Emergency Sanitation

Faecal Sludge Treatment Field-work Summary

Field Summary Report

June 2014

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Aknowledgements

This document on the treatment of faecal sludge for emergency situations was produced on the request of WASTE Advisers as part of the Emergency Sanitation Project (ESP) and the S(P)EEDKITS Project. The ESP project is funded by the US Office for Foreign Disaster Assistance (OFDA) and is a consortium of the International Federation of Red Cross and Red Crescent Societies (IFRC), WASTE and Oxfam GB. S(P)EEDKITS has received funding from the European Unions seventh Framework Programme (FP7/2007-2013) under grant agreement No 284931. The content of this document is based on the research conducted by Dennis Malambo, Elliette Gonzalez and Happiness Nobela with the support of Tineke Hooijnmans and Jack van de Vossenberg from Unesco IHE as well as the research completed by Lobke de Pooter with support from Jules van Lier from TU Delft.

EXECUTIVE SUMMARY

Over the past four decades there has been a reported increase in the occurrence of disasters (Center for Research on Epidemiology of Disasters (CRED), 2013). Outbreaks of diarrhoeal diseases including dysentery and cholera are common in emergencies with faecal-oral diseases accounting for more than 40% of deaths in the acute phase of an emergency (Connolly, et al., 2004). Sanitation is one of the vital barriers for diarrhoeal disease prevention and this research aims to expand the knowledge for possible simple faecal sludge treatment technologies that could be rapidly deployed upon the event of an emergency and are effective under challenging physical conditions such as unstable soils, high water tables and flood-prone areas. Three faecal sludge sanitisation methods: Lactic Acid Fermentation (LAF); Urea Treatment (UT) and Hydrated Lime Treatment (HLT) were investigated by undertaking small scale field trials with pit latrine sludge in Blantyre, Malawi.

The faecal sludge used in the treatment experiments was sourced from pit latrines around Blantyre using a desludging technology involving high pressure fluidization and a vacuum suction pump. Samples of the obtained faecal sludge were analysed and the results are presented in Table i. During the desludging process it was noted that there were a large number of stones, corn-cobs, menstrual rags, plastic bottles and other large objects which had to be removed through fishing prior to extraction with the vacuum pump.

Table i: Characteristics of initial Faecal Sludge used in Treatment Field Experiments

Parameter	Range
Temperature	21-27^{o}C
pH	6.0-7.6
COD	50-150 g COD/L
Ammonia	1.2-1.5 g NH3-N/L
Total solids	4-15%[a]
Volatile Solids	45-68% dry wt/ (2-10% wet wt)
Escherichia coli	3x 10^{6} -4x10^{7} CFU/100ml

[a] The large range 4-15% and illustrates the variations in faecal sludge characteristics induced by external factors such as climate-induced groundwater intrusion

It was observed that the sludge characteristics varies spatially and throughout time and the quality is influenced by a number of factors such as: storage duration ;temperature; intrusion of groundwater; performance of pit latrine; pit emptying technology and pattern as well as admixtures to faecal sludge e.g. grease/ kitchen/solid waste

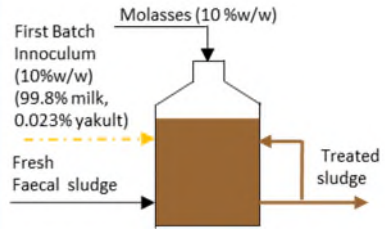
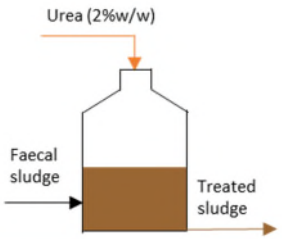
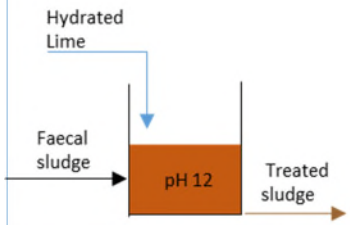
Over a period of 3 months (January – April 2014), field research was conducted in Blantyre, Malawi at the sochi sewage municipal wastewater treatment plant. The three treatment processes were investigated on a small-scale using 50L plastic containers as treatment reactors. Table ii compares the three faecal sludge sanitising methods and illustrates the advantages and limitations of each of these treatment technologies. Sanitation time is defined as the time required to achieve the WHO guidelines limit for e-coli of <10^{3} E-coli /100ml.

The field trials undertaken indicate that, based on small-scale experiments utilizing faecal sludge sourced from pit latrines in Blantyre, Malawi, all three treatment processes are able to satisfy the top four criteria for emergency faecal sludge treatment processes.

1. **Safety :** All three treatment process can be conducted safely and adhere to the safety, health and environmental norms and standards during operation and maintenance
2. **Sanitization:** All three treatment processes under certain process conditions are able sanitize faecal sludge to comply with the WHO guideline limit of 10^{3} E-coli /100ml

3. **Robustness:** All three treatment process can treat both liquid and solid sludge All three technologies could be undertaken in either an above ground tank or portable bladder and therefore could be effective under challenging physical conditions such as unstable soils, high water tables and flood-prone areas.
4. **Deployment:** All three treatment processes are low-tech and require readily available material: molasses (common livestock feed); urea (common fertilizer); and hydrated lime (common building material), and therefore have the potential for rapid deployment upon the event of an emergency.

Overall, based on the small-scale field trials, urea treatment, hydrated lime treatment and lactic acid fermentation were evaluated to be promising low-tech faecal sludge treatment technologies and are all potentially applicable to emergency situations. Additional research and up-scaling is required to optimize each treatment process and to establish robust procedures that could be easily implemented in the event of an emergency.

Criteria	Lactic Acid	Ammonia	Lime
Technology	Biological Treatment	Bio-Chemical Treatment	Chemical Treatment
Process			
Sanitisation time	7-15 days	4-8 days	2 hours
End pH of Faecal Sludge	3.8-4.2	9-9.5	11-12.5
Chemical Use	**Sugar Additive**	**Urea**	**Hydrated Lime**
Chemical Use	2g simple sugar[1]/kg sludge 10% w/w pre culture (Pre-culture: 0.2% Yakult, 99.8% Milk)→ 30g/L Lactic Acid	2%w/w Urea (20g Urea/kg Sludge – 9g TAN/kg Sludge)	17-30g Hydrated Lime/ kg Sludge
Chemical cost per m^3 faecal sludge[2]	**€2.20/m^3** (100L Molasses) **€31.20/m^3** (Pre culture: 100L Milk, 0.2L Yakult)	**€16/m^3** (20kg Urea)	**€12/m^3** (25kg Lime)
Limitations	Temperature dependence for Lactic Acid Bacteria fermentation	Initial homogeneous mixing required Air-tight container	Homogeneous mixing required
Additional Treatment/ Re-use	Drying bed/ inoculum for subsequent batches	Drying bed/ fertilizer	Drying bed/ soil conditioner for acidic soils

1 Simple sugar refers to glucose, fructose and sucrose
2 Chemical cost are based on Malawian market prices and converted from Malawian Kwacha

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CHAPTER 1 INTRODUCTION

1.1 Historical Disaster Trends

Natural disasters such as hurricanes, floods, earthquakes as well as and man-made disasters such as wars and political unrest, often lead to emergency situations. These emergency situations can be characterized by population displacement, widespread destruction of infrastructure and disruption of basic services that support peoples' livelihoods (Connolly, et al., 2004).

There has been a reported increase in the occurrence of natural disasters over the last four decades as illustrated in Figure 1 (Center for Research on Epidemiology of Disasters (CRED), 2013). This increase has clear implications on the morbidity and mortality resulting from communicable diseases.

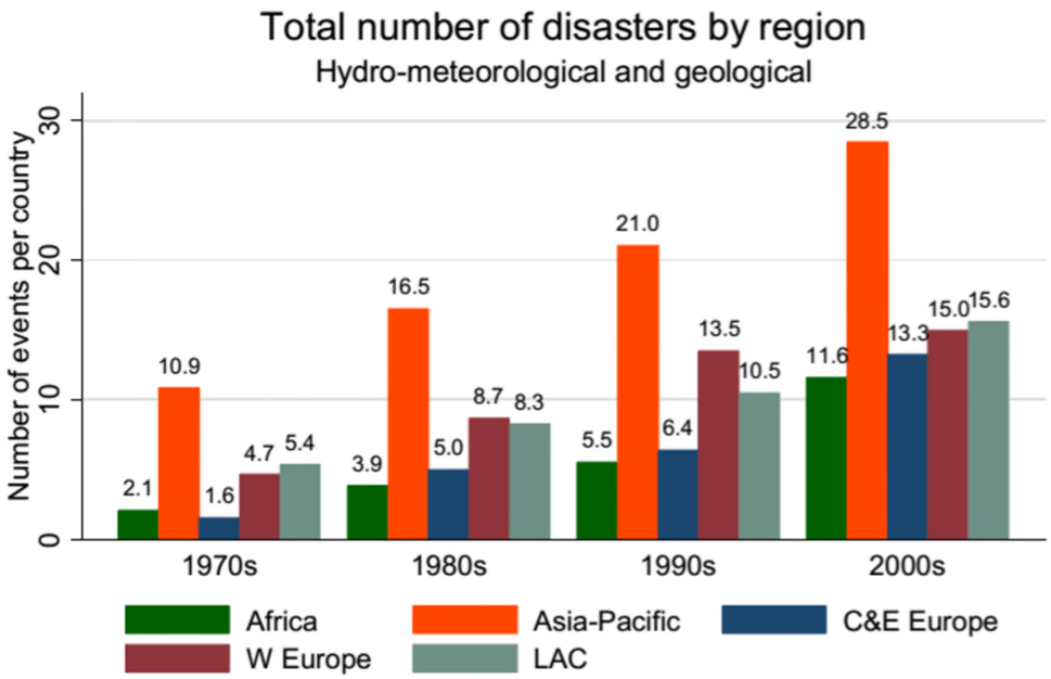


Figure 1: Incidence of Natural disasters by region, 1970-2008

(Source: (Center for Research on Epidemiology of Disasters (CRED), 2013)

1.2 Link between Sanitation and Disease during Emergency Response

The provision of clean water and hygienic sanitation, which are essential services for safeguarding public health, are often disrupted upon the event of a disaster or emergency situation (Fenner, Guthrie, & Piano, 2007). In the past, the low priority assigned to sanitation facilities and in particular to faecal sludge treatment and management during emergencies has led to the provision of unsuitable on-site sanitation systems in urban areas (Fenner, Guthrie, & Piano, 2007). Often the faecal sludge management merely consisted of indiscriminate dumping of the excreta in an urban environment which leads to terrestrial and aquatic environment contamination, high risk of transmission of gastro-intestinal infections as well as morbidity and mortality (Strauss & Montangero, 2002). Figure 2 illustrates unsafe disposal of faecal sludge that has occurred historically during emergency response.

Figure 2 : Usafe Disposal of Faecal Sludge during Haiti Emergency Response, 2010

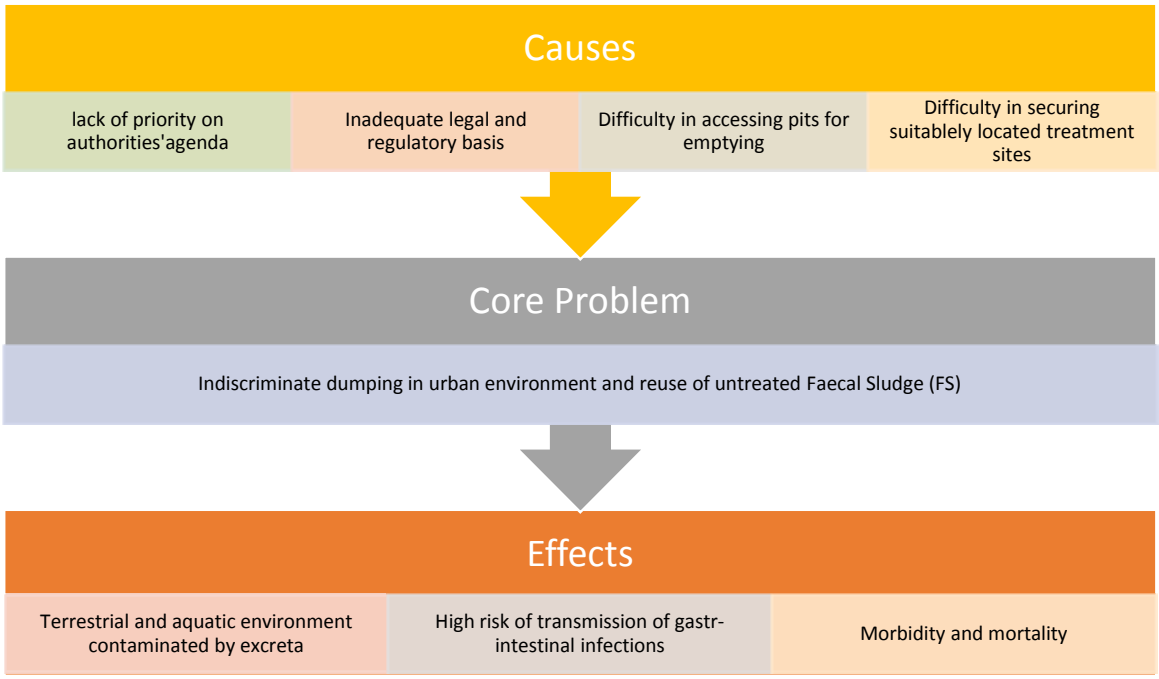


Figure 3: Causes problems and inadequate or missing excreta and faecal sludge management
Source: (Strauss & Montangero, 2002)

(Howard, 1996) states that where and how waste is disposed of is critically important to containing faecal-oral disease. The causes and problems associated with inadequate or missing excreta/faecal sludge management is illustrated in Figure 3 sourced from (Strauss & Montangero, 2002).

Outbreaks of diarrhoeal diseases including dysentery and cholera are common in emergencies (Brown, Jeandron, Cavill, & Cumming, 2012). Faecal-oral diseases may account for more than

40% of deaths in the acute phase of an emergency, with greater than 80% of deaths in children under 2 years of age (Connolly, et al., 2004). Containment and Treatment of faecal matter is a vital barrier against the spreading of diarrhoeal diseases in particular during emergencies when the population is more vulnerable.

The pathogenic nature of sludge in addition to vector attraction which enhances the spreading of disease, necessitates that sanitation and stabilization are the key objectives of faecal sludge treatment in order to reduce the risk to both public and environmental health.

The research conducted has been done in response to a call to investigate low-key faecal sludge treatment technologies that could be rapidly deployed upon the event of an emergency and are effective under challenging physical conditions e.g. unstable soils, high water tables and flood-prone areas.

Three simple faecal sludge treatment technologies that could be quickly implemented during an emergency were chosen to be investigated: lactic acid fermentation; urea treatment and hydrated lime treatment. All three treatment processes require readily available material: molasses (common livestock feed); urea (common fertilizer); and hydrated lime (common building material), and therefore have the potential for rapid deployment upon the event of an emergency.

1.3 Phases of emergency response

Within an emergency situation, three main stages exist that have different key objectives and priorities for faecal sludge treatment as illustrated in Figure 4.

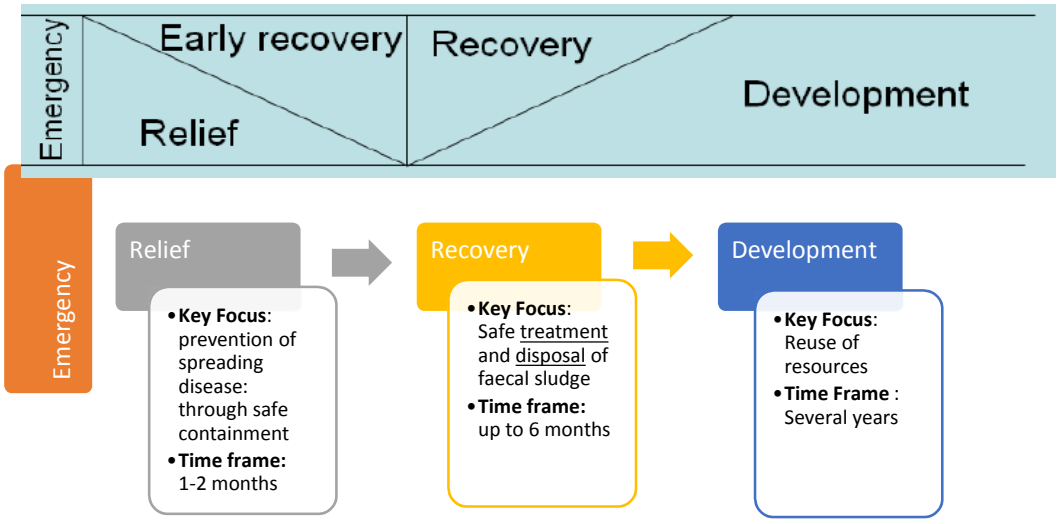


Figure 4 : Stages of Emergency Response

The purpose of the research undertaken was to provide a safe excreta disposal option applicable to the relief and early recovery phase. The risk of major epidemics and morality rates is the highest in this first stage. Therefore a key objective of this research is to identify applicable means to contain and treat excreta in this first phase to mitigate outbreaks of communicable diseases

CHAPTER 2 FIELD WORK OBJECTIVES AND SET UP

2.1 Key Criteria for Emergency Faecal Sludge Treatment

The evaluation criteria for analyzing the applicability of the treatment process for an emergency situation is presented in order of importance in Table 1. This order of importance was devised through consultation with emergency sanitation experts.

Table 1: Faecal Sludge Treatment Criteria for Emergency Situations

	Faecal Sludge Treatment Criteria	Proposed Indicator/ Measure
Safety	The treatment process can be operated safely. Ease of adhering to safety, health and environmental norms and standards during operation and maintenance (D5)(3.4)	• MSDS rating for chemicals • Exposure risk during process operation • JSA of operating procedure
Sanitisation	The ability of the treatment process to reduce the number of pathogenic organisms in the faecal sludge .	• Analyse the leachate and the sludge for meeting the WHO guidelines (<1000 MPN e-coli/ 100ml)
Robustness	The ability of the treatment to process different types of sludge (liquid, solid, semi liquid) (3.36). The adaptability of the treatment to be easily adapted or has the ability to function aboveground (for areas with hard surface or at risk of flooding) (3.,27)	• Test the treatment process with variable %ds sludge types. • Adapt the process to function aboveground
Deployment	The ability to deploy the facility within short period upon arrival in the field (B3)(weeks) (3.45)	• Procurement time for chemicals/equipment. Custom restrictions
Treatment Capacity	The ability of the process to treat a high capacity of faecal sludge. Measured in m^3/d	• Maximum capacity measured in m^3/d
Stabilisation/Vector reduction	The extent of Stabilisation to reduce vector attraction and odour	• Leachate: Measure COD • Sludge: Measure organic content (TVS)
Operability	The ease of operation of the treatment process.	No. of operators required, extent of training required for operation of treatment process.
Treatment period	The time required until both the effluent and sludge can be discharged or reused safely into the environment Ideally the treatment process should not require more than 1 month	Treatment Period till products are deemed "safe" from a public health and ecological standpoint
Power Supply	If power supply is required, the disposal method should include a stand-alone power generator	kWh / m3 treated
Useful byproducts External resources	The treatment process generates energy or other useful byproducts, creating external resources for the community.	Amount of useful bioproduct produced per m3 of FS influent (or per g ds)
Leachate and Sludge Further Treatment	The Leachate and sludge do not required additional, secondary treatment and can be disposed of in a landfill or similar	Cost and resources required for additional treatment

The top four most important criteria for a treatment process to be implemented during the first stage (acute phase) of an emergency.

1. **Safety :** Treatment process can be conducted safely and adheres to the safety, health and environmental norms and standards during operation and maintenance
2. **Sanitization:** Sanitize sludge to WHO guideline limits <1000 CFU E-coli/ 100ml
3. **Robustness:** process can treat both liquid and solid sludges as well as be effective under challenging physical conditions e.g. unstable soils, high water tables and flood-prone areas.
4. **Deployment:** treatment process is low-tech and utilizes readily available materials to allow for rapid deployed upon the event of an emergency

This order of importance of faecal sludge treatment criteria helped define the objectives for the three technologies investigated.

2.2 Field Testing objectives

The overall objective of the field trials was to investigate and evaluate the suitability of urea treatment, hydrated lime treatment and lactic acid fermentation processes as a means of treating faecal sludge and the applicability to emergency situations. The specific objectives are given below:

- **Safety:** To determine if the treatment process could be conducted safely
- **Sanitisation:** To determine if the treatment process could meet the WHO guidelines of E-coli <1000 CFU/100ml
- **Robustness:** To determine if the treatment process could be effective for both solid (>15% ds) and liquid (<15%ds) sludges
- **Treatment Time:** To determine the required treatment time to achieve objective 2: sanitization
- **Process conditions:** To determine the physical conditions required for each of the treatment process
- **Resource Requirement:** To determine the required chemical dosages, energy input and operating costs associated with the treatment process

2.3 Field Testing Parameters

To determine the required process conditions as well as the sanitisation and stabilisation extent of the treatment process a number of parameters were measured. The faecal sludge was characterised by measuring the total solids, volatile solids and Chemical Oxygen Demand (COD) before and after the experiment. In the Lactic Acid Experiments, the fermentation process was monitored by measuring pH, lactic acid concentration and enumeration of lactic acid bacteria. During the Urea treatment experiments, the ammonia composition was monitored by measuring pH, temperature and Total Ammonia Nitrogen (TAN). The sanitizing effect of each of the three treatment processes was monitored and assessed by the enumeration of the indicator organisms *Escherichia coli*. All methods are listed in Table 2 and were based on Standard Methods for the examination of water and wastewater (American Public Health Association (APHA); American Water Works Association (AWWA); Water Environment Federation (WEF), 2012)

Table 2: Analytical Methods used for analysing parameters for Lactic Acid Experiments

No.	Parameter	Method Lactic Acid Experiment	Method Urea Experiment 1	Method Urea Experiment 2	Method Lime Experiment 2
1	Temperature	SM-2550B	SM-2550B	SM-2550B	SM-2550B
2	pH	Potentiometric SM-4500-H^+	Potentiometric SM-4500-H^+	Potentiometric SM-4500-H^+	Potentiometric SM-4500-H^+
3	Lactic Acid	Reflectrometric : Merck Test strips	NA	NA	NA
4	Total sugar (Fructose & Glucose)	Reflectrometric: Merck Test strips	NA	NA	NA
5	Total solids	SM-2540D	SM-2540D	SM-2540D	SM-2540D
6	Volatile Solids	SM-2540E	SM-2540E	SM-2540E	SM-2540E
7	Odour	SM-2150B	NA	NA	NA
8	Lactobacillus casei Shirota	Pour plate SM-9215	NA	NA	NA
9	Escherichia coli	Pour plate SM-9020	Pour plate SM-9020	MPN method IDEXX – nutrient indicator (ONPG & MUG)	Pour plate SM-9020
10	Total Coliforms	NA	Pour plate SM-9020	NA	Pour plate SM-9020
11	Salmonella			NA	Pour plate SM-9020
12	Other Enterobacteriaceae			NA	Pour plate SM-9020
10	Enterococci			MPN method IDEXX defined substrate enterolert-E	
11	Total Ammonia Nitrogen (TAN		Indophenol blue method Hach LR TNTN tube test	Indophenol blue method Hach LR TNTN tube test	
12	Chemical Oxygen Demand (COD)			Hach tube test HR Oxidation by Potassium dichromate	Hach tube test HR Oxidation by Potassium dichromate

2.4 Experimental Set up

The experimental set up which was established in Malawi consisted of firstly identifying a pit latrine which could simulate an emergency situation. Bangwe market toilet was chosen as it is used by approximately 50-100 people per day and is emptied frequently giving an average sludge age of 2 weeks. The pit latrine was emptied using a desludging process developed by Water and Environmental Services (WES), consisting of a high pressure fluidization and a vacuum suction pump. The sludge was transported to the sochi sewage treatment plant on the desludging device mounted on a 2 ton light truck. At the sochi sewage treatment plant, the faecal sludge was poured into the 50L drums using the reverse suction pump. The three treatment processes were then investigated using a batch process within the 50L plastic drums. The physical and microbial properties of the sludge before, during and after treatment were analyzed using the laboratory facilities at the sochi sewage wastewater treatment plant as well as the University of Malawi laboratory. The Field trial set up is illustrated in Figure 5.

Figure 5: Field trial set up in Blantyre, Malawi

CHAPTER 3 FAECAL SLUDGE CHARACTERISATION

3.1 Pit Latrine Sludge Samples

Faecal sludge samples were taken from three separate pit latrines in the region of Blantyre Malawi. From each pit latrine 3 samples were taken with the first sample (1A,2A,3A) being scraped off the top to best represent "fresh" faecal sludge that could characterize sludge to be found during an emergency situation. .

9 samples were taken in total (1A,1B and 1C) from Pit latrine 1, (2A,2B and 2C) from Pit latrine 2 and (3A,3B and 3C) from Pit latrine 3. The samples were analyzed for pH, alkalinity, temperature, total nitrogen, total ammonia, total phosphorus, Chemical Oxygen Demand (COD), Total Solids (TS), Total Volatile Solids (TVS), Total suspended solids (TSS), Volatile suspended solids (VSS), Electrical Conductivity (EC) , Faecal coliforms and Ascaris eggs. The sample analysis was conducted by the laboratory technicians at the University of Malawi – The polytechnic.

All parameters were analyzed according to normal standard procedures and those were American Public Health Association (APHA), Association of Official Analytical Chemists (AOAC) and the British Standards (BS) as given in Table 3

Table 3 : Methodology used for faecal sludge parameter analysis

Parameter	Methodology	Standard
Temperature	Electrometric method	APHA 1998
Alkalinity	Titrimetric method	APHA 1998
Total nitrogen	Kjeldjal method	AOAC,2000
Total ammonia	Titrimetric method	AOAC 2000, WRC Project 2137
Total phosphorus	Colorimetric method	AOAC 2000
COD	Titrimetric method	BS 6068:Section 2.34 1988
TS	Gravimetric method	APHA 1998
TVS	Gravimetric method	APHA 1998
TSS	Gravimetric method	AOAC 2000
VSS	Gravimetric method	AOAC 2000
EC	Electromeric method	APHA,1998
Faecal coliforms	Membrane filtration method	APHA,1998
Ascaris eggs	Microscopy	AOAC,1995

Some parameters were analyzed in triplicates and others in duplicates due to time restrictions. Those analyzed in duplicates are COD, alkalinity, TS, TVS and VSS, faecal coliforms and Ascaris eggs. While total nitrogen, total ammonia, total phosphorus, temperature, pH and EC were analysed in triplicates.

Table 4 summarizes the results of the 9 pit sample analysis.

Table 4: Pit Latrine Sludge characterisation from three separate pit latrines

SAMPLE	pH	Alkal	Temp.	TN	T. Amonia	TP	COD	TS	TSS	TVS	VSS	EC	E-coli*	Ascaris*
		mg/l	°C	%	mg/l	mg/l	mg/l	%	mg/l	%	mg/l	MS(cm)	cfu/100m	
1A	7.16	9091	24.7	2.24	22	1033	2830	10.5	2800	53	945	11.57	Nil	+++
1B	7.17	8189	25.0	2.88	30	456	3200	12.0	3780	51	933	15.53	17500	+
1C	6.39	10245	25.1	2.56	26	643	4320	26.0	3240	40	938	12.92	30000	+
2A	6.84	7692	25.0	4.80	25	811	2880	21.0	3610	61	933	30.52	40000	Nil
2B	6.59	13636	25.0	2.56	36	1162	3600	19.0	5245	72	948	28.23	Nil	Nil
2C	6.49	11517	25.1	3.36	31	696	4400	18.0	2595	61	953	31.58	Nil	++
3A	6.75	16525	25.0	2.24	33	513	2240	25.0	4370	61	919	21.12	19200	+
3B	7.47	7142	24.9	2.24	36	304	3760	22.0	4190	55	924	16.96	Nil	+
3C	7.29	9810	25.1	2.97	26	623	3600	22.0	2935	53	975	18.07	28000	++

*It should be noted that the samples were analyzed approximately one month post collection from the pit latrine. Therefore the accuracy of the microbial analysis is questionable as the samples were not preserved correctly.

3.2 Faecal Sludge Characterisation post desludging

Over a period of 3 months between January and March 2014, Faecal Sludge was obtained from a number of pit latrines around the Bangwe township, located near Blantyre, Malawi. The Faecal sludge was extracted from the pit latrines using a desludging technology developed by WES involving high pressure fluidization and a vacuum suction pump. Samples of the obtained faecal sludge were analyzed at the Polytechnic, University of Malawi Laboratory and the Sochi Wastewater Treatment Plant Laboratory for physical and microbial characteristics. The Faecal sludge characterization for the samples obtained is presented in Table 5. The characterization of sludge varies spatially and throughout time and the quality is influenced by a number of factors such as:

1. Storage duration (months vs years)
2. Temperature
3. Intrusion of groundwater (climatic conditions)
4. Performance of septic tank or pit latrine
5. Tank/ pi emptying technology and pattern
6. Admixtures to FS e.g. grease/kitchen/solid waste

Table 5: Characterisation of Faecal Sludge sampled from three different pit latrines

	Sludge 1	Sludge 2	Sludge 3	Sludge 4	Sludge 5	Sludge 6
Date Collected	25-1-2014	31-1-2014	7-2-2014	18-2-2014	27-2-2014	11-3-2014
Latrine Location/Sludge Source	Private Household Latrine Mr Khalika - Bangwe township	Private Household Latrine Mr Davie - Bangwe township	Bangwe Market Latrine	Bangwe Market Latrine	Bangwe Market Latrine	Bangwe Market Latrine
Approximate Sludge Age	1 year	7 years	1 month	2 weeks	1 month	2 weeks
Amount of Water Added during fluidisation	70 L	200 L	180 L	250 L	50L	50L
Volume of rubbish fished out	2 L	50 L	40 L	25 L	25 L	2L
pH	7,3	7,6	7,3	6,72	6,04	6,6
Temperature	25,5°C	21°C	26°C	25°C	23,3°C	27,1°C
TS	9%	6%	4%	11%	12%	15%
VS	45%	55%	59%	68%	58%	66%
E-coli content (CFU/100ml)	3,00E+06	3,00E+06	4,00E+07	3,23E+06	2,23E+06	7,08E+06
Total Coliforms (CFU/100ml)	3,00E+06	4,00E+06	2,00E+06	5,00E+05	2,13E+06	4,42E+06

The results obtained from the characterization of the six sludge samples indicate the following:

- The amount of rubbish within the pit latrine is a function of time between desludging events and was greater for household latrines compared to market pit latrines.
- The pH was fairly neutral for all samples and ranged between 6.0 -7.6. The pH of the sample was observed to be influenced by the amount of fluidization water added as well as the moisture content of the sludge sample.

- The total solids concentration varied considerably between samples and appeared to be more related to climatic conditions rather than sludge age
- Comparing the sludge characteristics between the sludge obtained from the same Bangwe market pit latrine over a period of a month (sludge samples 3 to 6) provides an insight into the variations in faecal sludge characteristics induced by external factors such as climate-induced groundwater intrusion. This is illustrated when comparing the total solids of 4% for sludge 3, obtained from Bangwe Market pit latrine during the rainy season and the total solids of 15% for sludge 6, obtained after a two week dry-spell period.
- The volatile solids % ranged between 45-68% and in general in was lower for higher sludge ages implying decomposition of organic matter over time in the pit latrine.
- The magnitude of E-coli and Total coliform concentration of 10^6 CFU/100ml is fairly consistent across the obtained sludges.

Overall it was observed that the faecal sludge characteristics vary throughout the year due to seasonal fluctuations as well as based on function (public vs private latrine).

CHAPTER 4 LACTIC ACID TREATMENT

This Chapter has been completed based on the research conducted by Dennis Hanjalika Malambo in collaboration with Unesco IHE. Please refer to MSc Thesis MWI SE 2014-21 for more detailed information. This can be downloaded from the WASTE website http://www.waste.nl

4.1 Theory

Lactic Acid Fermentation has been readily used for sanitation within the food industry (Vandenbergh, 1993). Weak organic acids such as lactic acid have inhibiting capabilities on a wide range of microorganisms. The inhibitory effect of the undissociated organic acid is 10-600 times stronger than that of the dissociate form. The antimicrobial action of lactic acid is partially attributed to its ability in the undissociated form to penetrate the cytoplasmic membrane of microorganisms, resulting in the reduced intracellular pH and disruption of the trans-membrane proton motive force of the lipopolysaccharides molecules of the outer membrane of the pathogenic organism (Helander, von Wright, & Mattila-Sandholm, 1997).

In this field trial, lactic acid was formed through fermentation of sugars using lactic acid bacteria. Lactic Acid Bacteria (LAB) are bacteria which pose the ability to form relatively significant quantities of lactic acid from carbohydrates and are readily use for sanitation and fermentation processes in the food and fermentation industries. The strain of Lactic Acid Bacteria (LAB) used in the research was *Lactobacillus casei* Shirota which found in the probiotic fermented milk drink: *Yakult*. This bacteria is a gram-positive species which is a preferential nonaerobe but is also aerotolerant, acid-tolerant and strictly fermentative (Fujimoto, 2008). Each 65ml bottle of Yakult contains 6.5 billion live *Lactobacillus casi* shirota bacteria.

4.2 Methodology

Figure 6:

Lactic Acid Bacteria Starter Culture

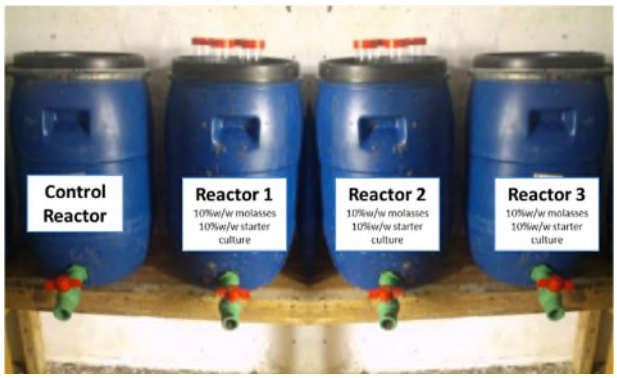


Figure 7:

Lactic Acid Bacteria Experimental Set up

Figure 8:

Power Mixing Device

4.2.1 Preparation of Pre-culture (inoculum media)

A pre-culture in milk was prepared as an inoculum for the treatment process (refer Figure 6). A case of Yakult was brought from the Netherlands and milk was sourced locally from a nearby dairy farm. The pre-culture was prepared at least 24-48 hours prior to the start of the treatment.

Apparatus

- 20 litre glass container
- 30ml pipette
- Plastic Funnel
- Bunsen burner

Materials

- 15 litres Pasteurized whole milk
- 65ml Yakult

Procedure

1. 15L of pasteurized whole milk was measured out into a 20L sterile glass container. The Bunsen burner ensures a sterile environment is maintained as the transfer is being made.
2. 30ml of Yakult is transferred into the glass container with the whole milk using a 30ml pipette and the container is closed off using some cotton wool with aluminium foil to allow for escape of CO2 gas.
3. Mixing of the contents is done manually by swirling the 20L glass container for 60 seconds.
4. The contents are allowed to stand still at room temperature for at least 48hours.
5. After 48 hours, it is anticipated that the LAB have attained exponential growth and the milk mixture has become thick as a result of lactic acid formation and is ready to be used as the Inoculum for the treatment process

4.2.2 Lactic Acid Treatment Experiment

The treatment experiment was conducted in triplicate (refer Figure 7). One reactor was used as a control, making a total of 4 reactors. The faecal sludge was obtained from a pit latrine in Limbe, Blantyre that had been in use for the last 7 years and had since never been emptied.

Apparatus

- 50L Plastic Container Reactors
- Mixer
- 1,000ml measuring cylinder
- 100ml sampling bottles
- Sprayer

Materials

- Faecal Sludge
- Inoculum
- Molasses

Procedure

1. Faecal Sludge in all the 4 reactors was weighed using a bathroom scale. This was in the absence of an analytical balance which was not available at the time.

2. Optimal concentration of sugar and inoculum addition established earlier in the laboratory experiments was used. 10% w/w molasses addition and 10% inoculum addition were used as optimal concentrations.
3. 10% w/w molasses was calculated using the weight of the faecal sludge determined in the first step, weighed and added to the 3 treatment reactors.
4. 10% w/w inoculum prepared 48hrs prior was also calculated using the combined weight of the faecal sludge and molasses added in the second step weighed and added to the 3 treatment reactors.
5. Mixing of the treatment mixture was done using a power mixer at the beginning of the experiment and prior to every sampling. 3 minutes of mixing in each of the 4 reactors was done. (Refer Figure 8)
6. Samples from all the reactors were collected after 0d, 2d, 4d, 7d, and 9d to establish the pH, Lactic Acid concentration and the viable cell count of the LAB and E. coli.

4.3 Experimental results

A summary of the sanitizing effect of Lactic Acid Treatment is illustrated in Figure 9. On day 7, the suppression of the *E.coli* to below detectable numbers was noted in all three of the treatment reactors. An average log reduction of more than 5 log units was recorded from $1.5x10^8$ to $< 10^3$ CFU/100ml. This pathogen reduction in the field was notably faster than the previous laboratory tests conducted which required 15 days before the e-coli count was below the detectable limit. From Figure 9 it can be deduced that pH conditions of approximately pH 4 induced pathogen inactivation. This correlated with the sanitization mechanism in the field being triggered when the lactic acid concentration reached the range of 30 g/L. The high lactic acid concentration and lactic acid bacteria count measured in the treated sludge could mean that the treated sludge has the potential to be used as the inoculum/starter culture for subsequent treatment batches.

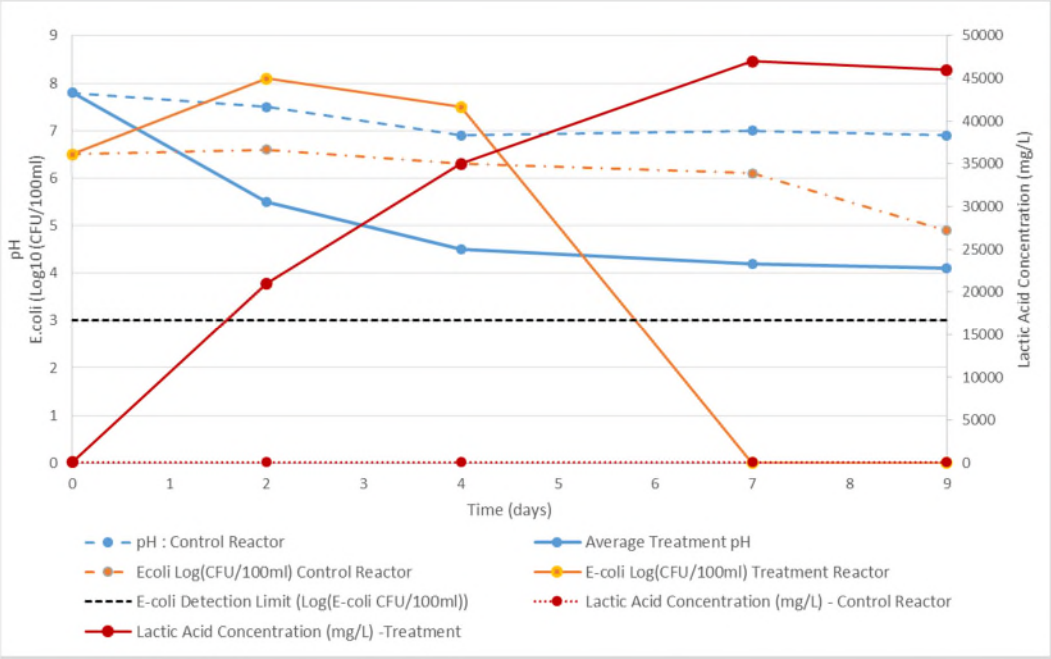


Figure 9: Correlation between Lactic Acid concentration, pH and E-coli removal

4.4 Treatment summary

Treatment Time
Lactic acid fermentation was able to sanitize faecal sludge to below the WHO guideline limit $<10^3$ *E.coli* CFU/100ml within 7 days

Treatment Conditions
The conditions required to achieve sanitiation were:

- pH <4
- Lactic Acid Concentration 20-30g/L
- Temperature of experiments > 20 degrees
- Batch Testing: Initial intense mixing

Chemical Dosage:

Pre-culture
The pre-culture was added in the ratio: 10% w/w wet sludge
The pre-culture consisted of 0.02% w/w Yakult, 99.8% Milk. This inoculum can be replaced by treated faecal sludge for subsequent treatments

Sugar Additive
Molasses was added in the ratio: 10% w/w wet sludge.

CHAPTER 5 UREA/AMMONIA TREATMENT

This Chapter has been completed based on the research conducted by Maria Eliette Gonzalez Perez in collaboration with Unesco IHE and Lobke de Pooter in collaboration with TU Delft. Please refer to MScThesis 2014-16 and field report for more detailed information. These can be downloaded from the WASTE website www.waste.nl

5.1 Theory

Urea Treatment is based on the sanitizing effect of uncharged ammonia (NH_3) which has been demonstrated to be a harmless chemical substance capable to efficiently inactivating bacteria (Vinneras, Nordin, Niwagaba, & Nyberg, 2008). Ammonia (NH_3) is known to be highly soluble in water as well as lipids (Nordin, 2010). This characteristic enhances the transportation of ammonia over the cell membranes and other cellular walls by diffusions. Once in the cell, Ammonia causes an increase in the internal pH, destruction of the membrane potential as well as denaturalization of the bacterial membrane and cell proteins (Bujozek, 2001). This eventually leads to cell decay and overall pathogen destruction. Additionally ammonia gas causes cell damage by quick alkalinisation of the cytoplasm (Nordin, 2010).
Catalyzed by the enzyme urease, which is present in faeces, urea added to faecal sludge will decompose into ammonia and carbonate as given in equation 1.

$$CO(NH_2)_2 + 3H_2O \xrightarrow{Urease} 2NH_4^+ + OH^- + HCO_3^- \quad (Eq.1)$$

The urea decomposition results in alkaline pH that affects the equilibrium between Ammonia and Ammonium – favouring the formation of ammonia as illustrated in Equation 2.

$$NH_{4\,(aq)}^+ + OH^-_{(aq)} \overset{K_a}{\leftrightarrow} H_2O_{(l)} + NH_{3\,(aq)} \overset{H}{\leftrightarrow} NH_{3\,(g)} (Eq.2)$$

The obtained unionized ammonia (NH_3) is the main sanitizing agent for pathogen inactivation. The equilibrium with ammonia gas is also important for the process as given by Henry's law. The solubility of ammonia gas in liquid thus depends on the temperature and partial pressures of ammonia gas above the liquid.

The dissociation constant K_a is temperature dependent (refer Eq-3, T is Temperature expressed in ^oC (Nordin, 2010)) and the fraction present as free uncharged ammonia (NH_3) as a percentage of Total Ammonia Nitrogen (TAN) is given in Eq-4 (Nordin, 2010).

$$pK_a = \frac{0.09018 + 2729.92}{(273.2 + T)} \quad (Eq.3)$$

$$f_{NH_3} = \frac{1}{(10^{pKa-pH} + 1)} \quad (Eq.4)$$

The fraction of dissolved ammonia is thus affected by pH and temperature with temperature being the dominant factor for moderate pH (8-10) and pH dominating above pH 11 (Nordin, 2010).

5.2 Methodology

Two Urea Treatment experiments were undertaken the field. The first experiment evaluated different urea dosages and the second experiment focused on the impact of mixing intensity at a set dosage.

5.2.1 Experiment 1

The urea treatment field experiment consisted of three reactors: one control and the two treatment reactors (refer Figure 10).

Apparatus

- 50L Plastic Container Reactors
- Mixer
- 100ml sampling bottles
- Sprayer
- Kitchen scale
- Bathroom scale

Materials

- Faecal Sludge
- Urea

Procedure:

1. All three reactors were filled with approximately 25-30L of faecal sludge and their weight recorded using a bathroom scale.
2. Urea prills sourced from a local agricultural dealer were weighed using the kitchen scale to achieve 1% and 3% w/w of the respective treatment reactors. The dosage was calculated based on equation 5, taking into account the 40% purity of the urea prills

$$Urea\ dosge = \frac{weight\ FS\ x\ urea\ conc\ (\%)}{urea\ purity\ (\%)} \quad (eqn\ 5)$$

3. The Urea was added to the two treatment reactors at dosage rates of to 1% and 3% urea w/w wet sludge respectively.
4. The three reactors including the control were manually mixed for 3 minutes and hermetically sealed with an aluminium ring to avoid ammonia loss throughout the experiment.
5. Samples were taken and analysed after 0d,4d,6d and 7d (refer Figure 11 & Figure 12).

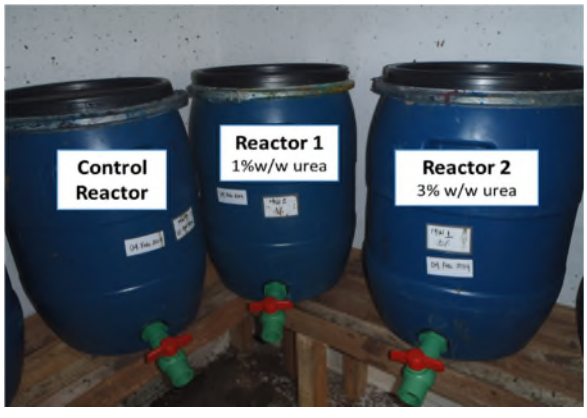


Figure 10*: Urea Testing Field Set Up*

Figure 11*: Sampling*

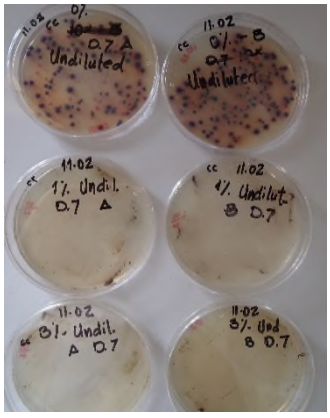


Figure 12 ***Plate Count using Chromocult Agar***

5.2.2 Experiment 2

The second experiment consisted of four 50L plastic drum reactors which were filled approximately two-thirds full with faecal sludge. Two drums served as controls and two drums were treatment reactors using a dosage rate of 2%w/w urea (refer .Figure 15)

Figure 13
Filling the drums

Figure 14
One of the two custom made mixers

Figure 15
Experiment 2
Overall set up

Figure 16
E-coli MPN method IDEXX –nutrient indicator

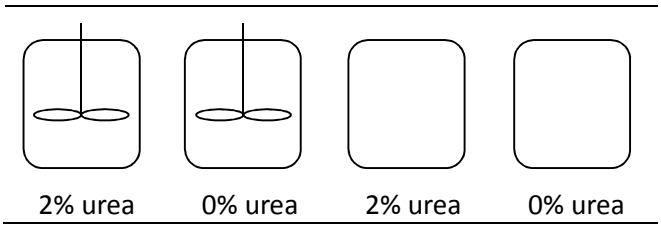


Figure 17 ***schematic overview experimental set-up Malawi***

Apparatus

- 4 x 50L Plastic Container Reactors
- 2 customised Mixers (refer Figure 13)
- 2 customised mixer stands
- 2L sampling bottles
- Sprayer
- Kitchen scale
- Bathroom scale

Materials

- Faecal Sludge
- Urea

Procedure:

6. All four reactors were filled with approximately 25-30L of faecal sludge and their weight recorded using a bathroom scale (refer Figure 13).
7. Urea prills sourced from a local agricultural dealer were weighed using the kitchen scale to achieve 2% w/w in the two treatment reactors.

8. The Urea was added to the two treatment reactors
9. The two treatment reactors were manually mixed for 3 minutes and hermetically sealed with an aluminium ring to avoid ammonia loss throughout the experiment.
10. The customised mixers (Figure 14) were set up for the one control and one treatment reactor, connected to a power supply and intensively mixed the reactors continuously for a period of 3 days
11. Samples were taken in duplicates at 0h,4h,6h,10h, 24h, 30h,48h and 72h. 400g samples were obtained from the intensively mixed drums, and the 400g sample from the non-mixed reactors were a composite sample of 200g from the top and 200g from the bottom tap (refer Figure 18).

Figure 18: sludge sampler (left); drums used for gravitational settling (middle); collection jars (right)

5.3 Experimental results

5.3.1 Experiment 1

As illustrated in Figure 19, the peak pH was recorded on day 2 after the addition of urea and remained stable around pH 9 for both 1% and 3% w/w urea additions. The ammonia concentration continued to increase over the period of 8 days. The concentration of E-coli measured below the WHO guideline limit of $<10^3$ CFU/100ml by day 4 for both 1% and 3% w/w urea additions (refer Figure 12), however other coliforms were detected until day 7 (refer Figure 20).

It should be noted that the ammonia concentration values calculated in experiment 1 involved the dilution of 10,000 times to enable the reading within the range of the device. Therefore the accuracy of the ammonia readings in experiment 1 is questionable which impacts the accuracy of the converted reading. An alternative spectrophotometer enabling a higher range for ammonia was utilized for experiment 2 which helps explain why there is such a discrepancy in results between experiment 1 and experiment 2.

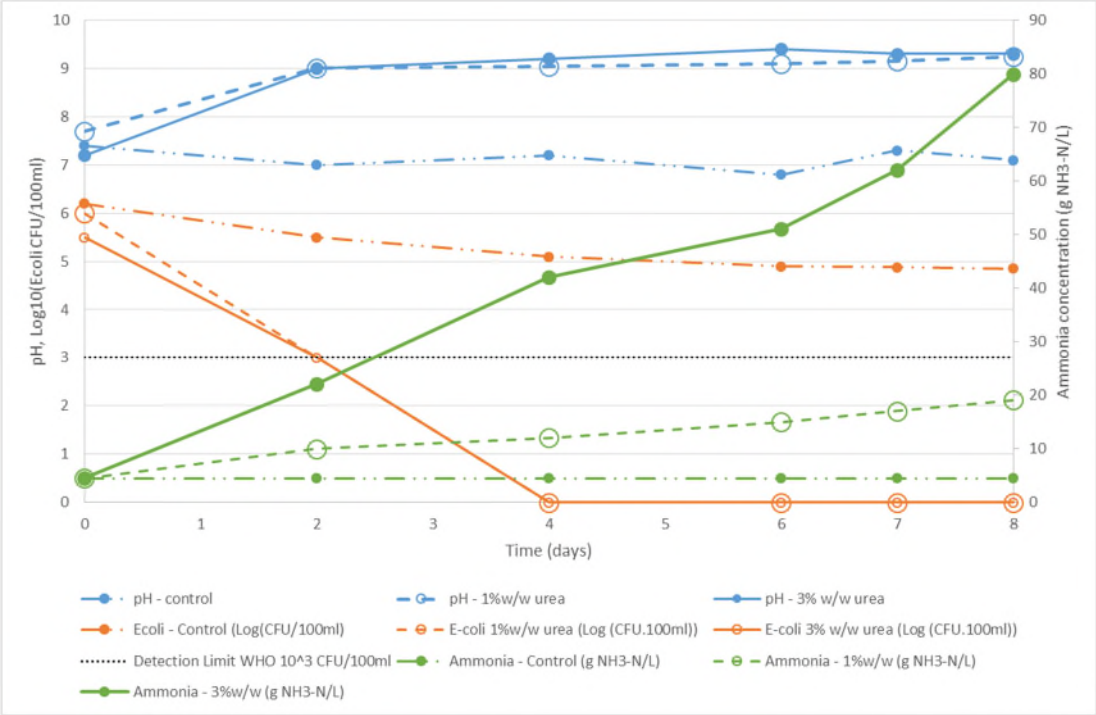


Figure 19 : Correlation between Urea Dosage, Ammonia concentration, pH and E-coli removal from Urea Experiment 1

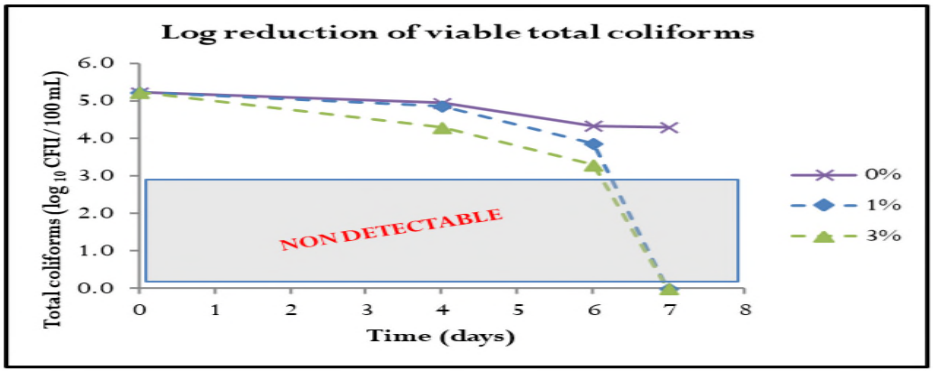


Figure 20 : Total coliform removal over time with urea treatment Experiment 1

5.3.2 Experiment 2

The data collected during field testing is presented below and accounts for intrinsic variation and repeatability. Treatment and control drums were sampled and analyzed in duplicate and the experiment was repeated.

The calculated average of the combined experiments is given along with the standard deviation between brackets. The scatter of values are large. This is mainly due to the difference in sludge composition.

Total ammonia nitrogen concentration

From Figure 21 it can be seen that during treatment the TAN concentrations increased from 1.9 (0.4) and 2.2 (0.1) g·N/l to 9.2 (3.0) and 11 (1.7) g·N/l, mixed and unmixed treatment respectively (Figure 4). The end values correspond to a conversion rate of 71% (mixed treatment) and 83% (unmixed treatment).

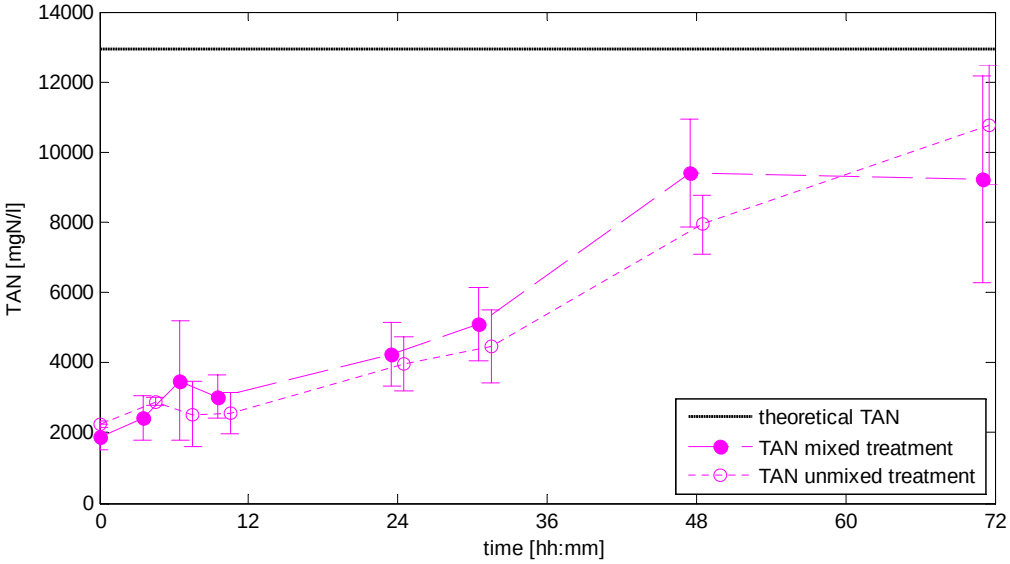


Figure 21: Total ammonia nitrogen (TAN) concentration during mixed / unmixed urea treatment

The total ammonia concentration in the control drums was constant over time with an average of 2.1 (0.5) g·N/l.

Ammonia concentration & pH

Urea treatment resulted in an increase in NH_3 concentration from 0.0 (-) g·N/l to 4.4 (1.6) and 5.0 (0.9) g·N/l, mixed and unmixed treatment respectively. The pH increased from 7.4 (-) to 9.4 (-) after mixed treatment and 9.3 (-) after unmixed treatment (Figure 22).

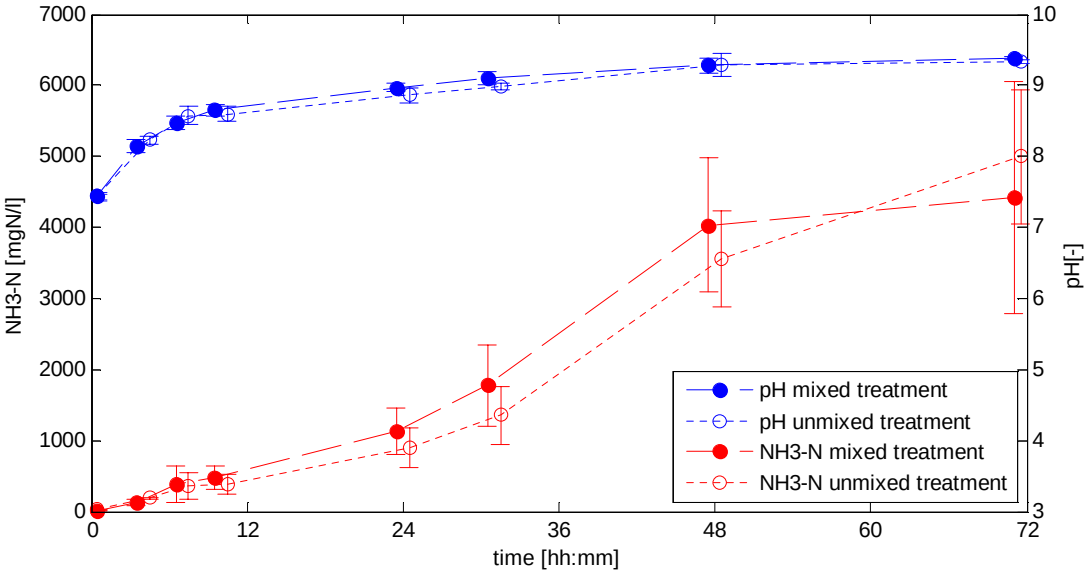


Figure 22: pH and ammonia concentration during mixed / unmixed urea treatment

In the control drums the initial and final pH were 7.4 (0.1) and 7.7 (0.2) under mixed conditions and 7.5 (-) and 7.9 (-) during gravitational settling.

E. coli count

Urea treatment resulted in a decrease in E. coli concentration from $8.5 \cdot 10^6$ ($1.5 \cdot 10^7$) and $1.2 \cdot 10^6$ ($8.5 \cdot 10^5$) MPN/100ml to $9.3 \cdot 10^3$ ($9.2 \cdot 10^3$) and $1.2 \cdot 10^4$ ($1.5 \cdot 10^4$) MPN/100ml, mixed and unmixed treatment respectively. After 72 hours of urea treatment (2% w/w) the WHO guideline regarding E. coli concentrations was not met (Figure 23).

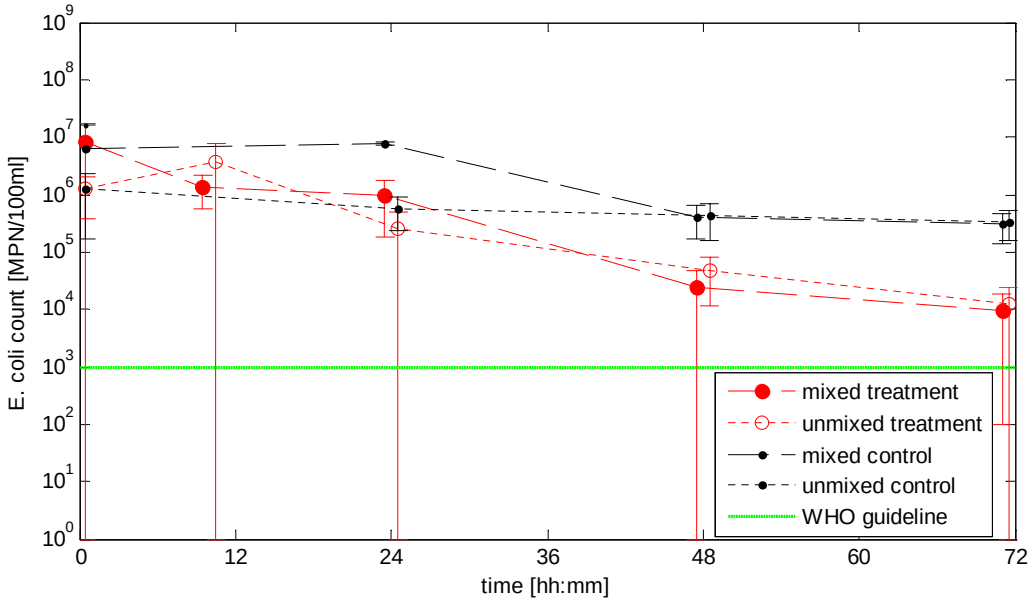


Figure 23 E. coli count during mixed /unmixed urea treatment and in the mixed / unmixed controls

In the controls the initial and final E. coli count were $6.5 \cdot 10^6$ ($1.0 \cdot 10^7$) and $3.1 \cdot 10^5$ ($1.6 \cdot 10^5$) MPN/100ml under mixed conditions and $1.3 \cdot 10^6$ ($1.1 \cdot 10^6$)and $3.4 \cdot 10^5$ ($1.8 \cdot 10^5$) MPN/100ml during gravitational settling.

Enterococci count

The initial and final Enterococci concentrations during urea treatment were $6.1 \cdot 10^7$ ($9.0 \cdot 10^7$) and $1.8 \cdot 10^7$ ($1.1 \cdot 10^7$) MPN/100ml and $4.9 \cdot 10^7$ ($5.2 \cdot 10^7$) and $4.1 \cdot 10^7$ ($4.0 \cdot 10^7$) MPN/100ml, mixed treatment and unmixed treatment respectively (Figure 24).

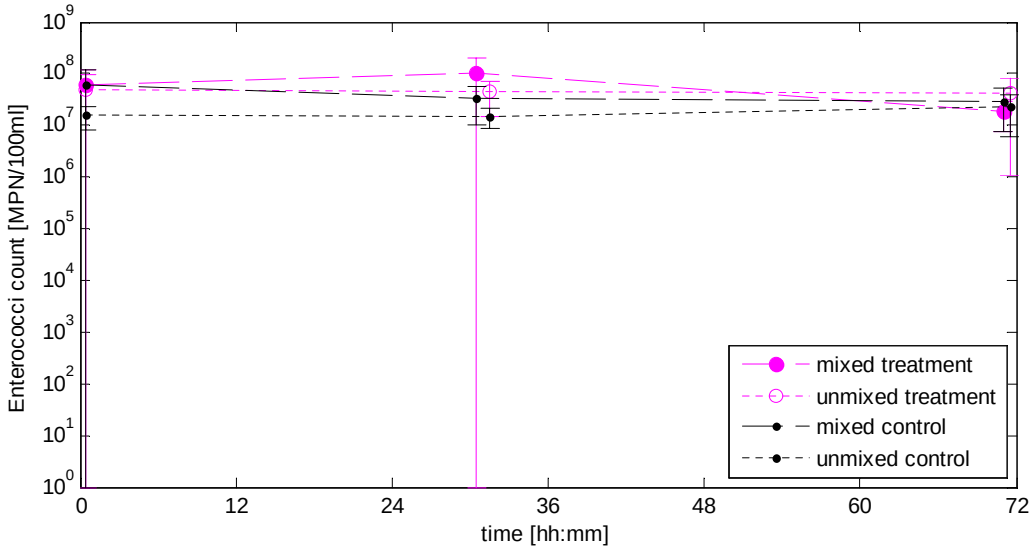


Figure 24: Enterococci count during mixed /unmixed urea treatment and in the mixed / unmixed controls

In the mixed and unmixed controls the Enterococci counts were $6.0 \cdot 10^7$ ($7.8 \cdot 10^7$) and $1.6 \cdot 10^7$ ($7.9 \cdot 10^6$) MPN/100ml at the start and the final counts were $3.0 \cdot 10^7$ ($2.2 \cdot 10^7$) and $2.3 \cdot 10^7$ ($1.7 \cdot 10^7$) MPN/100ml.

Treatment time

Based on the overall results it is concluded that the WHO guideline on safe sludge handling (E. coli $\leq 10^3$ MPN/100ml) cannot be met after three days of urea treatment (2% w/w). Looking at the two trials separately, the target was met in the first but not in the second experiment.

Extending the treatment time will result in a sludge that meets the guidelines regarding E. coli concentration. Increasing the urea dosage might not affect treatment time (i.e. $\leq 10^3$ MPN/100ml within three days), as the conversion rate is likely be governed by the bacteria present in the sludge and not by substrate availability.

The enumeration of Enterococci served as an additional indication on the sanitizing capacity of urea.
At the end of the treatment period the number of Enterococci was of the same order of magnitude as initially. Hence urea treatment (2% w/w) during three consecutive days did not affect the Enterococci present in the sludge.

Predictive modeling

The data obtained in the field testing were used to obtain a predictive model. Linear regression was applied as nonlinear exponential fitting underestimated the effect or urea addition.

The estimated treatment time for urea addition (2% w/w), based on the upper 95% confidence interval, is 5 days. The corresponding inactivation rate, k, is -0.088 (Table 2).

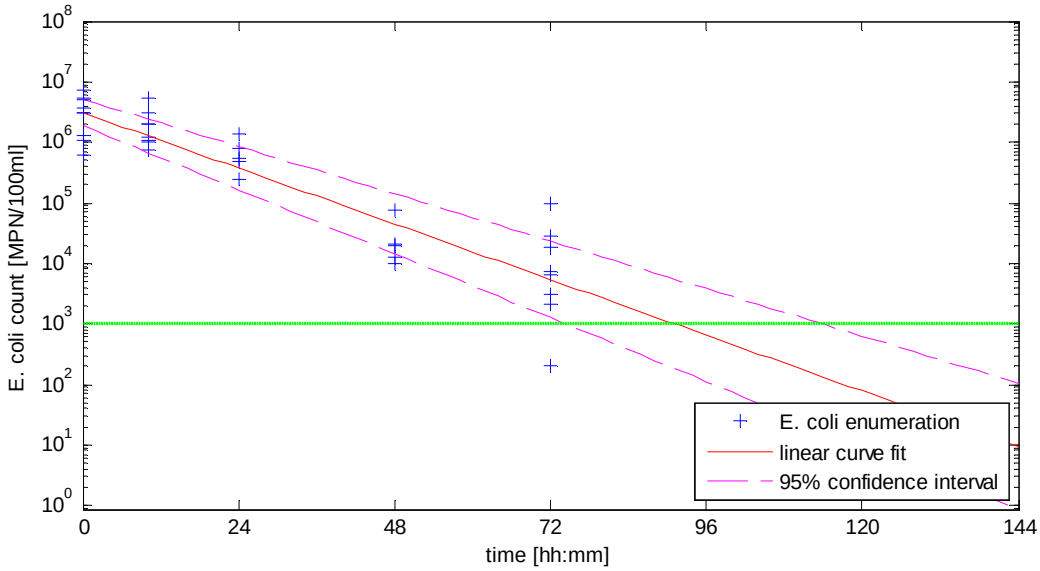


Figure 25: linearly fitted inactivation model including the 95% confidence intervals

Table 6: parameters of the fitted inactivation model

	$a \cdot e^{b*x}$		
a	$3.08 \cdot 10^6$	$1.85 \cdot 10^6$	$5.13 \cdot 10^6$
b	-0.088	-0.101	-0.075
r^2	0.837		

Effect of intensive mixing

Unmixed treatment resulted in a final pH and ammonia concentration of 9.3 (-) and 4.7 (0.5) g·N/l in the top layer compared to 9.4 (-) and 5.6 (0.7) g·N/l in the bottom layer (Figure 25).

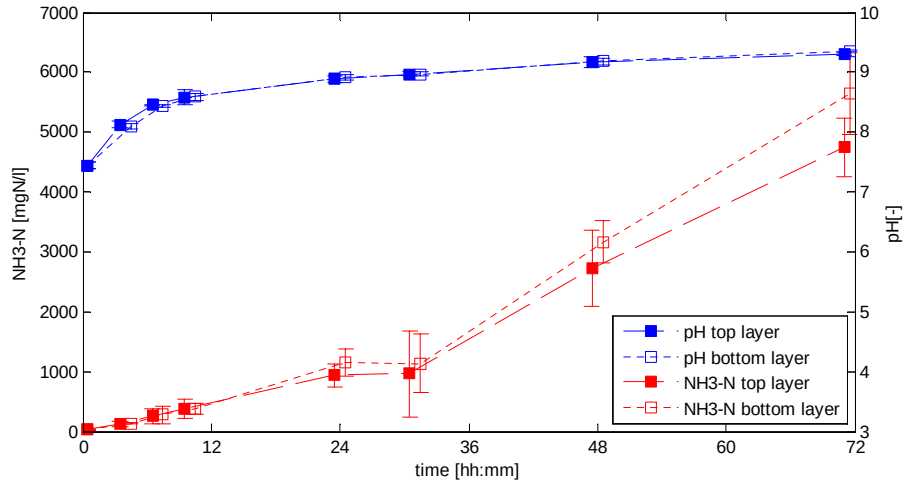


Figure 26: pH and ammonia concentration in the top / bottom layer

The pH and NH_3 concentration in the top and bottom layer indicate that after three days of unmixed treatment the ammonia distribution is relatively homogeneously (Figure 26). However pockets with lower pH and / or ammonia might still occur within the sludge.

The E. coli reduction rates for mixed and unmixed treatment ($^{2.9}\log_{10}$ / $^{2.0}\log_{10}$) and the rates for Enterococci ($^{0.5}\log_{10}$ / $^{0.1}\log_{10}$) do not result in conclusions on the effect of mixing. With longer treatment time the difference between mixed and unmixed conditions, both in ammonia distribution and removal rates might becomes more distinguished.

Extent of stabilization

The unmixed control treatment resulted in layering of the sludge. The top layer had a solid content of 14% / 19% whereas the bottom layer had a TS content of 2% / 1%, first and second experiment respectively. After one day of settling layering was already noticeable, approximately half of the volume consisted of liquid sludge the other half of an airy mass (Figure 27).

Figure 27: bottom and top mass (left); top view of the unmixed control (middle); top layer unmixed control (right)

During unmixed urea treatment the top and bottom layer have a comparable total solids content (top layer: 12%; bottom layer: 9%) indicating that no defined stratification takes place after urea addition. There is no significant change in COD for the four treatments.

5.4 Treatment summary

Experiment 1

- The addition of 1% urea concentration (with 40% purity) to faecal sludge at ambient temperature of 24C was sufficient to produce a sanitised sludge
- The WHO guidelines of $< 10^3$ E.coli CFU/100ml was reached within 4 days
- A log reduction of > 3 $\log_{10}$ of Escherichia coli, Salmonella and Total coliforms was achieved within a treatment time of 1 week and an ammonia concentration above 10g/L

Experiment 2

- To meet the WHO guideline on safe sludge handling (E. coli $\leq 10^3$MPN/100ml) urea treatment (2% w/w) has to be applied for a period exceeding three days
- A three day period of urea treatment (2% w/w) does not affect the Enterococci present in the sludge
- Without intensive mixing the ammonia distribution in sludge seems to be relatively homogeneous, hence mixing to ensure a uniform NH_3 concentration might not be necessary
- Layering did not take place in the unmixed treated sludge, whereas in the unmixed control two distinctive layers were present

CHAPTER 6 LIME TREATMENT

This Chapter has been completed based on the research conducted by Happiness Nobela in collaboration with Unesco IHE and Katie Anderson. Please refer to MSc Thesis MWI SE 2014-17 and the field work report for more detailed information. This can be downloaded from the WASTE website www.waste.nl

6.1 Theory

6.1.1 Process overview

Alkaline or Lime stabilization is a simple process which reduces odor, vector attraction and pathogen levels in wastewater and wastewater treatment sludges (also known as biosolids) ((Williford, Chen, Shammas, & Wang, 2007)The process involves the application of an alkaline substance such as calcium hydroxide ($Ca(OH)_2$) to increase the pH and create a highly alkaline environment which is hostile to biological activity (Schwing Bioset, 2009). Alkaline stabilization encompasses treatment processes utilizing hydrated lime (calcium hydroxide), quicklime (Calcium Oxide), fly ash, lime and cement kiln dust and carbide lime (Williford, Chen, Shammas, & Wang, 2007). The research conducted in this report focused purely on calcium hydroxide also known as hydrated lime or slaked lime.

Traditionally lime conditioning was used within the wastewater treatment process to improve the dewatering capabilities of the sludge, however over time added benefits of odor and pathogen level reduction were also observed (Williford, Chen, Shammas, & Wang, 2007). (Bina, Movahedian, & Kord, 2004) and (Kampelmacher, Van Noorle, & Jansen, 1972) highlighted the bactericidal value of adding lime to biosolids. Currently lime stabilization is a method that is readily applied as a post-treatment to sanitize wastewater treatment sludges (biosolids) in order for them to become suitable for application on agricultural land or disposal in a sanitary landfill (Williford, Chen, Shammas, & Wang, 2007).

(Czechowski & Marcinkowski, 2006) investigated the effect of physicochemical properties and molecular composition during the stabilization of sewage sludge with calcium hydroxide. It was observed that an increase of $Ca(OH)_2$ concentration causes the following effects:

- Enhanced ammonia release
- Preferential hydrolyses of fats and proteins from the sludge macromolecular network
- Transformation of free fatty acids contained in the sludge lipids→ release to calcium salts
- Addition of alkaline agent for the sludge stabilization accelerates equilibration of the process and reduces content of pathogenic microorganisms.

6.1.2 Sanitisation

Numerous studies describe the effectiveness of lime in reducing microbiological hazards in water and wastewater ((Riehl, 1952); (Buzzell & Sawyer, 1967); (Grabow, 1969); (US EPA, 1973); (Kampelmacher, Van Noorle, & Jansen, 1972), (Bina, Movahedian, & Kord, 2004)).

Calcium hydroxide ($Ca(OH)_2$) is an alkaline compound that can create pH levels as high as 12.4. At pH levels greater than 12, the cell membranes of harmful pathogens are destroyed. The high pH also provides a vector attraction barrier, preventing flies and other insects from

infesting the treated biological waste. Because lime has low solubility in water, lime molecules persist in biosolids. This helps to maintain the pH above 12 and prevent re-growth of pathogens (Schwing Bioset, 2009).

(Bina, Movahedian, & Kord, 2004)highlighted that lime is a cheap and easily accessible chemical that is effective in reducing both pathogens and vector attraction when correctly applied. The work of (Bina, Movahedian, & Kord, 2004)investigated the pathogen removal and vector reduction efficiency of lime treatments applied to achieve pH11 and pH12 conditions. Total coliform, faecal coliform, Salmonella and Helminth eggs were analysed to assess pathogen removal efficiency and the reduction in volatile solids and monitoring of pH was used to assess the vector reduction potential of lime treatment. The sanitation requirements for faecal coliform (<1000 MPN/g ds), salmonella (<3 MPN/4g) were achieved for the pH 12 experiment. Although the sanitation requirement for faecal coliform was achieved initially within 24h of the pH 11 experiment, regrowth of bacteria was observed after 72hours of storage. It was concluded that lime treatment was ineffective at reducing Helminth eggs at both pH11 and pH12. The vector attraction reducing requirements are defined as reducing >38% volatile solids, maintaining pH 12 for 2h or maintaining >pH11 for 22hours (Mignotte, 2001). These requirements for reducing vector attraction were only achieved for the pH 12 case (Bina, Movahedian, & Kord, 2004).

Evans noted that the lime addition to sludge releases ammonia which assists in the destruction of coliform bacteria (Williford, Chen, Shammas, & Wang, 2007). The work of Fitzmorris further corroborated Evan's observation, promoting that if contained within the reactor, the liberated ammonia acts as a biocide that further kills pathogens. Ammonia molecules are known to be highly soluble in water as well as lipids. This characteristic enhances the transportation of ammonia over the cell membranes and other cellular walls by diffusions. Once in the cell, Ammonia causes an increase in the internal pH, destruction of the membrane potential as well as denaturalization of the bacterial membrane and cell proteins. This eventually leads to cell decay and overall pathogen destruction (Nordin, 2010).

Overall pathogen reduction is achieved by the high pH levels and the ammonia concentration induced through the addition of lime (calcium hydroxide).

6.1.3 Stabilisation

High lime doses in biosolids affects chemical and physical characteristics of the biosolids ((Oerke, 1989)and (Smith, Goins, & Logan, 1996)). Although complex chemical reactions between lime and biosolids are not well understood it has been observed that the high pH environment induced by lime addition creates the opportunity for the following mild reactions to take place: saponification of fats and oils, hydrolysis and dissolution of proteins, decomposition of proteins to form methanol (US EPA, 1975).

Odorous gases containing nitrogen and sulphur are produced by microorganisms during the decomposition process. Under highly alkaline environments such as those created through the addition of lime, microorganisms responsible for decomposition are strongly inhibited or destroyed. There is no direct organic matter reduction during the lime stabilization process and the addition of lime does not make biosolids chemically stable. If the pH drops below pH 11, biological decomposition will resume resulting in the production of noxious odours (Williford, Chen, Shammas, & Wang, 2007). The solubility of calcium hydroxide provides free calcium

ions, which react and form complex compounds with odorous sulphur species such as hydrogen sulphide and organic mercaptans (Schwing Bioset, 2009)

Testing has shown that lime stabilization reduces the volatile matter content of wastewater treatment sludges above that predicted by dilution caused by lime addition (US EPA, 1975). Possible explanations for the loss in sludge biosolids include the reactions between lime and nitrogenous organic matter. Hydrolysis of proteins and destruction of amino acids are known to occur by reaction with strong bases. Volatile substances such as ammonia, water, and low molecular weight amines or other volatile organics may possibly be formed and lost to the atmosphere.

6.1.4 Lime Dosage

The amount of lime required to stabilize is determined by the type of biosolids, its chemical composition and the solids concentration (Williford et al, 2007). The lime dosage required to achieve the desirable pH is highly related to the solids concentration as illustrated in figure 1. A common lime dosage required to achieve the US EPA guidelines of pH 12 for a minimum of 2 hours is 0,25kg Lime per kg ww solids (assuming 20% solids). The work of (Paulsrud,1975 and USEPA,1977) reinforced this theory that the pH of the treated biosolids is required to be greater than pH11 for a period of 2 weeks. This is translated into high lime dosages to raise the initial pH and prevent decay in pH levels of the treated biosolids as illustrated in Figure 2.

Based on this relationship, a minimum of approximately 10% lime dosage was required to maintain pH >12.0 for 24 hours. Because the relationship, as shown in Figure 28 and Figure 29, is site specific it should only be used to approximate lime doses for similar feed solids. Where additional accuracy is required, bench pilot studies should be conducted using the solids to be treated (Williford, Chen, Shammas, & Wang, 2007).

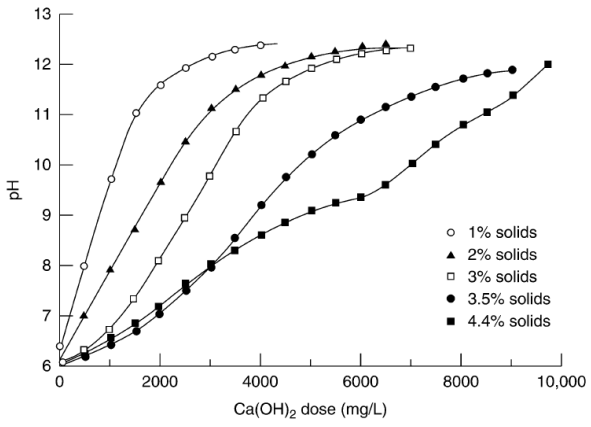


Figure 28 Lime doses for raising the pH of primary/trickling filter biosolids mixture at different solids concentrations (*Source:* US EPA,1975).

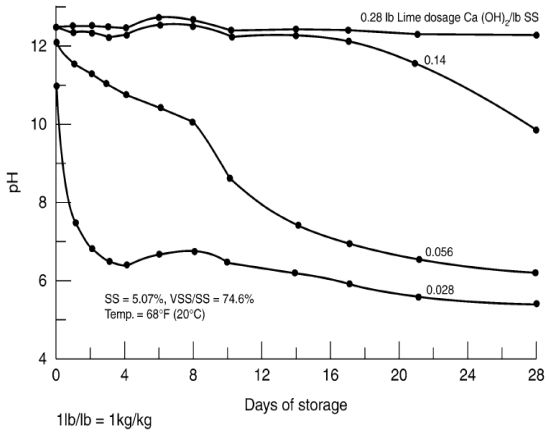


Figure 29 Change in pH during storage of primary biosolids using different lime dosages (*Source:*US EPA,1975).

6.2 Methodology

Two small-scale lime stabilisation experiments were conducted using pit latrine sludge in Blantyre, Malawi. The first experiment dosed lime based on the solids content of the sludge and was conducted using both quick lime (CaO) and hydrated lime ($Ca(OH)_2$). The second experiment was conducted only with hydrated lime ($Ca(OH)_2$) using pH control, thereby dosing lime to achieve a target pH.

6.2.1 Experiment 1: Lime dosage %ds

Lime Experiment 1 was conducted in triplicate. The first trial was conducted using quick lime and the subsequent two trials were conducted using hydrated lime (due to resources availability). These lime stabilisation experiments used lime dosage based on percent solids concentration in the range of 30-60% w/w lime to faecal sludge and aimed to increase the pH above pH 12 for the duration of 2 hours.

Figure 30 : Lime Experiment 1 Set up

Apparatus

- 50L Plastic Container Reactors
- Electric Mixer + agitator (including extension cable)
- 1,000ml measuring cylinder
- 100ml sampling bottles
- Sprayer
- Stirring Stick (50cm length)
- pH meter
- Weighing devices : Bathroom scale (5-200kg) and Kitchen scale (0-5kg)

Materials

- Faecal Sludge
- Hydrated Lime (sourced from Zambia with approximate 40% purity)
- Quick Lime (Laboratory grade 90% purity)

Procedure

1. Each 50L drum was filled with approximately 25L of faecal sludge collected from a pit latrine using the reverse vacuum pump from the ROM(the desludging device).
2. A Faecal Sludge sample was taken and analysed for pH, conductivity, TS and VS at the laboratory using the methods outlined in Chapter 2.3.
3. Each of the treatment drums were weighed using the bathroom scale and their mass recorded
4. Based on the Solids content (%TS) determined in step 2 and the sludge weight in the various treatment drums determined in step 3, The Lime additions (Quicklime in trial 1 and Hydrated lime in trial 2-3) were weighed using the kitchen scale to create the equivalent of 30%, 40%, 50%, 60% w/w and placed in sealed plastic bags. The dosage was calculated using the following formula:

$$Lime\ Dosage\ (kg) = \frac{TS\%\ x\ Sludge\ Mass\ (kg)}{Lime\ purity\ (\%)}$$

5. An initial sample was taken from each of the five drums and the pH recorded
6. The measure lime doses of 30-60% w/w were added to reactor 1-4 respectively
7. Each drum reactor was mixed subsequent to the lime addition using the electric mixer (refer Figure 31
8. 100ml Samples were taken from the top of the drum after 5min, 15mins, 30min, 60mins and 120mins subsequent to the lime addition from each of the five drum reactors.

Figure 31: Electronic Mixing used in Lime Experiment 1

6.2.2 Experiment 2: pH control

The second lime experiment utilized hydrated lime exclusively and focused on pH control. The results from Experiment 1 indicated that pathogen deactivation was more related to the pH achieved rather than the amount of lime added upon a weight and solids concentration basis. Therefore the focus of this experiment was to determine the threshold pH required to sanitize sludge to WHO guideline conditions. Experiment 1 utilised 30-60% lime doses, whereas Experiment 2 explored lower doses of 3-20% with the focus being on pH control. This experiment was conducted in triplicate on three separate days utilizing sludge sourced from the Bangwe market.

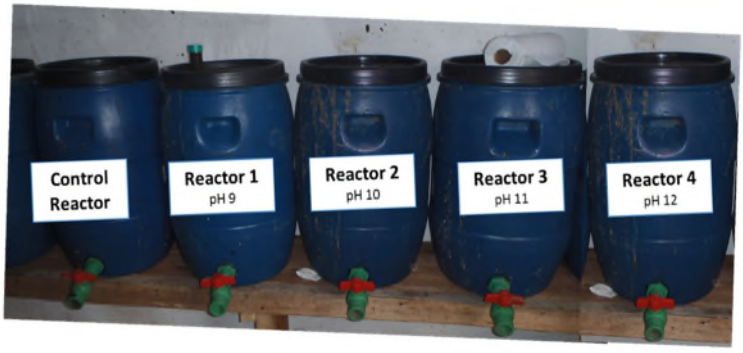


Figure 32 ***Hydrated Lime Experiment 2 Field Set Up***

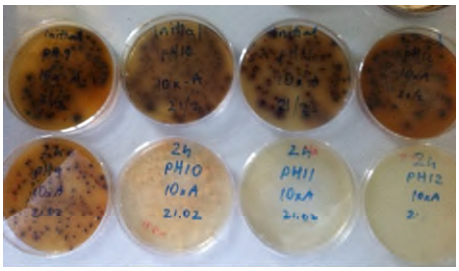


Figure 33:*Plate Count using Chromocult Agar*

Materials:

- 5 x 50L Plastic Drums
- Electric Mixer + agitator (including extension cable)
- Stirring Stick (50cm length)
- Hydrated Lime (sourced from Zambia with approximate 40% purity)
- Shovel
- pH meter
- Weighing devices : Bathroom scale (5-200kg) and Kitchen scale (0-5kg)
- 5 x 1L plastic sampling bottles
- 25 x 60ml plastic sampling bottles
- 4 x sealable bags

Procedure:

1. Each 50L drum was filled with approximately 30L of faecal sludge collected from a pit latrine using the reverse vacuum pump from the ROM(the desludging device).
2. The drums were labeled with a marker: Control, pH 9, pH 10, pH 11 and pH 12.
3. Each of the drums were weighed using the bathroom scale and the sludge weight determined by subtracting the empty drum weight.
4. The sludge in each of the drums was stirred using a stick in an attempt to make the sludge as homogeneous as possible
5. Initial samples from each drum were taken using the 1L plastic sampling bottles
6. The initial pH of each drum was measured using the pH meter and the value recorded
7. From the initial samples, the lime dosage was determined using the procedure detailed in Appendix A.

8. The required weight of hydrated lime for each of the pH drums (refer Table b in Appendix A for values) was measured using the kitchen scales and placed into 4 separate and labelled sealed plastic bags.
9. Using the 60ml plastic sampling bottles, a sample was taken from each of the 5 drums subsequent to stirring with the stick
10. Using the electric mixer, the control drum was mixed for 10 minutes and then a 60ml sample taken
11. The lime for the pH 9 drum was poured from the respective sealed plastic bag into the appropriated drum and stirred with the stick until the lime powder had been adsorbed into the sludge.
12. Using the electric mixer, the pH 9 drum was mixed for 10 minutes
13. A sample from the pH 9 drum was then taken using the 60ml plastic bottle and the pH recorded.
14. Steps 10 -12 were repeated for pH 10, pH 11 and pH 12 drum reactors.
15. Subsequent samples were taken from each of the drums at 1h, 2h, 5h and 1d after mixing using the 60ml plastic sampling bottles.

6.3 Experimental results

6.3.1 Experiment 1

pH

The pH recorded in the treatment reactors dosed with 30-60%w lime/ w ds ranged between 12.2-12.4 respectively. There was no pH difference detected between the experiments which utilized quick lime compared to those experiment which utilized hydrated lime. All trials conducted maintained pH conditions greater than pH12 for a period of two hours (refer Figure 34).

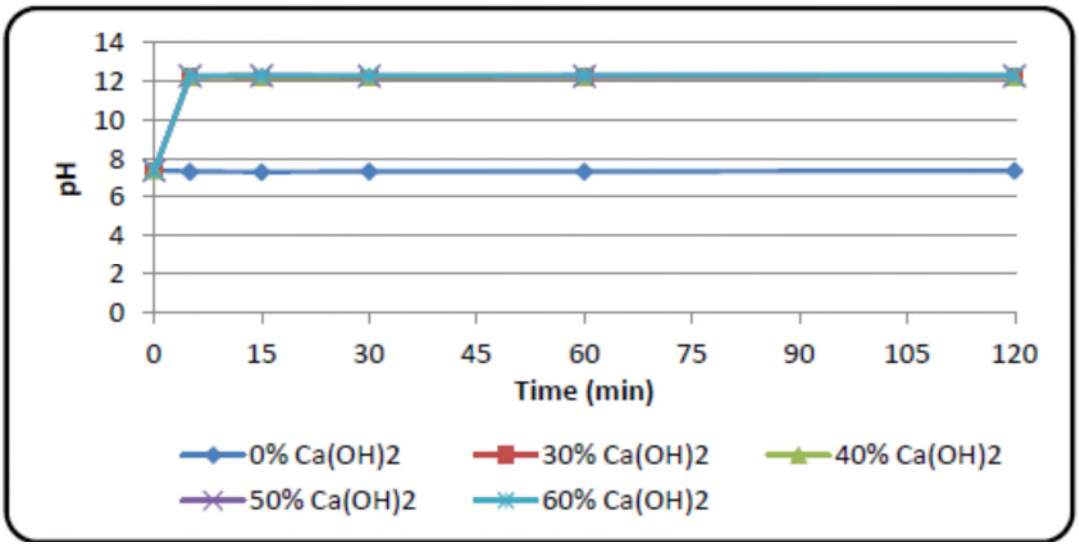


Figure 34: pH measurements during Lime Stabilisation Experiment 1, conducted in triplicate.

E.coli

The E.coli concentration was quickly reduced to below detectable limits and the WHO guidelines within 5 minutes subsequent to the lime dosage for all four reactors in all three experimnets. This implies a log reduction of E-coli greater than 4 Log_{10} (refer Figure 35 & Figure 36)

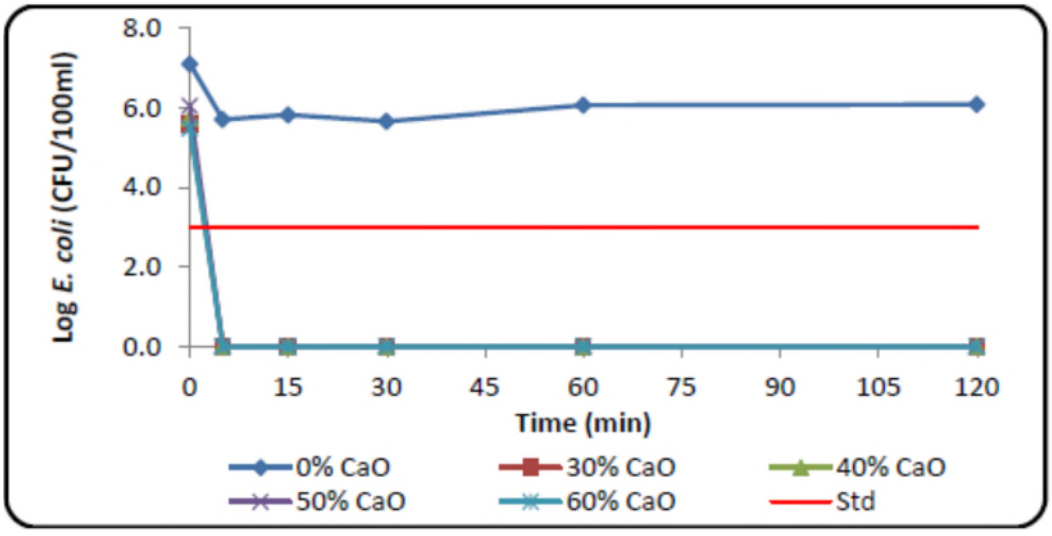


Figure 35: Log reduction in *E.coli* using quick lime : Experiment 1 Trial 1

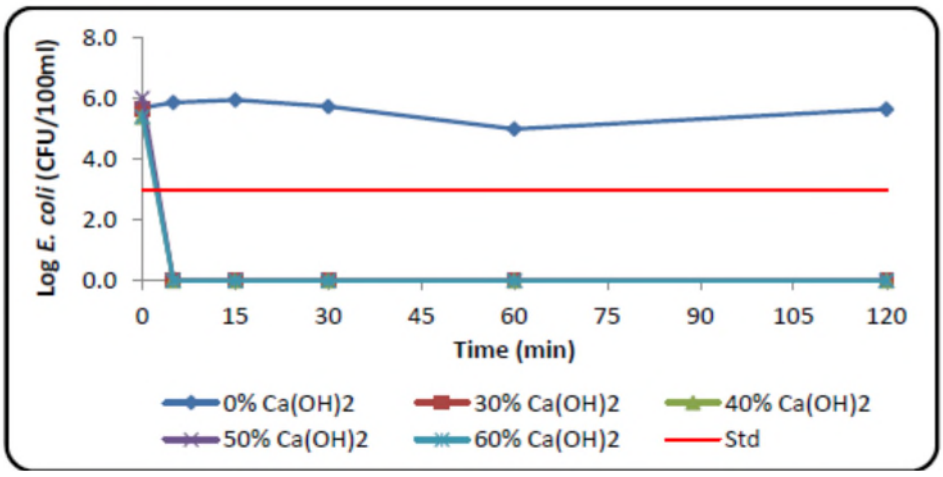


Figure 36: Log reduction in *E.coli* using hydrated lime : Experiment 1 Trial 2&3

Total Coliforms

Total coliform reduction exhibited similar trends to those observed with *E.coli* with rapid inactivation observed within 5 minutes for all treatment reactors (30-60%w/w ds) in both the quicklime and hydrated lime trials.

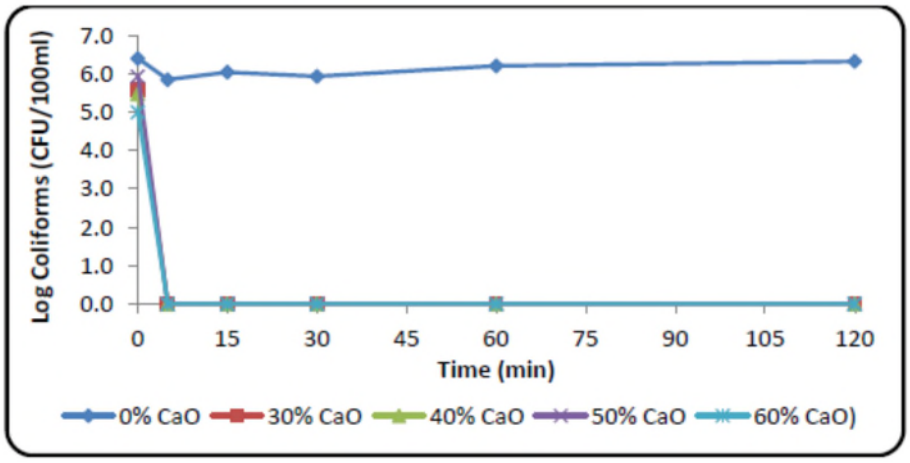


Figure 37: Log reduction in *Total Coliforms* using quick lime : Experiment 1 Trial 1

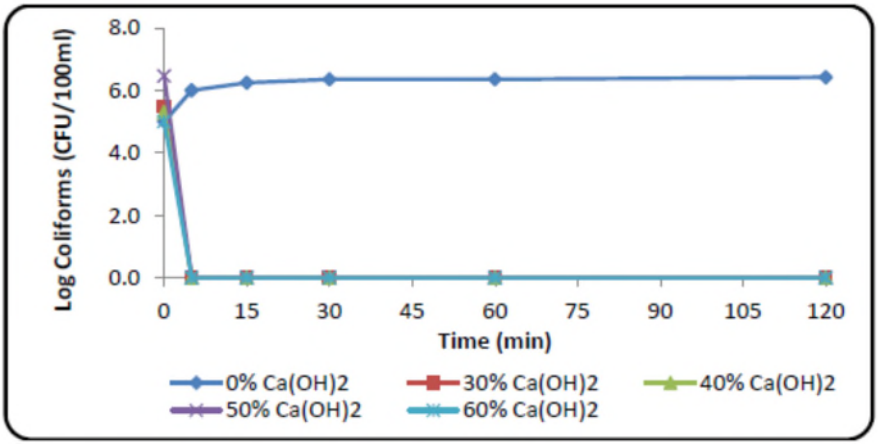


Figure 38: Log reduction in *Total Coliforms* using hydrated lime : Experiment 1 Trial 2&3

6.3.1 Experiment 2

Lime dosage

From literature based on lime stabilization of biosolids it is stated that the amount of lime required to stabilize is determined by the type of biosolids, its chemical composition and solids concentration. Figure 39 illustrates the lime dosage curves based on dry sludge weight associated with the three sludges used in trial 1-3 of Lime experiment 2. It is clearly evident that the shape of the curve is unique to each sludge. The amount of lime required to induce a pH rise is linked to the alkalinity of the faecal sludge which impacts the buffering capacity. From Table 5 in Chapter 3, the alkalinity of pit latrine faecal sludge is in the range of 8-16g $CaCO_3$/ L and due to the heterogeneous nature of faecal sludge, the alkalinity varies even within the same pit.

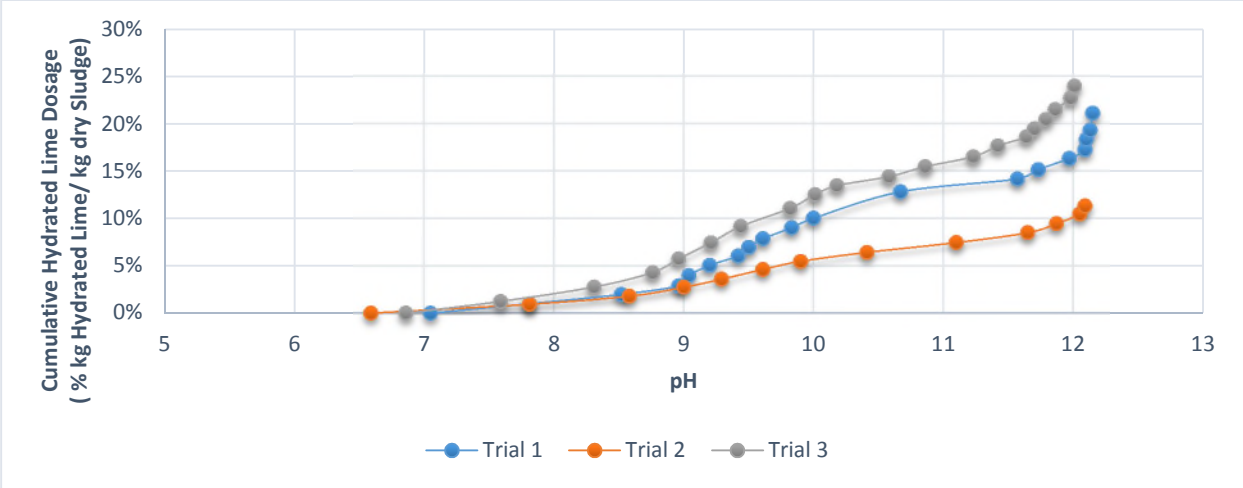


Figure 39: Lime Dosage based on dry weight of faecal sludge

Sanitisation :* Escherichia *coli

The indicator organisms used to analyze pathogen reduction were *Escherichia* coli (*E.coli*), Total Coliforms (Escherichia coli, Enterobacter, Citrobacter, Klebsiella), Salmonella and other Enterobacteriacae.

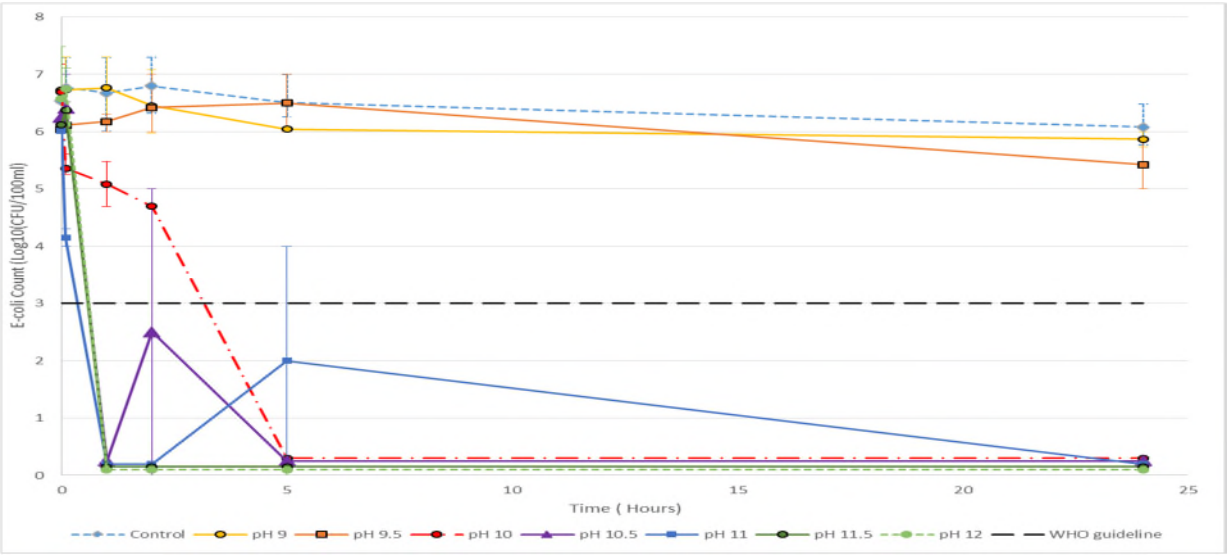


Figure 40: E-coli reduction using hydrated lime for pit latrine faecal sludge treatment controlling pH

As illustrated in Figure 40, a reduction from an average e-coli content of 10^7 CFU/100ml to $<10^3$ CFU/100ml within 24 hours is possible for pH conditions greater than pH 10. However taking into account all individual readings, in order to guarantee that the e-coli concentration will be reduced to below the WHO guideline limit of $<10^3$ CFU/100ml, the pH is required to be greater than pH 11.5 (refer Figure 40).

Total Coliforms

The combined results of all three experiments for total coliforms (e-coli + other coliforms (Enterobacter, Citrobacter, Klebsiella)) reduction based on target pH is illustrated in Figure 41. All coliform values are given as Log_{10} (CFU/100ml) .

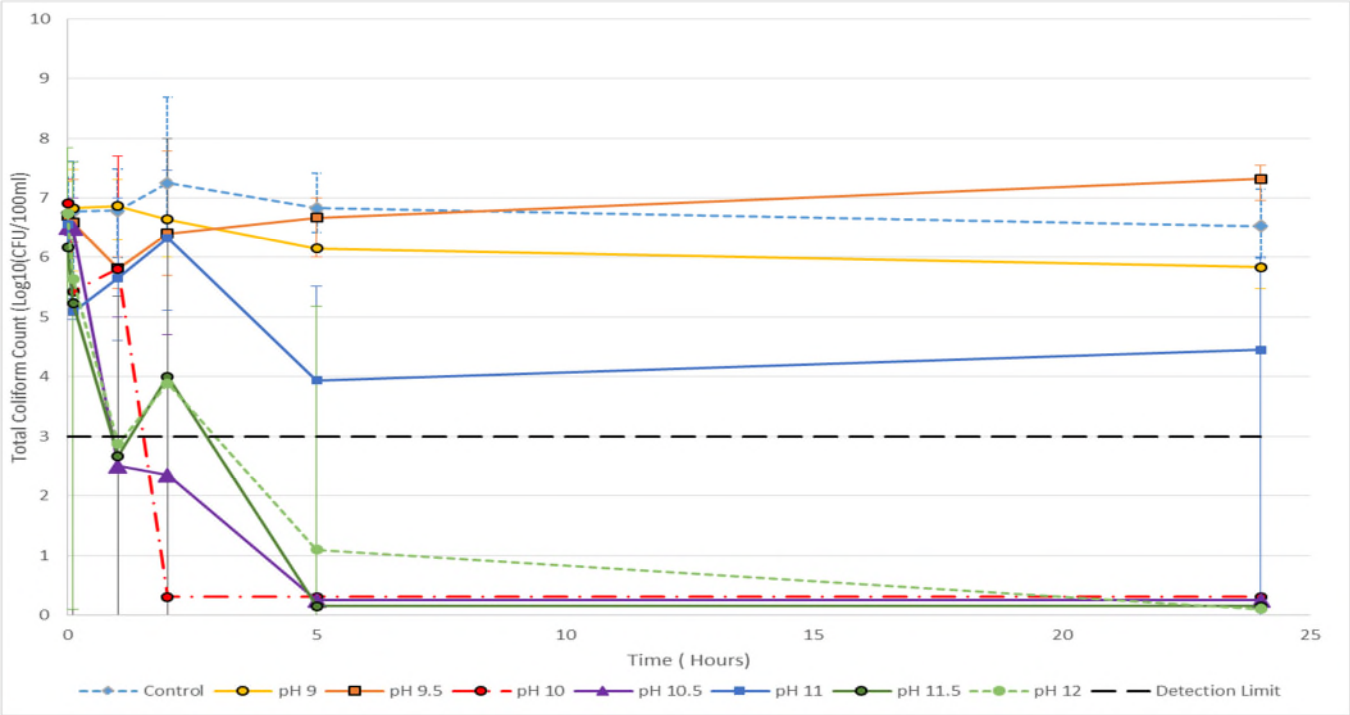


Figure 41: Total Coliform Reduction with Hydrated Lime controlling pH

Other coliforms (Enterobacter, Citrobacter, Klebsiella) proved to be more resistant than Escherichia coli and as expected the treatment time for a similar log reduction was longer in all experiments being approximately 5 hours for Total Coliforms compared to 1 hour for *Escherichia* coli for pH >10. Similarly in order to guarantee log reduction in other coliforms pH >11.5 was required. This is consistent with the literature that states that below pH 12, regrowth will occur within the sludge as at lower pH conditions (pH 10-11) pathogens are only inactivated and not destroyed

Salmonella

The combined results of all three trials for salmonella reduction based on target pH is illustrated in Figure 42. All Salmonella values are given as Log_{10} (CFU/100ml). Salmonella was observed to be less resistant to the hydrated lime treatment compared to Escherichia coli and other coliforms. The average salmonella concentration being reduced from 10^6 CFU/100ml to $<10^3$ CFU/100ml by pH conditions above pH 9.5 within 2 hours.

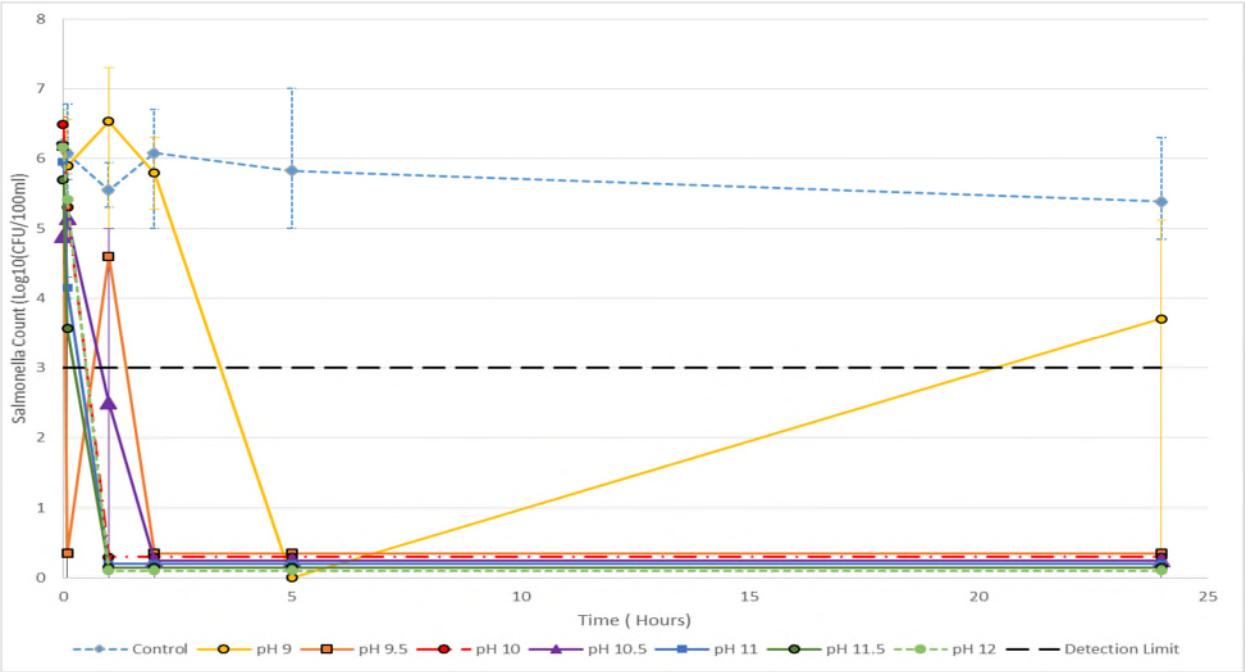


Figure 42: Salmonella Reduction with Hydrated Lime controlling pH

Other Enterobacteriacae

The combined results of all three trials for other Enterobacteriacae reduction based on target pH is illustrated in Figure 43. All other Enterobacteriacae values are given as Log_{10} (CFU/100ml) . Other Enterobacteriacae were observed to be more resistant to hydrated lime treatment relative to salmonella, Escherichia coli and other Coliforms. Other Enterobacteriacae were only reduced to below the detection limit of 10^3 CFU/100ml in two experiments using pH 12 conditions. This implies that merely pH stress is not able to deactivate other Enterobacteriacae within 24 hours. It is recommended that additional studies be conducted to investigate extended treatment time and also combination treatments with toxins such as ammonia which could assist in reduction of more resistant pathogens.

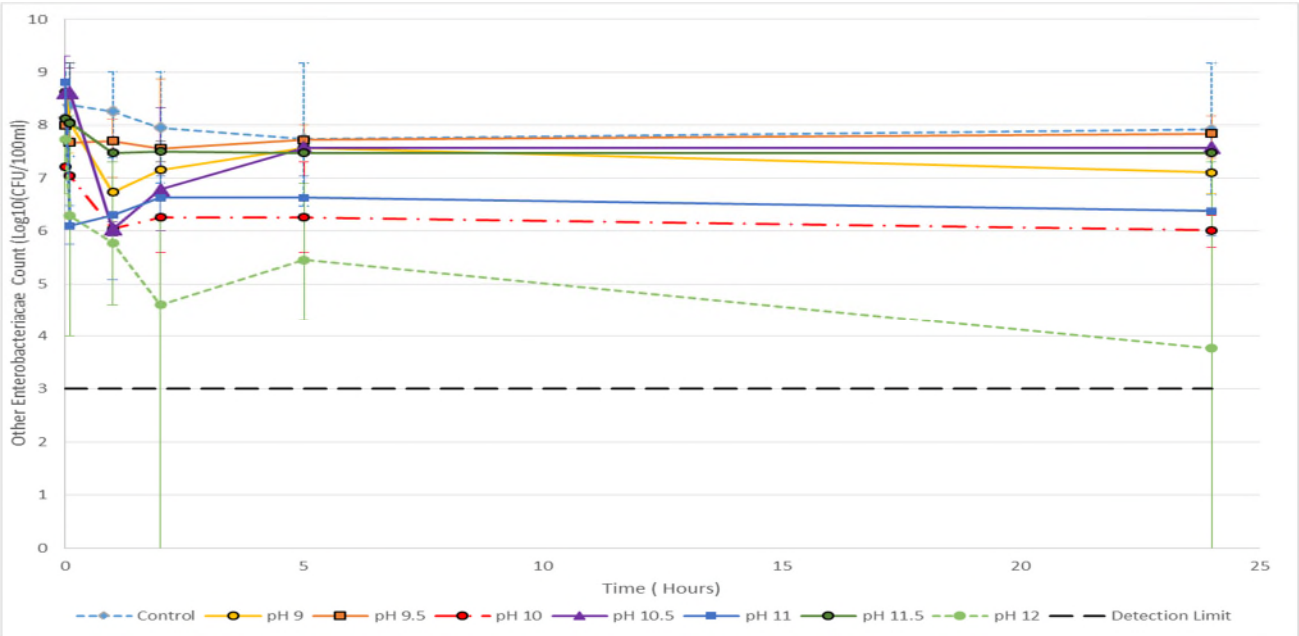
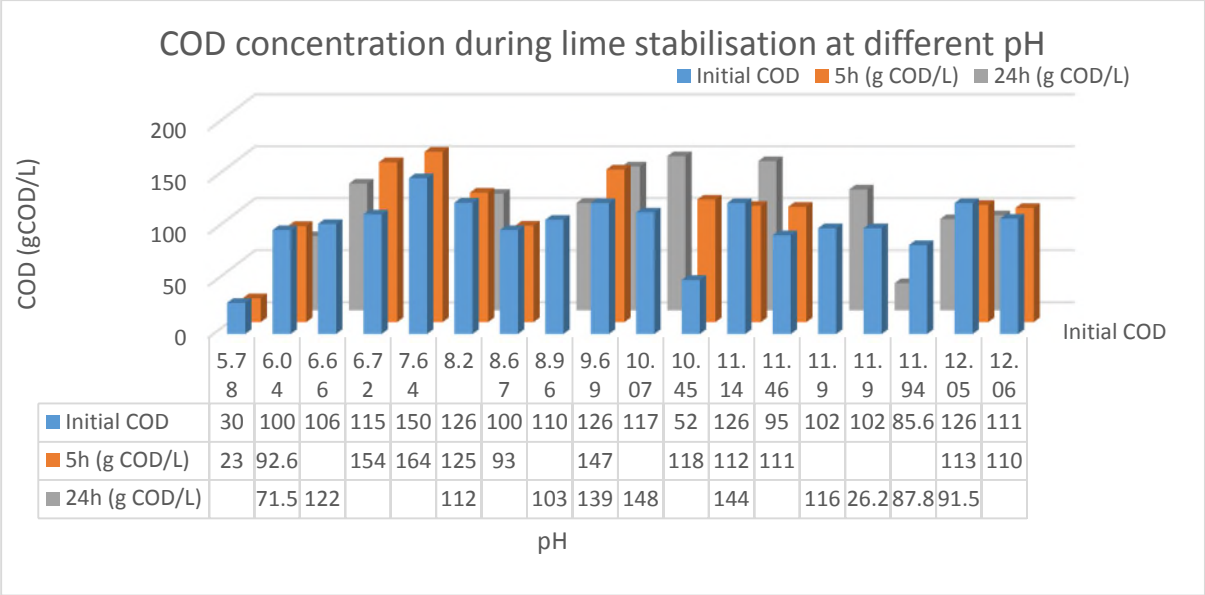


Figure 43: Other Enterobacteriacae Reduction with Hydrated Lime controlling pH

Chemical Oxygen Demand (COD)

The COD measurements recorded during the three lime stabilization trials are summarized in Figure 44 based on initial pH. Overall taking into account the error associated with the COD measurements using the Hach Lange 8000 method for sludge samples, no reduction in Chemical Oxygen Demand was observed for any of the lime stabilization experiments.



pH	5.78	6.04	6.66	6.72	7.64	8.2	8.67	8.96	9.69	10.07	10.45	11.14	11.46	11.9	11.9	11.94	12.05	12.06
Initial COD	30	100	106	115	150	126	100	110	126	117	52	126	95	102	102	85.6	126	111
5h (g COD/L)	23	92.6		154	164	125	93		147		118	112	111				113	110
24h (g COD/L)		71.5	122			112		103	139	148		144		116	26.2	87.8	91.5	

Figure 44: Chemical Oxygen Demand during Lime Stabilisation at different pH levels

Total solids (TS) and Volatile Solids(VS)

The initial and final TS and VS that were recorded for the Lime Treatment trial 3 are illustrated in Figure 45. Variability between initial TS and VS of the different reactors within an experimental batch - demonstrates the heterogeneity of faecal sludge. Taking this into account – the small changes in TS and VS that occurred during the lime stabilization process are relatively insignificant. Naturally an increase in TS was observed for the reactors dosed with lime due to the physical chemical addition. However this % solids increase due to chemical addition was minimal varying between 3% - 21% increase in total solids depending on the target pH within the reactors. Overall no significant decrease in VS was observed implying that stabilization occurring with lime dosages (3-18%w/w ds) is limited within a 24 hour period.

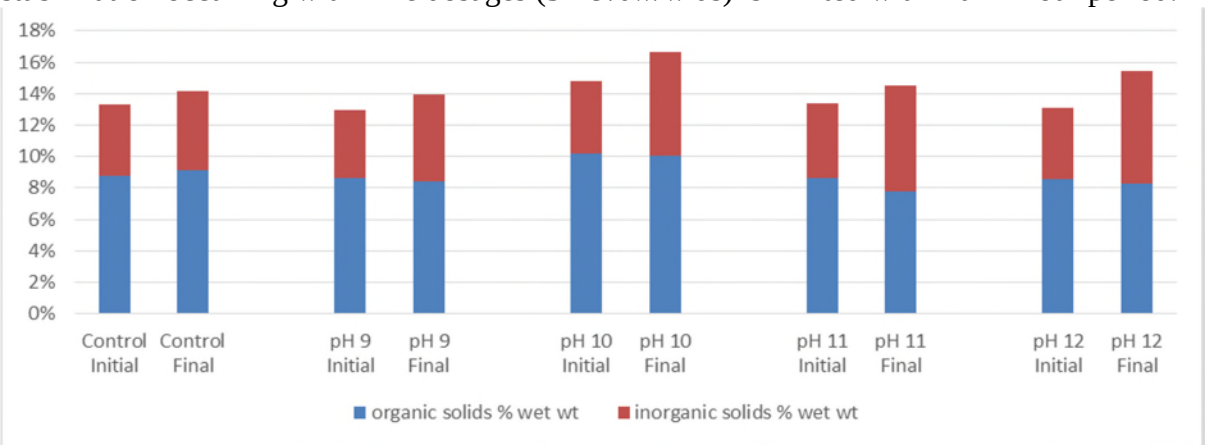


Figure 45: Initial and Final total and Volatile Solids measurements from Lime Trial 3

6.4 Treatment summary

Experiment 1:

- Lime Treatment is a rapid method to sanitize sludge and can be achieved with both quicklime (CaO) and hydrated lime ($Ca(OH)_2$) additions.
- During the field trials no noticeable difference between quicklime and hydrated lime treatments was observed for the 30-60% w/w ds treatment experiments.
- Sanitisation to levels below the WHO guideline limit of $<10^3$ *E.coli* CFU/100ml was achieved by all reactors 30-60% lime w/w ds.
- Total coliforms and e-coli were reduced to below detectable levels within 5 minutes subsequent to the 30%w/w Lime addition and remained below detectable limits throughout the 2 hour experiment.
- The addition of 30%w/w lime resulted in a pH increase to approximately pH 12.2
- pH conditions remained above 12 for all treatment reactor throughout the 2 hour experiments
- Lime addition also eliminates odour which will in turn reduce vector attraction
- Pathogen die-off is related to pH rather than a direct function of the amount of lime added to the reactor.

Experiment 2:

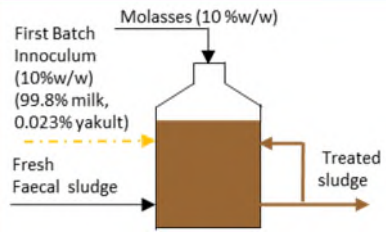
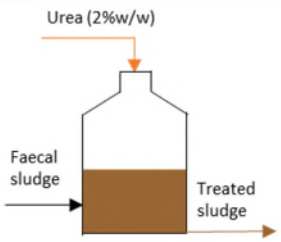
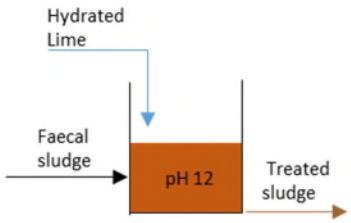
- Faecal sludge sourced from a pit latrine can be sanitized to WHO guideline limit of $<10^3$ CFU/100ml through hydrated lime treatment maintaining >pH 11.5 for a period of 2 hours.
- Salmonella was the least resistant of the indicator organisms, being reduced from 10^6 CFU/100ml to $<10^3$ CFU/100ml by pH conditions above pH 9.5 within 2 hours.
- Other coliforms (Enterobacter, Citrobacter and Klebsiella) were reduced to below detectable limits ($<10^3$ CFU/100ml) within 5 hours for pH conditions >pH 11.4
- Other Enterobacteriacae are more resistant to hydrated lime treatment and were not consistently removed even in pH 12 over a period of 24 hours.
- The lime dosage to achieve pH 11.5 conditions is case specific due to the heterogeneity of faecal sludge. In the three trials conducted lime doses range between 9-20%w/w ds.
- Stabilisation was not observed with initial and final COD and VS measurements being comparable

In conclusion Lime stabilization at pH>11.5 has the ability to sanitize faecal sludge derived from pit latrines to the WHO guideline limits within 2 hours.

CHAPTER 7 SYSTEM COMPARISON

The three sanitisation methods: lactic acid fermentation, urea treatment and lime stabilisation were all able to achieve the WHO guideline limit for e-coli of $<10^3$ E-coli /100ml. Table 7 compares the three faecal sludge sanitising methods and illustrates the advantages and limitations of each of these treatment technologies. Sanitation time is defined as the time required to achieve the WHO guidelines limit for e-coli of $<10^3$ E-coli /100ml.

Table 7: Emergency Faecal Sludge Treatment Comparison

Criteria	Lactic Acid	Ammonia	Lime
Technology	Biological Treatment	Bio-Chemical Treatment	Chemical Treatment
Process			
Sanitisation time	7-15 days	4-8 days	2 hours
End pH of Faecal Sludge	3.8-4.2	9-9.5	11-12.5
Chemical Use	**Sugar Additive**	**Urea**	**Hydrated Lime**
Chemical Use	2g simple sugar/kg sludge 10% w/w pre culture (Pre-culture: 0.2% Yakult, 99.8% Milk)→ 30g/L Lactic Acid	2%w/w Urea (20g Urea/kg Sludge – 9g TAN/kg Sludge)	17-30g Hydrated Lime/ kg Sludge
Chemical cost per m^3 faecal sludge[1]	**€2.20/m^3** (100L Molasses) **€31.20/m^3** (Pre culture: 100L Milk, 0.2L Yakult)	**€16/m^3** (20kg Urea)	**€12/m^3** (25kg Lime)
Limitations	Temperature dependence for Lactic Acid Bacteria fermentation	Temperature dependence for urea decomposition with urease Initial homogeneous mixing required Air-tight container	Initial homogeneous mixing required
Additional Treatment/ Re-use	Drying bed/ inoculum for subsequent batches	Drying bed/ fertilizer	Drying bed/ soil conditioner for acidic soils

[1] Note chemical costs are based on product costs sourced from Malawi originally in Malawian Kwacha.

The treatment time to achieve the sanitisation target greatly differed for the three processes. Lime was able to sanitize the sludge within 2 hours, urea required 1 week and lactic acid fermentation needed approximately 2 weeks.

Whilst all three process are relatively simple, the biological nature of lactic acid fermentation as well as the enzyme aspect of the urea treatment make the efficiency of these two processes dependent upon temperature and hence less robust compared to the lime treatment. However the lime treatment is heavily dependent upon homogeneous mixing at the start of the process to ensure that a completely sanitized sludge is produced.

The produced sanitised sludge from each of these three processes is very different in nature: Lactic acid fermentation produces an acidic sludge that has a high content of lactic acid bacteria and hence has the potential to be used directly as an inoculant for subsequent treatment batches. The acidic sludge would require neutralisation in addition to stabilisation prior to being discharged safely into the environment. The sludge produced by the urea treatment is slightly alkaline (pH 9) and has a very high nitrogen content which corresponds to agricultural benefits and reuse potential. The urea-treated sludge is not stabilised and has been exposed to anaerobic conditions, therefore it is an odours material. Hydrated lime produces a highly alkaline sludge which is not odorous, but has limited reuse potential aside from acidic soil conditioning. This sludge would require neutralisation in addition to stabilisation prior to being discharged safely into the environment.

The chemical costs associated with each of the three sanitisation processes were estimated using the Malawian market prices as this is where the trials were conducted. Lactic acid fermentation has the highest cost for the initial batch €31.20/ m^3 sanitised sludge, however the lowest cost for every subsequent batch of €2.20/ m^3. Urea is heavily subsidies in Malawi and hence the urea and lime treatment were comparable being €16/ m^3 sanitised sludge and €12/ m^3 sanitised sludge respectively. The cost of lime treatment is heavily dependent upon the alkalinity of the raw faecal material.

Each sanitisation method has its advantages and disadvantages: lime is the preferred method in terms of treatment time, urea is the preferred method in terms of re-use and lactic acid is the preferred method in terms of economics. Overall there is no sanitisation method that is clearly favourable regarding all aspects but all three have the potential to be implemented and effective during an emergency situation where sanitisation of sludge is vital to preventing the spread of communicative diseases.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

Three emergency faecal sludge sanitation options were investigated through small scale experiments using Fresh Faecal Sludge over 3 months (Jan–April 2014) in Blantyre, Malawi. Preliminary testing has indicated that based on the small-scale field trials, urea treatment, hydrated lime treatment and lactic acid fermentation are promising low-tech faecal sludge treatment technologies and are all potentially applicable to emergency situations.

All three treatment processes are able to satisfy the top four criteria for emergency faecal sludge treatment processes.

1. **Safety :** All three treatment process can be conducted safely and adhere to the safety, health and environmental norms and standards during operation and maintenance
2. **Sanitization:** All three treatment processes under certain process conditions are able sanitize faecal sludge to comply with the WHO guideline limit of 10^3 E-coli CFU /100ml
3. **Robustness:** All three treatment process can treat both liquid and solid sludge All three technologies could be undertaken in either an above ground tank or portable bladder and therefore could be effective under challenging physical conditions such as unstable soils, high water tables and flood-prone areas.
4. **Deployment:** All three treatment processes are low-tech and require readily available material: Molasses (common livestock feed); Urea (common fertilizer); and Hydrated Lime (common building material), and therefore have the potential for rapid deployment upon the event of an emergency.

The preliminary result have been promising, however further research is required to prove these simple technologies and create robust processes. The following recommendations are given for future research :

- **up-scaling** each of the three sanitisation processes to treat community volumes is recommended with the additional aim to test the protocols developed in the WASTE document: "*Proposed upscaled faecal sludge sanitisation processes*" which can be downloaded from the WASTE website
- **on-site latrine**-based application of these three treatments should be investigated.
- **multiple testing locations** with alternative climatic environments should be chosen for future field trials to test the robustness of each of the processes and the impact of ambient temperature upon the treatment efficiency.
- **Post-treatment and reuse options** for the sanitised sludge produced by each of the treatment processes should be investigated

Overall, based on the small-scale field trials, urea treatment, hydrated lime treatment and lactic acid fermentation were evaluated to be promising low-tech faecal sludge treatment technologies and are all potentially applicable to emergency situations. Additional research and up-scaling is required to optimize each treatment process and to establish robust procedures that could be easily implemented in the event of an emergency.

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