, as start-up feedstock. In the initial stages of biogas production, the gas outlet valve was closed to allow the accumulation of gas in the digester. A sufficient amount of biogas for cooking purposes was estimated based on the general principle that 1 m^3 of biogas can cook 3 meals for a family of 5 people. On the other hand, the household was estimated to produce about 3.5 kg kitchen waste comprising mainly sadza and green vegetable. Additionally, an adult was estimated to produce 0.3 kg of faecal matter per day.

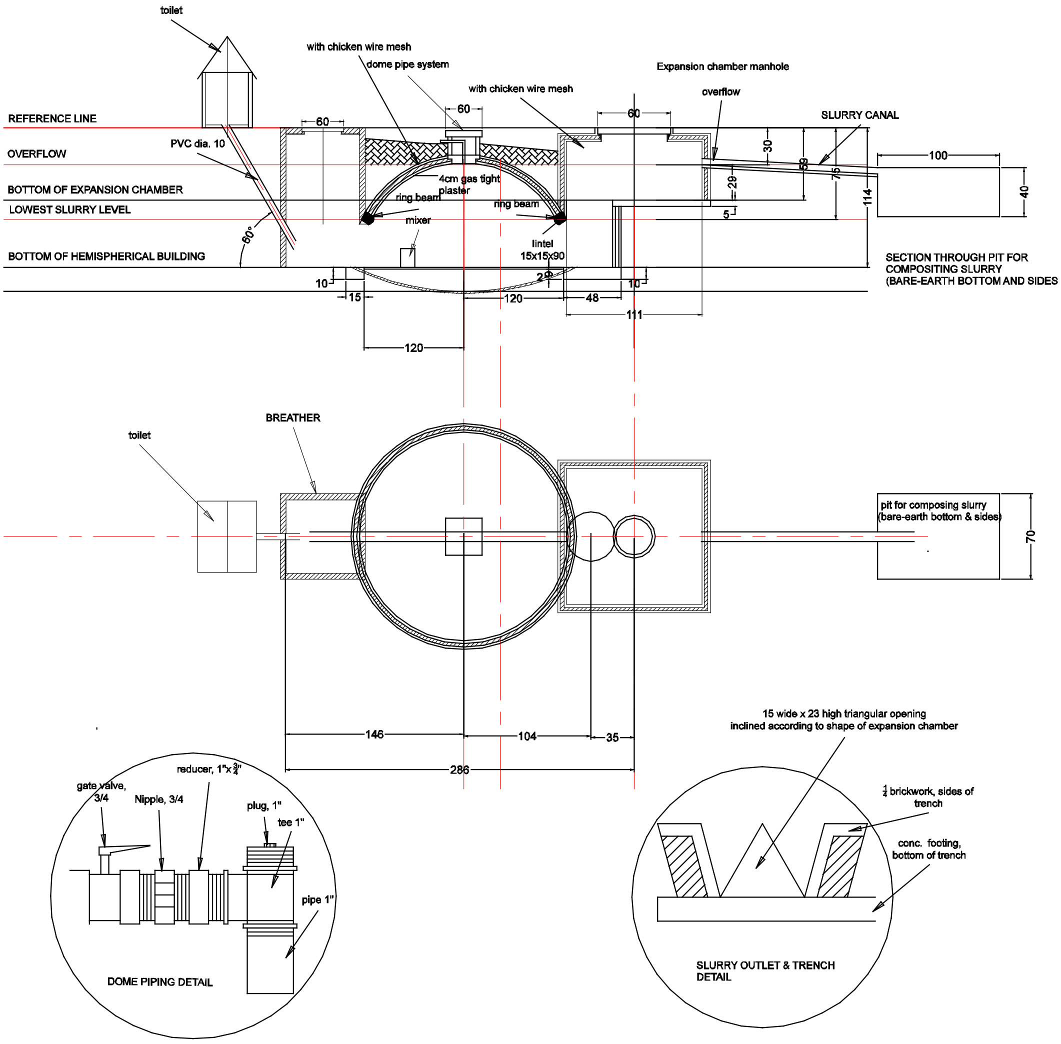

Figure 4-1: Sketch diagram of the bio-digester

Figure 4-2: Commissioning of bio-digester at Shackleton, Chinhoyi

FIGURE 4-3: A SEQUENCE OF BIOGAS DIGESTER DEVELOPMENT STARTING FROM (A) LAYING FOUNDATION, (B) AN ALMOST COMPLETE DOME-SHAPED BIO-DIGESTER. THE THREE MEN ON THE MID TOP PHOTO ARE STANDING ON THE SITE OF THE TOILET. THE PIPE FROM THE RECTANGULAR TOILET BOX CONNECTS TO THE BIO-DIGESTER, (C) A COMPLETED DOME-SHAPED BIO-DIGESTER WITH THE GAS DELIVERY PIPE AT THE CENTRE. (D) CATTLE RUMEN CONTENTS BEING LOADED ONTO THE LORRY AS A START-UP MATERIAL. THE RUMEN IS CO-DIGESTED WITH FAECAL MATERIAL FROM THE TOILET, (F). THE DELIVERY PIPE WAS CONNECTED TO A VALVE, WHICH IN TURN WAS CONNECTED TO THE GAS DELIVERY PIPE WHICH PASSED THROUGH A CONDENSER AND A (G) DE-SULPHURISER. (H) THE GAS IS CONNECTED TO A TWO-PLATE LPG GAS STOVE. NOTICE THE BLUE FLAME OF THE GAS ON THE LEFT PLATE.

4.3.4 Economic analysis of faecal sludge bio-digester project

4.3.4.1 Bill of quantities for a bio-digester

The costs of constructing a 4 m^3 bio-digester are shown in Table 4-3 below. The construction labour was partly contributed by the community and has been estimated at 20% of the material costs. It is also assumed that the digester will produce gas for a lifetime of at least 10 years and that repair and maintenance costs during the said period are negligible.

Total construction costs for a 4 m^3 biogas unit are thus estimated at USD 1200 per unit.

TABLE 4-2: BILL OF QUANTITIES FOR THE CONSTRUCTION OF A 4 M^3 BIO-DIGESTER IN ZIMBABWE

ITEM	QUANTITY	UNIT COST (USD)	TOTAL COST (USD)
Materials			
Excavation	1	35	35
19 mm (¾) Quarry stones	4 W/barrows	3	12
River sand	20W/barrows	2	40
Cement	300 kg	0.25	75
Clay bricks	600	0.13	78
Rhino bond	25 kg	47	47
Impermo	5 kg	5.5	27.5
Desulphuriser	1	20	20
Pressure gauge	1	10	10
8 mm hose clips	10	1.5	15
Gas delivery pipe	15 m	0.99	14.85
PVC Cement	200 mℓ	2.4	2.4
Mesh wire	2 m x1.8 m	4	8
Gas delivery pipe	0.5 m	0.5	0.25
Deformed iron bars, mm	6	2	12
¼ Ball cork valve	1	3.5	3.5
Condenser	1	20	20
6 m X110 mm PVC pipe	1	9	9
Biogas stove	1	35	35
Misc. construction costs			500
TOTAL COST OF MATERIALS			**964.5**
LABOUR(20% of material costs)			192
TOTAL COST			**APPROX 1200 USD**

4.3.4.2 Return on investment

The return on investment (ROI) is defined as the ratio of a profit or loss made in a fiscal year expressed in terms of an investment and is shown as a percentage of increase or decrease in the value of the investment during the year in question.

The basic formula for **ROI** is:

ROI = Net Profit / Total Investment 100 (as a percentage)*

The biogas yield of the digester is 0.3-0.5 m^3 gas/m^3 digester volume per day (SSWM, 2018), or 1.2 m^3 of gas per 4 m^3 digester per day.

1 m^3 of biogas is generally accepted to be equivalent to 0.45 kg of LPG. Thus, the daily biogas production of 1.2 m^3 of gas is equivalent to 0.54 kg of LPG. The current price of LPG in Zimbabwe is generally USD 1.50 per kg.

Thus, the daily biogas produces an LPG equivalent of 0.54 kg x USD 1.50 or **USD 0.80 per day**

Thus, the ROI

= (USD 0.80 x 365 days in a year/total investment of USD 1200) x 100

= **24.6%**

This is an exceptionally good ROI.

4.3.4.3 Payback period

The digester will pay for itself in a period equivalent to the total investment divided by daily returns, or USD1200/USD0.8per day = 1480 days = **4 years.**

However, since the digester has a lifetime of more than 10 years, with little or no repair and maintenance costs, for the rest of the period beyond the 4 years (more than 6 years) it will be producing “free” biogas.

4.3.4.4 Other Considerations

It should be noted that this analysis has not considered other direct and hidden benefits of the digester. These include, but are not limited to, the following:

- Benefits associated with the fact that AD produces fertiliser, which is used to produce crops such as vegetables
- Protection of valuable underground drinking water sources, such as wells that would otherwise be affected and require cleaning up or the use of other expensive alternatives
- Reduction of sanitation costs

4.4 Results and discussion

Some selected properties of the faecal matter and cow dung feedstock used in the pilot study are shown in Table 4-3. Generally, the feedstock contained relatively high BOD, COD, volatile solids and phosphorus concentrations.

TABLE 4-3: SELECTED PROPERTIES OF RAW FEEDSTOCK USED IN AN ANAEROBIC DIGESTION PILOT STUDY

Parameter	Faecal matter	Cow dung
Total solids (%)	17.8 ± 2.10	34.7 ± 1.2
Volatile solids (%)	21.9 ± 1.3	63.1 ± 2.3
Moisture content (%)	75.2 ±3.1	68.3 ± 5.6
BOD (mg/ℓ)	16250 ± 340	21000 ± 360
COD (mg/ℓ)	25660 ± 260	35000 ± 300
Nitrogen (%)	2.05	2.51
Phosphorous (%)	1.30	0.12
Potassium %	0.01	0.01
Calcium (mg/kg)	1.09	2.82
Magnesium (mg/kg)	0.34	0.68
Sodium (mg/kg)	0.51	0.60

4.4.1 Biogas production

Using the gauge measurements in the expansion chamber, the amount of gas being produced by the community digesters was estimated to be approximately 0.9-1.1 m^3 of biogas per day. During the initial 5-10 days after feeding the bio-digester with the inoculum followed by the faecal matter/vegetable waste feedstock, gas production was slow, as shown by the low pressure gauge readings (0-2 bar). However, gas production reached its peak at day 20 after the addition of the feedstock. The general trend in gas production was that relatively larger quantities accumulate during the night than during the daytime. These trends are attributed to the use of the biogas for cooking during the day.

4.4.1.1 Shackleton Community bio-digester

The community using the biogas from the digester in Shackleton consists of 10 individuals and is able to cook three meals a day. The gas is produced from waste generated by 4 adults and 6 children with the addition of approximately 3.5 kg of kitchen waste per day. It was also observed that only during breakfast and lunch is adequate biogas for cooking produced. During supper, biogas can only last for half the normal cooking times. However, it is expected that the biogas would continue to increase with time to such an extent that excess biogas would be produced. For these reasons, it might be necessary to modify the system so that the gas is stored before consumption, which would also improve gas supply to the household.

4.4.1.2 Hopley and Hatcliffe Community bio-digesters

In Hopley, the biogas digester is used by the community but is built at a site that largely relies on a total of 16 individuals from different families. The bio-digester provides biogas continuously without being exhausted, which could possibly be attributed to the increased deposition of faecal matter by more individuals. In Hatcliffe, a total of 12 individuals from different families are using the pit latrine that directly feeds into the bio-digester from which they are being able to cook three meals a day from the biogas produced.

FIGURE 4-4: BIOGAS GENERATED FROM THE DIGESTER AT HOPLEY (*LEFT*) BEING USED FOR COOKING (*RIGHT*)

4.5 Conclusion

The co-digestion of latrine sludge (faecal matter) with kitchen waste has the potential to produce sustainable amounts of biogas for a household of five. It is certainly clear that the major limitation here is the feedstock, both in the form of kitchen waste and human faecal matter. Unfortunately, the supply of these two substrates for increased energy generation is a paradox for the poor communities. Hence, other cheap alternative substrates must be identified for co-digestion in order to supplement the kitchen waste. Further research may be required to find alternative substrates that can be used to increase the fuel production capacity of these systems. This system is recommended as a sustainable waste disposal and energy supply system for low income households with no access to reticulated system and electricity. This system is a safer alternative for human health as well as an environmentally friendly technology in a number of ways (nutrient cycling system and organic fertilizer).

5 Potential use of anaerobically digested faecal sludge as fertiliser/soil amendment

5.1 Introduction

Anaerobically digested faecal sludge contains plant nutrients such as nitrogen, phosphorus, potassium, calcium and magnesium, and has the potential to be used in agriculture for crop production. The application of the sludge as a soil amendment is largely dependent on its microbiological properties (for safety), plant nutrient concentrations and the type of soil. The previous studies in this project have shown that pathogens contained in anaerobically digested faecal sludge used for biogas generation were still above the WHO recommended levels for disposal in agricultural land. Further treatment is therefore required before disposal in the environment. In this study, anaerobically digested faecal sludge was further heated using the generated biogas to reduce the pathogens before use in agriculture. Plant growth studies were conducted in the greenhouses at Chinhoyi University of Technology using anaerobically digested faecal sludge from Harare and Chinhoyi.

5.2 Objectives

The objectives of this study were:

- To determine the effect of anaerobically digested faecal sludge on plant growth
- To determine the effect of anaerobically digested faecal sludge on moisture holding properties of a sandy soil

5.3 Materials and methods

5.3.1 Study sites

Faecal sludge from Hatcliffe (Harare) and Shackelton (Chinhoyi) was selected for this study. Faecal sludge from the sites was anaerobically digested to generate biogas, which was used in the households. The anaerobically digested faecal sludge was then heated again using the biogas in order to reduce the pathogen load. The microbiological and chemical composition of the sludge was characterised prior to digestion and after digestion.

5.3.2 Pot experiments

A pot experiment was conducted to determine the effects of anaerobically faecal sludge on Indian mustard (*Brassica juncea)* grown in sandy soil. Sandy soils have inherent low nutrient reserves and low water-holding capacity. This crop was chosen as a test crop because it is widely grown in peri-urban areas of Zimbabwe for sale and household consumption and is eaten cooked. The experimental design was a 5 x 3 randomized complete block design with five treatments and three blocks. The treatments used were:

- *Treatment 1 (control):* 12.5 kg sandy loam soil per pot
- *Treatment 2*: 12.5 kg soil per pot + 5 g compound C (6:17:15, 0.1B) fertiliser as basal fertiliser
- *Treatment 3*: 12.5 kg soil + 250 g dried faecal sludge
- *Treatment 4*: 12.5 kg soil + 500 g dried faecal sludge
- *Treatment 5*: 12.5 kg soil + 750 g dried faecal sludge

Plant biomass yield was the primary variable. The sandy loam soil was taken from Chinhoyi University of Technology farm from the topsoil of 0-10 cm depth. It was passed through a 6 mm sieve to remove large objects. Sun-dried faecal sludge from two of the study sites was weighed according to the experimental treatment protocol and thoroughly mixed with the sandy soil using a garden fork. The same procedure was repeated with the fertiliser treatments. After mixing, distilled water was applied to the experimental pots by capillary action until field capacity.

Ten *Brassica jancea* seeds were sown in each pot, followed by applying 10 g of the same sandy soil to cover the seeds. In the first 5 days of sowing, 200 mℓ of distilled water was applied to each pot on daily basis. From day 7 to day 40, 200 mℓ of water was applied every 3 days.

After 10 days of sowing, the seedlings were thinned to one seedling per pot followed by watering. Agronomic practices (weeding, spraying, etc.) were followed until harvesting at 40 days after sowing. The fresh and dry weights of the edible plant were analysed for each treatment. Microbial population in terms of total coliforms, faecal coliforms and *E. coli* were measured in the soil before the start of the experiment and immediately after harvesting.

5.4 Results and discussion

5.4.1 Plant biomass

Fresh plant biomass increased in soil treated with faecal sludge, starting from 2% application rate compared to the unamended soil (control) (Table 5-1), and all the treatments were significantly different ($p < 0.05$). The significant increase in plant biomass was attributed to relatively high nutrient concentrations of the sludge and high water holding property (Table 5-1). There was no significant difference between the dry weight of treatment 4 and 5. The latter treatments had the largest moisture content, which was attributed to the relatively higher amounts of organic matter in the soil. The availability of nutrients and water in the soil promotes biomass accumulation in plants.

TABLE 5-1: MEAN WEIGHT OF THE INDIAN MUSTARD AT 40 DAYS AFTER SOWING

	Treatment number				
	1 (No amendment)	**2 (Inorganic fertiliser)**	**3 (2% sludge)**	**4 (4% sludge)**	**5 (6% sludge)**
Fresh weight (g)	60.6	367.9	354.9	454.5	532.1
Dry weight (g)	24.4	130.0	88.3	126.2	95.9
Least significant difference (l.s.d) of means (5% level): Fresh weight = **10.43**; Dry weight = **30.35**					

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Appendix 1: Household diet questionnaire

Introduce yourself to the people. Inform them that you are from Chinhoyi University of Technology and the purpose of the survey. Tell the household that the survey is for research purpose only and not for donor handouts. This ensures authenticity of the answers they will give in the interview. The survey will take 15 minutes on average. Do not take much time unnecessarily. Only HHs with latrines older than 2 years are to be interview in this survey.

1. Geographical location

1.1: Name of Area (Peri-urban name)	
1.2:Ward	
1.3: Geographic coordinates	

2. HH demography

2.1 Name of HH	
2.2 Name of HH head	
2.3 Total number of people at the HH	
2.4 Number of children	
2.5 Number of adults	

NB: People who have used the latrine up to the day of interview

3. Sanitation

3.1 What type of pit latrine does the HH use?	
3.2 Date of first use (This should indicate at least 2 years to the day of interview): (D.M.Y)	
3.3 Direction sanitation structure facing	
3.4 Depth of contents on interview date	
3.5 The type of cleansing material used	

3.6 Do you add anything after using the sanitation structure?. e.g. water, ash, sand	
3.7 How do you clean your structure	
3.8 Other uses of the sanitation structure, e.g. bathing	

4. Dietary information

4.1 How do you earn a living?	
4.2 How many are employed at this HH?	
4.3 How many meals do you normally have per day?	
4.4 What do you normally take for:	B/Fast…………………………………. Lunch…………………………………. Super…………………………………..
4.5 What else is eaten outside main meals	

Appendix 2: Statistical analysis of greenhouse experiments

GenStat Release 14.1 (PC/Windows 7) 01 October 2009 12:21:55

GenStat Fourteenth Edition

GenStat Procedure Library Release PL22.1

```
1 %CD 'C:/Users/Chris/Documents'
2 "Data taken from File: \
-3 C:/Users/Chris/Desktop/Doc Results/Averages Fresh Weight.xlsx"
4 DELETE [REDEFINE=yes] _stitle_: TEXT _stitle_
5 READ [PRINT=*; SETNVALUES=yes] _stitle_
9 PRINT [IPRINT=*] _stitle_; JUST=left
```

Data imported from Excel file: C:\Users\Chris\Desktop\Doc Results\Averages Fresh Weight.xlsx

on: 1-Oct-2009 12:24:04

taken from sheet "Sheet1", cells A2:C21

```
10 DELETE [REDEFINE=yes] TRT,BLOCK,Fresh_weight
11 UNITS [NVALUES=*]
12 FACTOR [MODIFY=yes; NVALUES=20; LEVELS=5; REFERENCE=1] TRT
13 READ TRT; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
TRT	20	0	5

```
15 FACTOR [MODIFY=yes; NVALUES=20; LEVELS=4; REFERENCE=1] BLOCK
16 READ BLOCK; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
BLOCK	20	0	4

```
18 VARIATE [NVALUES=20] Fresh_weight
19 READ Fresh_weight
```

Identifier	Minimum	Mean	Maximum	Values	Missing

Fresh_weight	48.63	354.0	577.0	20	0

```
%PostMessage 1129; 0; 30208456 "Sheet Update Completed"
"One-way design in randomized blocks"
DELETE [REDEFINE=yes] _ibalance
A2WAY [PRINT=aovtable,information,means,%cv; TREATMENTS=TRT; BLOCKS=BLOCK; FPROB=yes;\
PSE=diff,lsd,alldiff,alllsd; LSDLEVEL=5; PLOT=*; EXIT=_ibalance] Fresh_weight; SAVE=_a2save
```

Analysis of variance

Variate: Fresh_weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	3	7652.8	2550.9	6.57	
BLOCK.*Units* stratum					
TRT	4	512371.2	128092.8	330.09	<.001
Residual	12	4656.7	388.1		
Total	19	524680.7			

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

BLOCK 1 *units* 5	-37.0	s.e.	15.3

Tables of means

Variate: Fresh_weight

Grand mean 354.0

TRT	1	2	3	4	5
	60.6	367.9	354.9	454.5	532.1

Standard errors of differences of means

Table	TRT
rep.	4
d.f.	12
s.e.d.	13.93

Least significant differences of means (5% level)

Table	**TRT**
rep.	**4**
d.f.	**12**
l.s.d.	**30.35**

Stratum standard errors and coefficients of variation

Variate: Fresh_weight

Stratum	d.f.	s.e.	cv%
BLOCK	3	22.59	6.4
BLOCK.*Units*	12	19.70	5.6

28 SET [IN=*]

GenStat Release 14.1 (PC/Windows 7) 01 October 2009 10:41:29

____

GenStat Fourteenth Edition

GenStat Procedure Library Release PL22.1

____

```
1 %CD 'C:/Users/Chris/Documents'
2 "Data taken from File: \
-3 C:/Users/Chris/Desktop/Doc Results/Dry Weight Averages.xlsx"
4 DELETE [REDEFINE=yes] _stitle_: TEXT _stitle_
5 READ [PRINT=*; SETNVALUES=yes] _stitle_
9 PRINT [IPRINT=*] _stitle_; JUST=left
```

Data imported from Excel file: C:\Users\Chris\Desktop\Doc Results\Dry Weight Averages.xlsx

on: 1-Oct-2009 10:53:50

taken from sheet "Sheet1", cells A2:C21

```
10 DELETE [REDEFINE=yes] TRT,BLOCK,Dry_weight
11 UNITS [NVALUES=*]
12 FACTOR [MODIFY=yes; NVALUES=20; LEVELS=5; REFERENCE=1] TRT
13 READ TRT; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
TRT	20	0	5

```
15 FACTOR [MODIFY=yes; NVALUES=20; LEVELS=4; REFERENCE=1] BLOCK
16 READ BLOCK; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
BLOCK	20	0	4

```
18 VARIATE [NVALUES=20] Dry_weight
19 READ Dry_weight
```

Identifier	Minimum	Mean	Maximum	Values	Missing
Dry_weight	19.74	92.95	142.2	20	0

```
%PostMessage 1129; 0; 31650248 "Sheet Update Completed"
"One-way design in randomized blocks"
DELETE [REDEFINE=yes] _ibalance
A2WAY [PRINT=aovtable,information,means,%cv; TREATMENTS=TRT; BLOCKS=BLOCK; FPROB=yes;\
PSE=diff,lsd,means; LSDLEVEL=5; PLOT=*; EXIT=_ibalance] Dry_weight; SAVE=_a2save
```

Analysis of variance

Variate: Dry_weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	3	624.67	208.22	4.55	
BLOCK.*Units* stratum					
TRT	4	28864.91	7216.23	157.59	<.001
Residual	12	549.50	45.79		
Total	19	30039.08			

Information summary

All terms orthogonal, none aliased.

Tables of means

Variate: Dry_weight

Grand mean 92.9

TRT	1	2	3	4	5
	24.4	130.0	88.3	126.2	95.9

Standard errors of means

Table	TRT
rep.	4
d.f.	12
e.s.e.	3.38

Standard errors of differences of means

Table	TRT
rep.	4
d.f.	12
s.e.d.	4.78

Least significant differences of means (5% level)

Table	**TRT**
rep.	**4**
d.f.	**12**
l.s.d.	**10.43**

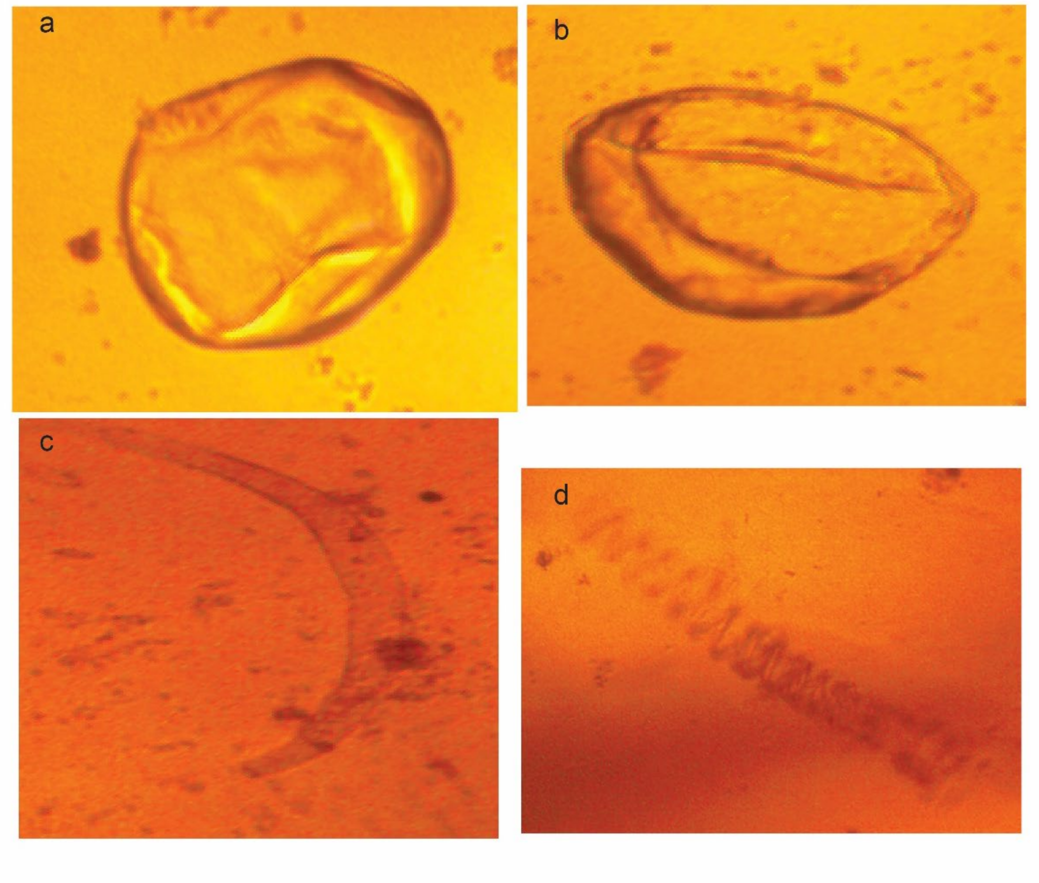
Stratum standard errors and coefficients of variation

Variate: Dry_weight

Stratum	d.f.	s.e.	cv%
BLOCK	3	6.45	6.9
BLOCK.*Units*	12	6.77	7.3

28 SET [IN=*]

Appendix 3: Some artefacts commonly found in pit latrine faecal sludge using the flotation method



Images (a) and (b) resemble decomposing helminth eggs. Image (c) looks like a decaying tapeworm. Image (d) resembles spiral bacteria.

Appendix 4: Homeless People Federation Community: Chinhoyi

Model Skyloo pit latrines, built in Chinhoyi by the homeless people's federation

The two-hole urine diverting Skyloo interior

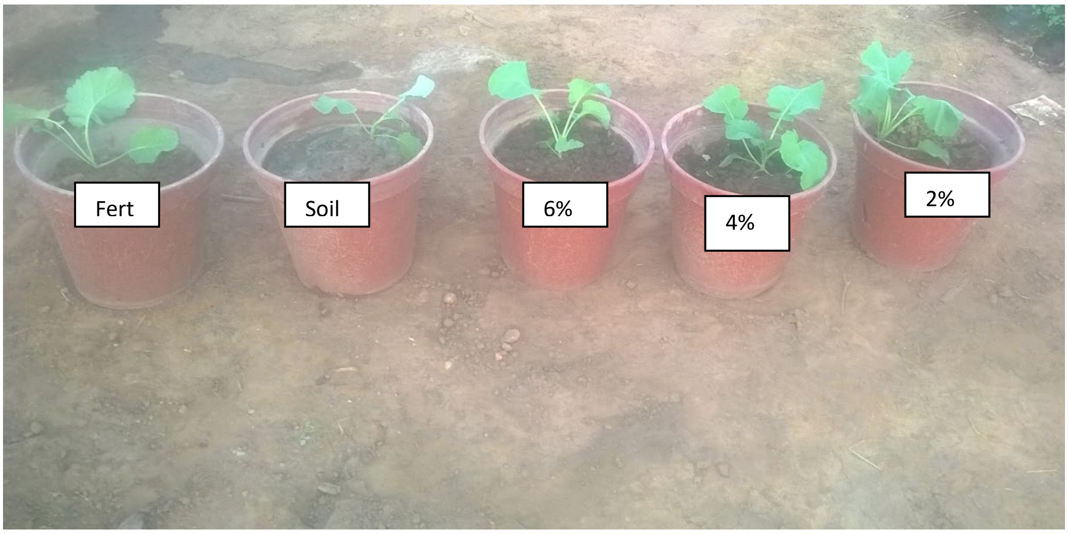
Appendix 5: Biogas Guideline Data

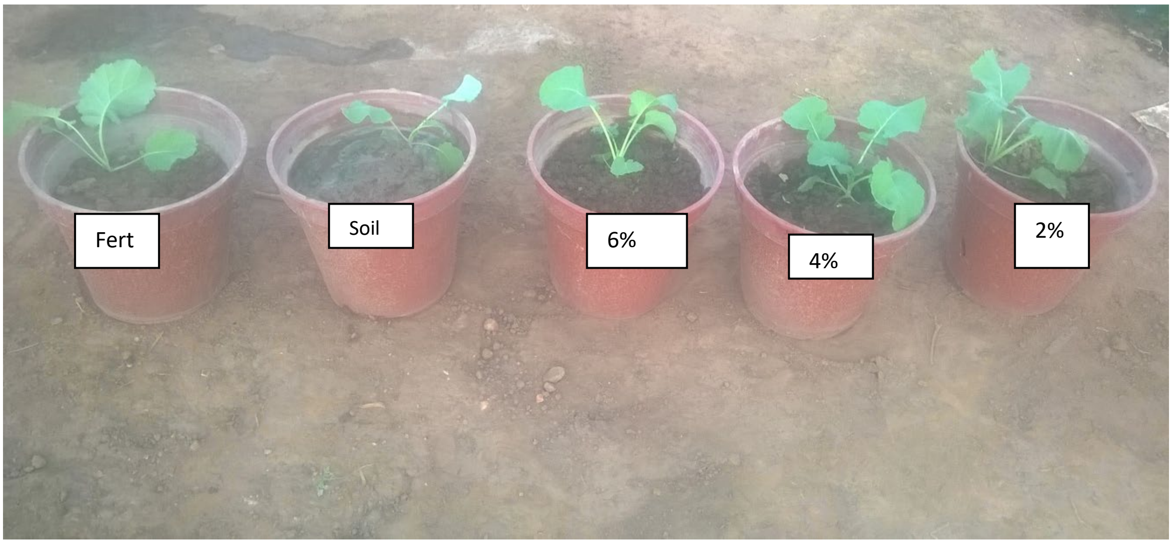
Suitable digesting *temperature*	20 to 35°C
Retention time	40 to 100 days
Biogas energy	6 kWh/m^3 = 0.61 ℓ diesel fuel
***Biogas* generation**	0.3-0.5 m^3 gas/m^3 digester volume per day
Human yields	0.02 m^3/person per day
Cow yields	0.4 m^3/Kg dung
Gas requirement for cooking	0.3 to 0.9 m^3/person per day
Gas requirement for one lamp	0.1 to 0.15 m^3/h

Adapted from WERNER et al. (1989); ISAT/GTZ (1999), Vol. I; MANG (2005)

Source: Sustainable Sanitation and Water Management (SSWM) (2016) Anaerobic Digestion (Small-scale), http://www.sswm.info/content/anaerobic-digestion-small-scale

Appendix 6: Pot Experiment Pictures


Fert
Soil
6%
4%
2%


Fert
Soil
6%
4%
2%