

UNIVERSITY OF HOHENHEIM
INSTITUTE FOR PLANT PRODUCTION AND AGROECOLOGY IN THE
TROPICS AND SUBTROPICS (380)
SECTION: AGROECOLOGY



Master Thesis

Optimising faecal sludge co-composting in the semiarid Tropics

By

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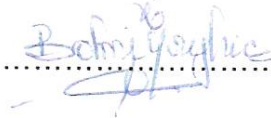
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This research was funded by the Eiselen Foundation Ulm

December 2007

DECLARATION

I hereby declare that the following research is the outcome of personal findings. It has not been presented elsewhere; in part or wholly for a degree. The works of other authors which served as additional sources of information have been duly acknowledged.


.....

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DEDICATION

To my parents Mr. John Timngum Boh and Theodora Nsang whose desire is that I attain the highest rung of the academic ladder. I appreciate your unending support.

ACKNOWLEDGEMENT

I would like to extend my appreciation to Prof. Dr. Joachim Sauerborn for accepting that I do my thesis with him and for his guidance. I am also grateful for the advice of Prof. Dr. Folkard Asch who also accepted to be a second reviewer of my work.

I am thankful to Dr. Germer, who inspired me with the concept of nutrient recycling especially the use of human excreta in agriculture. You were with me in the field and gave me useful hints. My gratitude also goes to Dr. Jan Grenz who read through my manuscript and made valuable comments. I am indebted to Dr. Björn Vinnerås of the Swedish University of Agricultural Sciences for providing me with some relevant literature and advice. I would also like to thank Dr. Phillip Werner of the University of Hohenheim and Dr. Phillip Amoah of the International Water Management Institute, Ghana, for analysing my samples.

My special thanks also go to Rev. Sr. Rosa Maria and all the Rev. sisters of the Carmelite Monastery, Sasse-Buea for their spiritual and moral support. I would like to thank Mrs. Guemto Bettina, Klaus, Astrid and Clara for making it possible for me to pursue my studies in Germany. I am grateful for support given me by ÖHG, Hohenheim.

I would also like to appreciate the support of Dr. Laryea, Mr. Kwandahor, Mr. Mitterer (Toni), Mr. Adai Solomon, Mr. Louis Addy and all the staff and students of Valley View University for their support and for providing a conducive environment during my research. I am also grateful for the support of Emmanuel Jonny, Liza and all the Staff of Orphanage Africa during my field work.

To my friends, Cosmos Amuji, Stephen Nfor, Milly-Kevin, Ndah Hysenth, Oliver Mundi and to all whose names I am not able to mention here, I am thankful. Last and not the least, I wish to express my gratitude to my fiancé, Enowashu Esther Eneckeh; you were there at all times.

December, 2007

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LIST OF ACRONYMS AND ABBREVIATIONS

cfu	colony forming units
C _{org}	Organic Carbon
DM	Dry matter
EC	Electrical Conductivity
FAO	Food and Agricultural Organization
fw	fresh weight
GI	Germination Index
HS	High sludge
HTF	High turning frequency
IWMI	International Water Management Institute
K	Potassium
l	litre
LS	Low sludge
LTF	Low turning frequency
MS	Medium sludge
MTF	Medium turning frequency
N	Nitrogen
OA	Orphanage Africa
P	Phosphorus
UHOH	University of Hohenheim
UNDP	United Nations Development Program
UNMDGs	United Nations Millennium Development Goals
USEPA	United States Environmental Protection Agency
VIP	ventilated improved pit latrines
VVU	Valley View University
WHO	World Health Organization

1. INTRODUCTION

1.1 Background

This study aims at simultaneously addressing several problems related to nutrient flows between man and the environment. Today, valuable plant nutrients enter directly into the environment untreated or are lost through sewage treatment systems which until now have been regarded as a proper way for the disposal of human excreta. In developing countries, the number of people who die due to poor sanitation is already high and is expected to increase in the next decades (Esrey, 2001). The nutrients that now pollute rivers and lakes could be a valuable resource: soils of the tropics tend to be inherently poor in organic matter and nutrients (Winblad and Kilama, 1980; Strauss et al., 2003) due to climatic conditions and poor agricultural practices that have resulted in erosion and other forms of degradation. In Sub-Saharan Africa, prices for mineral fertilisers are high due to poor infrastructure, thus these fertilisers are unaffordable to low income earners who constitute a bulk of the population particularly in land-locked regions (WHO, 2006b). Human excreta, which are available at every household, could become a reliable source of low-cost fertiliser to such poor farmers if properly sanitised. This will help improve soil fertility, result in an increase in food production and thus resolve the twin-problem of hunger and poor sanitation prevalent in the developing countries.

The number of towns and cities in the developing countries is rapidly increasing, with the highest increase expected for Sub-Saharan Africa (UNDP, 2002). As a consequence, soil nutrients are continuously mined from the rural areas to feed the growing population with an estimated 17kg ha^{-1} N, 5kg ha^{-1} P and 25kg ha^{-1} K removed through harvested crops (Grenz and Sauerborn, 2007). This results in a nutrient imbalance between rural and urban areas. If on the other hand those nutrients which are 'exported' in the form of agricultural products (which latter

become faeces) are sanitised and reused in urban or peri-urban agriculture, nutrient pressure on rural soil resources may decrease, giving a chance to more sustainable practices.

The presence of pathogenic bacteria, viruses and helminth eggs in human excreta especially faeces may be a limiting factor for their use in agriculture. Therefore, there is a need to develop a proper way of sanitising and recycling the nutrients in human excreta for eventual use in agriculture.

1.2 Problem Statement

Over the years, there has been the use of faecal matter, termed 'night soil', with considerable neglect of the health risks involved in handling and using it in agriculture. Considering that large amounts of pathogens occur in human faeces (Schönning et al., 2007; Vinnerås et al., 2006), this practice can result in health and environmental hazard where no proper treatment is ensured before use in agriculture or discharge into the environment. In the past and in some parts of the world today, faeces are applied directly to the soil or to crops without any form of sanitisation (Esrey et al., 1998). Cofie et al. (2005) reported that over 66% of farmers in Tamale, Ghana, directly apply human faeces to agricultural land before cultivation. Besides, open defecation, which is still practised in most rural and semi-urban areas of developing countries, can be a threat to health, given that the nearby bushes and streams where this occurs can eventually become agricultural land. The eggs of some pathogenic roundworms excreted in human faeces are known to survive in the environment for a long time (Phi et al., 2004). There exists little information on the direct health and environmental impacts of such a practice. However, according to the WHO (2006a), the prevalence of poor sanitary and health conditions in developing countries is closely linked with the management of sanitary wastes in general and human excreta in particular. The Millennium Development Goal (MDG) number 7 targets to reduce the proportion of people living without proper sanitation by 50% until the year 2015 (UN, 2000). While rethinking the environmental safety of conventional practices to excreta disposal, solutions that make use of the nutrients in them should be considered.

Conventional excreta disposal methods have been proven to pose problems: while the “flush-and-forget” systems end up with faecal sludge deposited on landfills or open water bodies causing pollution and contaminating both terrestrial and aquatic life, the pit latrines or “drop-and-store” still do not provide a better way out for excreta disposal. This is because groundwater gets contaminated through leaching leaving those depending on boreholes and wells for water supply at high risk (Winblad, 1997; Drangert, 1998). Apart from pathogens, human excreta may contain heavy metals and pharmaceuticals that can also be hazardous especially to the aquatic environment. The magnitude of this, however, depends on the quantities consumed by the population. The occurrence of pharmaceutical substances in Berlin’s wastewaters has been linked to the overly short retention time (Schönning and Stenström 2004; Herberer et al., 1998).

According to Vinnerås, (2007), safely closing the nutrient loop in agricultural ecosystems entails breaking the pathogen loop, which can be achieved by sanitising faecal-derived fertiliser as a first step. There is a need for traditional users of human excreta in agriculture to change their attitude towards the use of untreated excreta. Such a need can be met if users are provided with a low-cost, efficient technique for sanitising excreta.

The fertiliser value of urine is comparable to that of some mineral fertilisers, while faeces are more like animal manure, thus capable of increasing the organic matter content of the soil and providing a suitable habitat and feedstock for soil microorganisms that can enhance plant growth. Thermophilic composting is one of the ways through which pathogens in faecal matter can be inactivated, making it safe for use in agriculture (Vinnerås et al., 2003a; Schönning & Stenström, 2004). The efficacy of this treatment, however, depends on environmental conditions, the quality of the feedstock and the treatment processes the compost passes through. Co-composting faeces can result in compost that is odourless and non-repulsive for manual handling.

Contemporary research has focused on large-scale methods of treating faeces to the neglect of rural smallholder farmers who may need simpler techniques to

increase crop production. There is not much information on how they can produce fertilisers from their own excreta with the resources they have. Faeces have traditionally been disposed of in pit latrines and where they have been used in agriculture, farmers have hardly given a thought to health risks they are exposed to not only during handling but also in consumption of excreta-fertilised products. Co-composting faeces and local species of grass that traditionally would be burnt or incorporated into the soil or fed to animals, may be a useful technique for rural farmers in developing countries. In this case, the grass provides fibrous structural material that can enhance the composting process.

1.3 Aims and objectives

This research aims at sanitising faecal matter in a simple, easily adopted, co-composting process that minimises nutrient losses to produce a compost that is not only easy to handle manually but rich in nutrients that can help ameliorate deteriorated, nutrient-deficient soils of the semiarid tropics and subtropics. The objectives were:

1. To determine optimum sludge load and turning frequency during composting that facilitate rapid pathogen deactivation under semiarid tropical conditions;
2. To evaluate the effect of sludge load and turning frequency on the final nutrient composition;
3. To assess the effect of sludge load and turning frequency on compost maturation rate.

1.4 Conceptual framework

Ecological sanitation (ecosan) is a new approach for managing wastes in ecosystems. It represents a shift from the linear solution of disposing anthropogenic solid and liquid wastes including human excreta, to a circular flow solution involving the reuse of nutrients contained in the 'wastes'. Such an approach may not only improve the health and nutritional well-being of humanity

but also conserve and protect water resources especially for water-deficient areas of the semiarid tropics and subtropics (Esrey, 2001; WHO, 2006a, 2006b).

The practise of using unsanitised faecal matter in agriculture does not only expose those who handle them but also those who consume excreta-fertilised products (Schönning et al., 2007). Besides, the pollution caused both by punctual over fertilisation (which could also lead to eutrophication) and pathogens, considerable amounts of nutrients are being lost due to the absence of sanitary installations or by existing ones is quite enormous. There is a need to improve sanitary systems to cater for disease incidents, environmental degradation and eutrophication problems. An ecologically sound approach would be one that recovers and uses these nutrients in agriculture, and this is the fundament of the ecosan approach.

In some parts of the Tropics especially sub-Saharan Africa, soils are deficient in plant nutrients due to erosion and leaching which might have resulted from unsustainable agricultural practices and high rainfall regimes. Human excreta, which are relatively rich in plant nutrients (Table 1) are abundantly available free of charge. Vinnerås (2002) has reported that a person can excrete a daily average of 13g nitrogen (N), 1.5g phosphorus (P) and up to 4g potassium (K), which is equivalent to an annual per capita excretion of 4.76kg N, 0.55kg P and 1.46kg K.

Table 1. Proposed Swedish default values for excreted mass and nutrients

Parameter	Unit	Urine	Faeces	Toilet Paper	Black water (urine + faeces + toilet paper)
Wet matter	kg/person, year	550	51	8.5	610
Dry Matter	kg/person, year	21	11	8.5	40.5
Nitrogen	g/person, year	4000	550		4550
Phosphorus	g/person, year	365	183		548

Source: Vinnerås (2002)

Although the nutrient fraction in faecal matter is smaller than in urine, the higher concentration of phosphorus and potassium in faeces can enhance crop growth (Morgan, 2003; Jönsson et al., 2004). The challenge is to hygienise excreta in a way that it is both easy and unriskey. Urine is relatively easy to sanitize compared to faeces. Composting human faeces from source-separating toilets could render

them easy to handle, providing an affordable fertiliser and soil conditioner to poor farmers (Jönsson et al., 2004). This alternative could be better than the conventional 'end-of-pipe' systems which may be costly to establish, operate and maintain resulting in the loss of valuable plant nutrients to recipient water bodies or landfills.

An important ecosan aspect is "closing the loop" which is the concept of sanitising and reusing human excreta in agriculture (Jönsson et al., 2004). The holistic cycle of ecosan involves collecting the nutrients in human excreta through ecological sanitary means and returning them to the soil through agricultural use. A more sustainable approach to conventional systems would thus be 'sanitise-and-use' (Winblad and Simpson-Hebert, 2004). This requires a change of attitude towards faeces and urine, to regard them more as valuable resources which are capable of improving the livelihood of people.

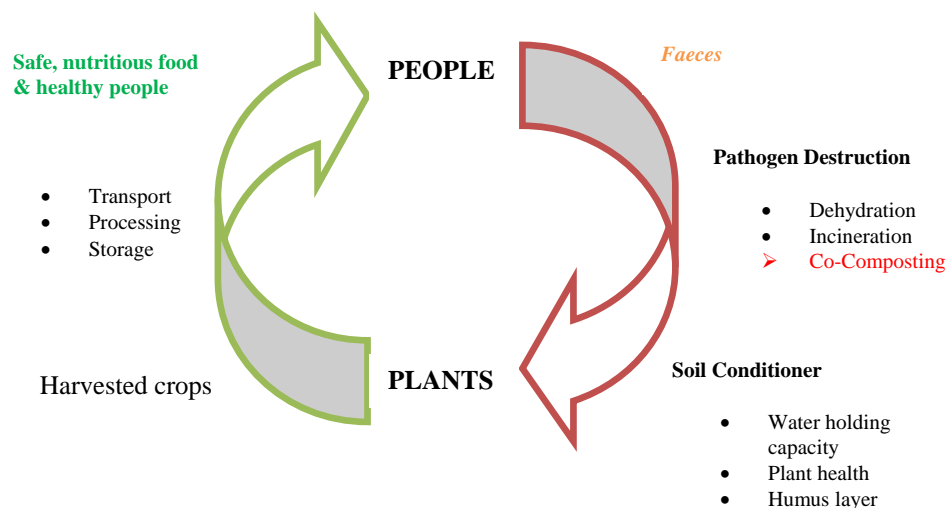


Figure 1: Model for closing the Nutrient Loop in an agricultural ecosystem; adapted from Esrey, (2001)

In the model above, faeces from people can be hygienised by destroying pathogens through various processes: dehydration, incineration and co-

composting. These processes will result in a compost product from faeces that can serve as a soil conditioner, improving the soil's water holding capacity and providing a rich humus layer for soil microbial activity. Harvested crops can be further processed and made 'safe' by cooking before consumption. This may improve crop yields and reduce the problem of food insufficiency already prevalent in some parts of the world today, especially countries south of the Sahara (Jönsson et al., 2004).

1.5 Hygienic aspects of using faeces in agriculture

Faeces contain most of those pathogens excreted from the body which can cause gastrointestinal infections. Therefore, users of human excreta must be aware of the health risks involved and take precautions when dealing with excreta for use in agriculture. In 'no-mix' excreta collection systems, faecal cross-contamination has been reported as the major source of risk from the use of urine and grey water in agriculture (Shönning et al., 2007; WHO, 2006a, 2006b; Höglund, 2001). Other transmission pathways reported include accidental ingestion, transportation to water courses used for recreation and portable water sources through open defecation, and through the consumption of excreta-fertilised crops. Reducing pathogen excretion should be considered important in minimising the risk of a further spread of pathogens (Schönning et al., 2007; WHO, 2004). Efforts to destroy the pathogens at the source before recycling the nutrients contained in excreta will not only decrease the risk of exposure when working with faecal fertiliser, but eventually reduce the chances of infection from the consumption of excreta-fertilised crops.

Arfaa & Ghadirian (1977) and Xu et al. (1995) state that where untreated human excreta are used as a fertiliser there is an elevated prevalence of *Ascaris* infection. Hookworm infection is also common in wet climates especially where excreta are used (Needham et al., 1998; Xu et al., 1995; WHO, 2006b). The WHO (2006a) has reported that failure to treat and manage wastewater and excreta in the world today is responsible for major adverse health and environmental effects. Faeces are responsible for the transmission of a wide range of infectious diseases,

including cholera, typhoid, various types of viral hepatitis, polio, schistosomiasis and a variety of helminth infections. A majority of these excreta-related illnesses occur in children living in the poor countries of the world. It is estimated that diarrhoea is responsible for 3.2 percent of all deaths (WHO, 2004), while more than 16 million people contract typhoid and over 1 billion people suffer from intestinal helminth infection (WHO, 2006a; 2004). In a study carried out in Vietnam by Humphries et al. (1997), hookworm infection was compared between women who used traditional excreta treatment before application to crops and those who applied fresh faeces. Women who used untreated fresh faeces had higher infection rates of hookworm than those who did not. Where human excreta are not used in agriculture, open defecation which is still widely practiced in some parts of the developing countries might be responsible for excreta-related diseases. There is a high prevalence rate of gastrointestinal diseases such as diarrhoea, cholera, typhoid fever, ascariasis, and hookworm infections in areas where poor hygiene, sanitation and water quality prevail.

The responsibility of minimising the health risks lies with the user of excreta and excreta-fertilised products (WHO, 2006b). To ensure safety in the use of nutrients in human faeces in agriculture, it is important to create barriers on the transmission pathways and reduce the risk of pathogen transmission. Thermophilic co-composting of faeces before application to the field may be a suitable approach to break the pathogen cycle when use of faeces in agriculture is an option. Esrey et al. (1998) have in the F-5 diagram (Figure 2) identified the possible transmission routes and points of interception that would break the cycle of infection and re-infection of pathogenic organisms.

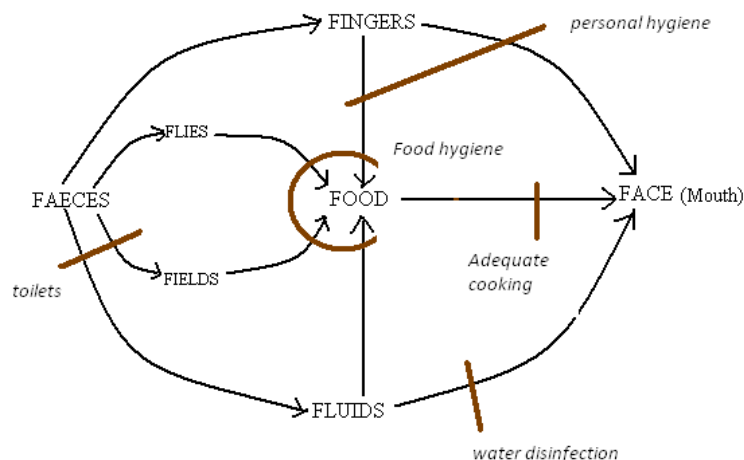


Figure 2: Barriers necessary to prevent the spread of pathogens (after Esrey et al., 1998)

The F-5 diagram suggests a multiple barrier treatment of faeces to reduce the risk of infection since no single treatment seems adequate for sanitising faeces. Personal hygiene plays an important role in breaking the pathogen cycle, but where faeces have to be used as a fertiliser, intercepting and sanitising faecal matter in the toilet or before application becomes an absolute necessity. As this, too, may not be adequate, food must be properly cooked before consumption. Proper food hygienic practices such as preventing contact of harvested food from the fields with the soil, keeping cooked food away from flies could also help to break the pathogen cycle when nutrients and organic matter in faeces have to be recycled.

1.6 Treatment techniques of faecal matter for use in agriculture

Although handling human faeces is still seen as a taboo in many cultures yet in some parts of the world, raw sewage is used in agricultural and aquaculture (Drangert, 1998; Lienert et al., 2003; WHO, 2006b). This practice dates back as far as the 12th century AD in Japan. In China, composting human and animal excreta for agricultural use has been in existence for a long time (Esrey et al., 1998). Developing adoptable techniques that would properly hygienise human excreta before use in agriculture is, therefore, an absolute must if the world's growing

population is to be fed through sustainable practices with a reduced risk of infection by the use of excreta or consumption of excreta-fertilised products.

There is increasing interest in treatment techniques for faeces and faecal sludge. The driving forces behind these are increasing environmental concerns generated by conventional disposal systems and the search for ways to recover nutrients and organic matter for use in agriculture (WHO, 2006b). Feachem et al. (1983) observed that the treatment of faeces is considered particularly important in societies that use human excreta in agriculture. Various attempts and suggestions have already been made, ranging from drying, incinerating, storage, chemical treatment with urea and digesting to composting as a means of sanitizing faeces before use in agriculture (Vinnerås et al., 2003a; 2003b; Niwagaba et al., 2006; Koné and Strauss, 2004; Schönning and Stenström, 2004; Vinnerås, 2007). The method used to treat faeces in each case, however, depends on the reason for which it is treated and also on the characteristic of the sludge (Niwagaba et al., 2006; Koné and Strauss, 2004). Compared to urine, sanitising faeces still presents a challenge today, considering that a greater fraction of excreted pathogens is present in faeces (Höglund, 2001; Vinnerås, 2002).

Incineration could effectively sanitise faeces in a matter of hours. Unfortunately, this process may also produce toxic pollutants such as dioxins and furans that may pose health and environmental problems (Ketlogetowe et al., 2004; WHO, 2004, Madigan and Martinko, 2006; Haug, 1993; Niwagaba et al., 2006). Apart from this, Niwagaba et al. (2006) found out that up to 94% of the initial nitrogen and plant-available phosphorus content could be lost to the atmosphere during incineration of faecal matter. This reduces the potential for incineration as a treatment option for faecal matter for use in agriculture, given that nitrogen is the most growth-limiting plant nutrient (Jönsson et al, 2004).

Storing faeces has also been reported to reduce the pathogen load to levels convenient enough for further processing. However, the extent of hygienisation depends on the duration of storage, the pH of the faecal matter and the prevailing

climatic conditions of the area. WHO (2006b) has recommended storage times for faecal matter (Table 2).

Table 2. Recommendations for storage treatment of dry excreta and faecal sludge before use at household and municipal levels^a (WHO, 2006b)

Treatment	Criteria	Comment
Storage; ambient temperature 2 – 20°C	1.5 – 2 years	Will eliminate bacterial pathogens; re-growth of <i>Escherichia coli</i> and <i>Salmonella</i> may need to be considered if rewetted; will reduce viruses and parasitic protozoa below risk levels. Some soil-borne ova may persist in low numbers
Storage; ambient temperature 20 – 35°C	> 1 year	Substantial to total inactivation of viruses, bacteria and protozoa; inactivation of schistosome eggs (<1 month); hookworm (<i>Ancylostoma/Necator</i>) and whipworm (<i>Ascaris</i>) eggs (≥4 months), whereas a more or less complete inactivation of <i>Ascaris</i> eggs will occur within one year.

^aNo addition of new material

Though after storage the faeces may look and smell like earth, it is important to consider that some risk of contamination still exists. The recommended period of storage seems too long for smallholder farmers who may want to make use of available faeces in growing their crops.

Chemical treatment of faecal matter from urine-diverting toilets has also been reported to significantly reduce bacteria pathogens. Treatment with urea for two months and 50 days of storage significantly reduced the number of viable *Escherichia coli* and *Ascaris suum* eggs (Vinnerås et al., 2003b). Addition of peracetic acid, hydrogen peroxide and acetic acid was also found sufficient to disinfect faecal matter within 1 – 12 hours. However, pathogenic bacteria re-growth was observed in these treatments when organic matter content increased or when there was no storage.

Thermophilic composting at temperatures >50°C has been reported as an effective way of curing faecal matter for 'safe' usage in agriculture (Haug, 1980). However, in composting system where insulation is not used, it may be difficult for composted faecal matter to be heated to the same temperature to achieve uniform

sanitisation (Vinnerås, 2007). When comparing composting, storage and chemical treatment with urea, Vinnerås (2007) found that treatment with urea was the most efficient which significantly reduced the pathogens due to increase in pH. This may be problematic where farmers cannot afford to buy urea. Storage at 20°C reduced the presence of faecal coliform but *Enterococcus* spp. remained resistant.

Vinnerås et al. (2003b) stated that there exists no single efficient, reliable, and scale-independent treatment of toilet waste for safe recycling of plant nutrients. A multiple-treatment barrier as recommended by Esrey et al. (1998) may be a more adoptable approach considering that under different physiochemical conditions, faecal pathogens behave differently. Reducing the risk of exposure at the initial stage of handling should be of utmost importance. Primary treatment involving the addition of wood ash and or storage (in collection chambers as with double-vault toilets¹) may be helpful but this could be followed by secondary treatments such as urea addition, composting and/or further storage to sufficiently deactivate pathogens (Jönsson et al., 2004). In small-scale treatment systems, co-composting could be a comparatively low-cost, efficient treatment option for poor farmers who may want to recycle their own toilet wastes.

The efficiency of the rate of disinfection, transformation and nutrient recovery in the co-composting of vegetation and a urine-faecal sludge mix may depend on the mixture ratio and turning frequency. The following research investigates the significance of these parameters on the quality of the final compost product.

¹ Urine-diverting toilets with two chambers used in alternation

2. MATERIALS AND METHODS

2.1 Ghana

Ghana is located between latitudes 11°N and $5^{\circ}30'\text{S}$ of the equator and longitudes 3°W and 1°E of the Greenwich Meridian. It has a total surface area of $238,533\text{ km}^2$ and borders Burkina Faso in the North, the Gulf of Guinea in the South, Togo in the East and the Ivory Coast in the West (Figure 3). It is predominantly a low-lying country with the highest altitude on the Akwapim-Togo ranges measuring 880 m above sea level. Accra, where this study was carried out, is Ghana's capital and is located on the Greenwich Meridian (Longitude 0°). Its climate is tropical with a tropical forest belt and densely forested hillsides.



Figure 3: Map of Ghana

The eastern coastal belt is warm and comparatively dry; the south-western corner, hot and humid, and the north hot and dry. Two main seasons characterise the country with the highest average rainfall recorded in the months of May and June (about 198 mm) while the annual average minimum temperatures reaches 22.9°C . The soils of Accra are red earths mostly Acrisols and Nitisols according to FAO classification, developed mainly over parental materials formed in situ. However,

there exist patches of tropical black and grey earth soils typical of savannah areas. Acrisols and Lixisols are the main soil types at VVU (Sauerborn and Germer, 2005).

2.2 Study Site

The study was carried out at Valley View University (VVU) and Orphanage Africa (OA) both in Greater Accra, Ghana's smallest administrative region with a surface area of 3,245 km². Valley View University is located in Oyibi village, 35 km on the Accra-Dodowa Road, while OA is in Ayeniah I, about 1 km from Dodowa. Though very close in location, VVU which is located in the rain shadow of the Akwapim mountain range records climatic differences with the weather station at Aburi Botanical Gardens on top of this mountain. Rainfall is more frequent and intense at Ayeniah than Oyibi village. Data collected at VVU since 2003 show that annual average precipitation is the same as in Accra though there are seasonal variations.

2.3 Compost Trial Design

2.3.1 Compost Setup

The trial design constituted nine compost piles with different treatments (Figure 4). Three mixtures of plant materials and faecal sludge² of 1:1, 1:2 and 1:3 for Low Sludge (LS), Medium Sludge (MS) and High Sludge (HS) loads, respectively, and turning frequencies of every 3rd, 5th and 10th day were used as composting variables. The piles that were turned every 3rd, 5th and 10th day were classified as High Turning Frequency (HTF), Medium Turning Frequency (MTF) and Low Turning Frequency (LTF), respectively. The design was identical at VVU and OA (Figure 4) and the locations were used as pseudo-replicates.

² Used here for a mixture of faeces, urine and paper.

		Mixture Ratio		
		1:1	1:2	1:3
Turning Frequency	3day	LS/HTF	MS/HTF	HS/HTF
	5day	LS/MTF	MS/MTF	HS/MTF
	10day	LS/LTF	MS/LTF	HS/LTF

Figure 4: Compost layout

A sandwich set-up of alternating layers of biomass and faecal sludge that were added successively as the faecal sludge was brought to the compost site was used. Biomass feedstock was the same for all the compost piles; ≈ 169 kg fresh weight (fw) for VVU and ≈ 106 kg fw for OA. Compost piles at VVU with LS received ≈ 135 kg fw; MS, 271 kg fw and HS, 406 kg fw of faecal sludge, respectively, at the beginning of the trial. At OA, the corresponding compost received 67 kg, 135 kg and 202 kg fw of faecal sludge. .

2.3.2 Compost Feedstock

a) Biomass

Shredded plant material (dominantly *Panicum maximum*, *Azadirachta indica* and the leaves and twigs of *Mangifera indica*) from the two sites was used as structure material and carbon source. At VVU, *Panicum maximum* was weeded from the university's mango plantation and shredded together with *Azadirachta indica* and *Mangifera indica* leaves pruned from the same area. The pruned leaves of the latter had been lying in the plantation for one month and were drier than the rest of the plant material used. The shredded biomass mixture was transported by tractor to the composting site. The same plant material mixture was used for OA. The

biomass used was from nearby farms, pruned leaves and twigs from a neighbouring plantation were brought to the compost site by means of a hand-pulled trailer. The moisture content pH, electrical conductivity and nutrient concentration in biomass differed between the sites (Table 3). Vegetation at OA was drier than at VVU since most of it had been weeded three weeks before trial set-up.

Table 3. Composition of compost feedstock

Location	Compost Feedstock	DM (%)	pH	EC (dS/m)	% DM Nutrients and Organic Carbon (n=3)			
					N	P	K	C _{org}
VVU	Biomass*	36.54	7.10	0.88	1.34	0.06	2.56	37.59
	Range				(1.10-1.50)	(0.03-0.70)	(2.20-3.16)	(36.37-38.95)
	Faecal sludge (faeces + urine + paper)	29.55	6.08	0.98	3.27	3.780	1.45	21.89
	Range				(2.44-4.43)	(3.37-4.11)	(1.01-2.18)	(16.58-28.06)
OA	Biomass*	67.49	7.01	0.96	1.51	0.07	2.13	37.13
	Range				(1.51-1.60)	(0.06-0.07)	(1.75-2.36)	(34.91-38.71)
	Faecal sludge (faeces + urine + paper wood ash + sawdust)	16.07	7.49	1.01	1.77	1.630	4.32	29.33
	Range				(1.66-1.85)	(1.55-1.71)	(3.96-4.39)	(26.72-32.15)

*(*Panicum maximum*, *Azadirachta indica*, *Mangifera indica*)

DM=Dry Matter; EC= Electrical Conductivity; C_{org}=Organic Carbon

b) Faecal sludge

Faecal matter used for the trial was collected from ventilated improved pit (VIP) latrines at both sites. At VVU, a four-chambered toilet has been in use for 15 years with no form of hygienic disinfection. Faecal sludge was drawn from all four chambers of the toilet. The faecal sludge was a mixture of faeces, urine and paper, (Table 3). Toilets from which sludge was drawn at OA constituted six chambers with approximately 70 users and had been in use for two years. The management of OA had ash and sawdust applied to the toilet once a month and once a fortnight, respectively, as a hygienic treatment of the faeces in the toilets. The faecal sludge at OA had a similar composition as VVU with the exception of wood ash and sawdust addition. Also found in the sludge at OA were diapers which required sorting. Faeces were drawn manually from the toilet chambers at both sites by

means of specially designed shovels and were transported to the composting sites in wheelbarrows.

2.4 Data Collection

2.4.1 Assessment of physiochemical properties

a) Temperature monitoring

Compost temperatures were recorded with an air/soil temperature probe (Mastech[®] MS6501, China) from the inner core and outer layer (at about 15cm depths) of each compost pile. This was done twice a day, at 7am and 2pm (except for Saturdays at VVU). The average was calculated as daily mean for core and outer layer. Temperatures were also measured every 2 hours after piles had been turned and every 2 hours after addition of water to the compost. This was done in order to monitor the length of time it takes for high temperatures to be reinstated after turning and/or irrigation. The moisture content of the compost piles was manually monitored regularly throughout the trial period. This was done by taking a handful of the compost from the inner core and from 15cm inside the compost and squeezing it. Moisture deficiency was detected by the failure of water to appear between fingers and/or no compost-ball formation after squeezing (Bakx, 2002). In such a case, 12 – 24l of tap water were used to irrigate the compost.

b) Biomass – pH, conductivity, moisture and nutrients

From the shredded plant material, three homogeneously mixed samples of about 5 litres were taken. Three sub-samples of 300g mixture of the plant material were filled in labelled plastic bags and transferred to the laboratory. In the lab, 150g of fresh material were taken out and air-dried for 7 days at an average temperature of 26°C on labelled paper boxes. The dry matter was packed into labelled plastic bags, stored at room temperature and transported to UHOH³ for analyses of nitrogen, potassium, phosphorus, and organic carbon content (N, P, K and C_{org}). From the remaining 150g of fresh plant material, 20g were chopped into pieces of 8-10mm and 200ml 0.01-M CaCl₂-solution was added in 500ml plastic bottles. This

³ University of Hohenheim

was mixed several times for 1 hour and filtered through household coffee filter paper. The pH of the filtrate was measured with a calibrated pH-electrode, (Greisinger, GMH3530, Germany). Another 20g of chopped fresh plant material were added to 200ml of distilled water in 500ml bottles and mixed by manual shaking several times within 2 hours and filtered. Twenty-five ml of the filtrate were poured into 30ml beakers and electrical conductivity was measured with a calibrated electrode (Greisinger GHM3430, Germany) at approx. 27°C. The fresh weight of the remaining material was determined and the material was air-dried on labelled papers for 10–15 days at an average temperature of 27°C. The material was further dried in a microwave (MICROMAXX[®], China) several times at max power for 3-5minutes until the weight was constant.

c) Faecal sludge – pH, conductivity, moisture, nutrients content and faecal indicators

Randomly collected samples of faecal sludge were drawn from the four-chamber toilet at VVU and mixed thoroughly to get a main homogenous sample. Three were taken and filled into a calibrated measuring cylinder and settled through hitting on the ground and the filling volume was read. Three sub-samples of 50g each were drawn from the homogenised sample and filled in 500ml plastic bottles. These samples were immediately transported to the International Water Management Institute (IWMI), Accra, in an ice-cooled box for analyses of faecal indicators (*Salmonella* spp., *faecal Streptococcus*, and *Escherichia coli*). Twenty g from the main homogenized sample were added to 200ml 0.01-M CaCl₂ solution in 500ml plastic, mixed several times for one hour and filtered. Twenty-five ml of the filtrate were poured into a 30ml beaker and the pH was measured with a pH electrode calibrated at the range of 6.9 to 8.3. Another 20g from the same sample were added to 200ml distilled water. It was mixed manually by shaking several times during 2 hours and filtered. Twenty-five ml of the filtrate were filled in 30ml beakers and the EC measured with the electrode at 27.1°C.

At OA, the faecal sludge was thoroughly mixed in the toilet chambers, and three homogenous samples of 300g each were taken. The same procedure was repeated for the faecal sludge from VVU. One hundred and fifty g of the remaining

faecal sludge were air-dried for several days and later in a microwave at maximum power, and weighed every 3 minutes until the weight was constant. The dry matter was filled in plastic bags, kept at room temperature until the end of the trial and transported to UHOH for nutrient analyses.

d) Compost trial – Sampling, pH, conductivity, moisture and nutrient contents

Approximately 600g of compost samples were collected from 10 different positions (five from the middle and another five from 10-15cm inside the compost heap), put into a 12l bucket and pooled into one sample (Figure 5a). This was repeated for each compost category. One hundred and fifty g of the homogenised sample from each compost category were filled into 500ml plastic bottles, placed in an insulated box of ice blocks (Figure 5b) and immediately transported to IWMI for assessment of faecal indicator die-off at different stages of compost development (Figure 5c).



Figure 5: Collection of samples for analyses

This was repeated three times for each compost category during the compost trial, namely on the 27th, 54th and 84th day of composting. Four hundred and fifty g of the remaining compost were transported to the lab, where 20g of the homogenized fresh compost from each compost category were added to 200ml 0.01-M CaCl_2 solution in 500ml plastic bottles, mixed several times during one hour and filtered. Twenty-five ml of the filtrate was poured into a 30ml beaker and pH was measured with a pH electrode calibrated at the range of 6.9 to 8.3 (Figure 6). Another 20g from the same sample were added to 200ml of distilled water. It was mixed thoroughly by shaking manually several times for 2 hours and filtered. Twenty-five ml of the filtrate were poured into beakers of 30ml and the EC measured with a calibrated electrode at 27.1°C.



Figure 6: Measurement of pH and EC of composts

The sampling procedure was the same for VVU and OA. Another 150g of compost from the main samples of each compost category were air-dried for 5 to 7 days (Figure 7), filled into plastic bags, stored at room temperature and transported to UHOH at the end of the trial for nutrient analyses. The remainder of the compost samples were weighed and dried in an oven for 24 hours at 105°C and re-weighed to calculate the dry matter (DM) content of the compost.



Figure 7: Air-drying of samples

2.4.2 Phytotoxicity tests

A plant bioassay with garden cress, *Lepidium sativum*, modified after Himanen et al. (2006) was carried out three times during the trial to test for phytotoxicity of the compost at different stages of development. One mixed sample of 250g each from homogenous samples of 10 randomly collected sub-samples per compost pile was chopped, when necessary, to sizes between 8 to 10mm. The chopped samples of each compost pile were filled in 1l plastic bottles with lids. Discs of 8cm diameter of polyethylene fly screens (untreated) were fixed in position with plastic-coated copper wire. Cotton was placed on the mesh and sprinkled with water until the first drop passed through the mesh. 0.5g of water cress seeds were sown on the cotton-coated mesh frame. The compost was irrigated with tap water to ensure ad libitum availability of water to the seedlings. The seeds were suspended 2.5 – 3.0cm over the compost in the plastic bottles to avoid any root contact with the compost. For a good circulation of air in the plastic bottles, two holes of approximately 5mm diameter were bored on the lid of the plastic bottles. The set up was placed on a flat surface under a tree for 7 days at average temperatures of 25°C and 12 hours of light per day (Figure 8). Seed germination was monitored and moisture content adjusted as necessary. For each germination test, there was one replicate. Four controls with garden soil were established as well. Seven days after germination, seedlings were cut directly above the cotton surface and the fresh weight of the shoot biomass was immediately measured and expressed as a percentage of the control with garden soil (Araújo and Monteiro, 2005).



Figure 8: Phytotoxicity test with garden cress

2.4.3 Pathogen Analyses

a) *Salmonella* spp., faecal *Streptococci* and *Escherichia coli*

At IWMI, Accra, faecal indicators (*Salmonella* spp., faecal *Streptococci* and *Escherichia coli*) in faecal sludge and each compost category were analysed. The die-off was assessed three times during the trial period, on the 27th, 54th and 84th day of composting. The total number of faecal bacteria in the sludge/compost was expressed per unit dry weight. To achieve this, 20g of each sludge/compost sample were placed in a glass dish and dried in an oven at 105°C for 24hrs. After drying, the samples were placed in desiccators and allowed to cool before re-weighing. The dry weight of the compost was calculated and used to determine the equivalent amount of sludge/compost (wet weight) to be taken for the microbiological analysis.

Membrane filtration was used to enumerate bacteria types in compost (APHA–AWWA-WEF, 2001). About 20g (dry weight) of each sludge/compost sample were weighed into 180ml of sterile, phosphate-buffered saline and homogenised water. Further tenfold serial dilution was done after which diluted samples were filtered through white, grid-marked, 47mm-diameter, Millipore HA-type cellulose filters with a pore size of 0.45mm. Samples were filtered using a vacuum pump at a pressure of 65 kPa (500mm Hg) and a triple glass filtration unit (Millipore, Bedford). The filters were placed with the grid side on Petri dishes of Chromocult coliform agar (Merck, KGaA Darmstadt, Germany) for *Escherichia coli*, Bismuth Sulfite Agar for *Salmonella* spp. and M-Enterococcus Agar (Merck, Germany) for *Streptococci*. Inoculated plates were incubated for 24 to 48 h at 37°C.

Colonies on Chromocult agar with dark blue to violet colour were counted as presumptive *E. coli*, black centre, light edges surrounded by a black precipitate with metallic sheen (so-called rabbit's or fish-eye) colonies on Bismuth Sulfite Agar were counted as *Salmonella* spp., and red, maroon or pink colonies were counted as presumptive faecal *streptococci*. Presumptive colonies were confirmed on MacConkey No. 2 agar (Oxoid CM109).

b) Helminth eggs (*Ascaris suum*)

To ascertain the die-off rate of parasites, *Ascaris suum* eggs extracted from pigs were put into little probes and placed inside bags made of spongy nets of red and blue colours. Three probes were put into each bag and the bags fastened with a rope (blue for the blue bag and yellow for the red bag) for easy access. These bags were incorporated into the compost with HTF and LTF immediately after the piles had been set up. The red bags were placed in the middle of the compost and the blue bags 15cm inside the compost. Three times (at monthly intervals), egg probes were removed one at a time, washed and placed in 30ml beakers and labelled. The beakers were filled with 25ml of distilled water and placed in the refrigerator at temperatures of $<4^{\circ}\text{C}$ until the end of the trial. At the end of the trial, egg probes were transported to UHOH for analysis in the Institute for Environmental and Animal Hygiene. At UHOH, the probes were placed in breeding chambers for five weeks and the viable eggs were expressed as a percentage of the eggs recovered.

2.5 Data Analysis

The SPSS version 13.0 software package was used to perform statistical analyses. *t*-tests for significant differences in pathogen die-off, compost toxicity, pH and conductivity were conducted. To evaluate the relationship between pH, EC, NPK, pathogen die-off, temperature and time during the trial Pearson's correlation from the same package was used. Graphs were drawn using Sigma Plot 10 software.

3. RESULTS

3.1 Physiochemical changes during composting

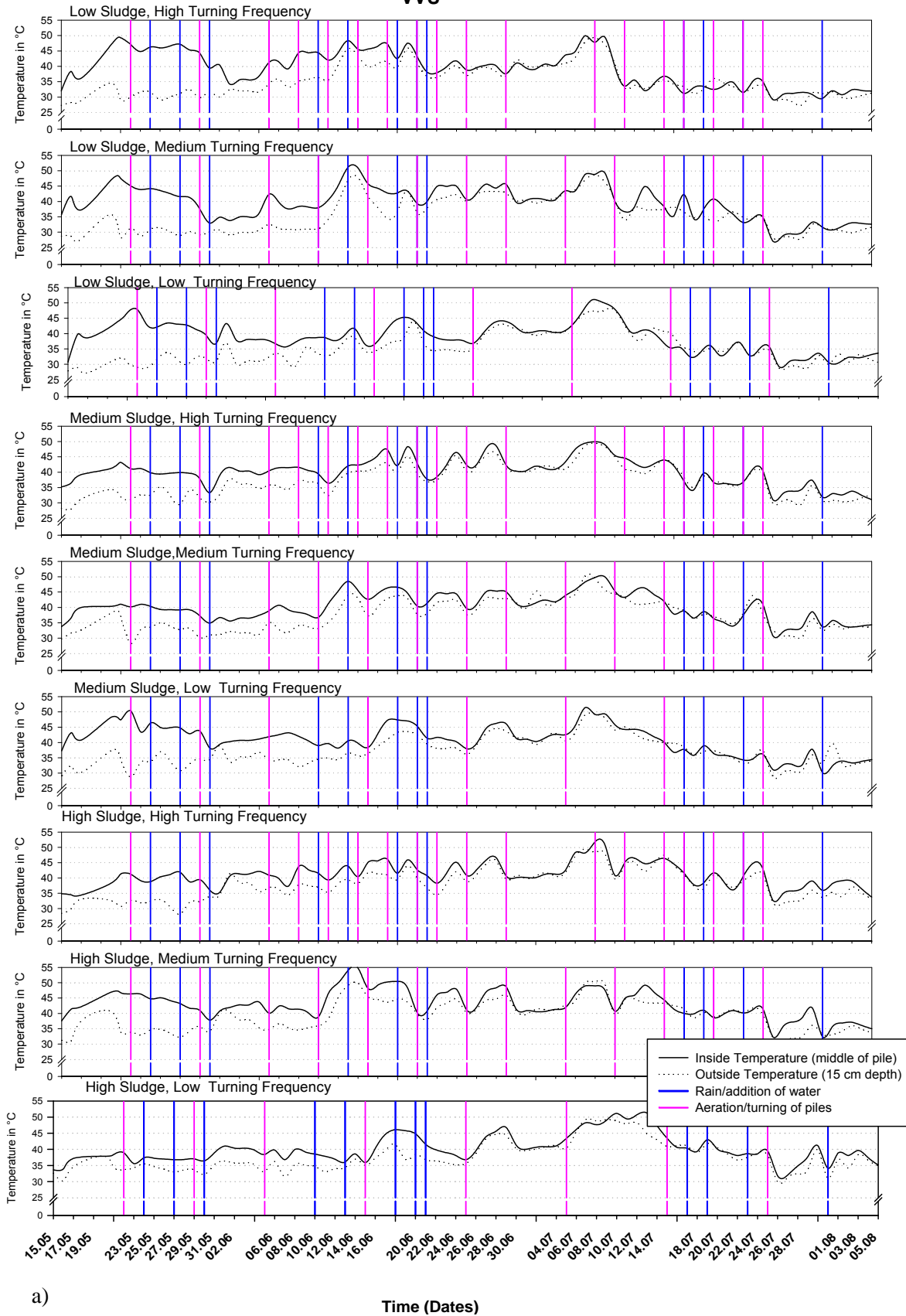
3.1.1 Temperature courses during composting.

Three stages characterised temperature changes during composting. These were (i) the active stage during which there were high temperatures (thermophilic phase) probably resulting from high microbial activity, (ii) the low activity stage with relatively low temperatures (mesophilic phase) and (iii) the maturation stage where the compost temperatures stabilised at $<5^{\circ}\text{C}$ above the ambient. Average ambient temperatures during the trial were 27.7°C at VVU and 30.1°C at OA. Temperatures between 35°C and 45°C were considered to be within the mesophilic range; 45°C was considered the lower threshold temperature of the thermophilic phase. All compost categories showed two characteristic peaks of temperatures (Figure 9a & 9b), but each category sustained temperature for a different number of days.

Distinct temperature courses were noticed at the two sites. At OA, thermophilic temperatures were attained 2 days after the compost piles were set up (Figure 9b), whereas at VVU it took about 8 days for the first thermophilic temperatures to be recorded. Unlike at OA, at VVU only compost piles with LS, MS/LTF, and HS/LTF attained these temperatures during this time. At both locations, there were deviations in the single treatments based on sludge load or turning frequency.

At VVU, composts in the LS treatment had at least two thermophilic phases during the trial (Figure 9a). The compost with MTF had the highest temperature (51°C) during the second thermophilic phase. However, only the compost with LTF recorded thermophilic temperatures for more than 5 days during the two thermophilic phases. By the 60th day of composting, temperatures had decreased by 10°C below the peak values attained for this category. Temperatures continued to decrease until the end of the trial. In the MS compost category, thermophilic temperatures were not reached for compost with HTF and MTF until 12 days after the first turning. This lasted for less than 5 consecutive days.

VVU



a)

Time (Dates)

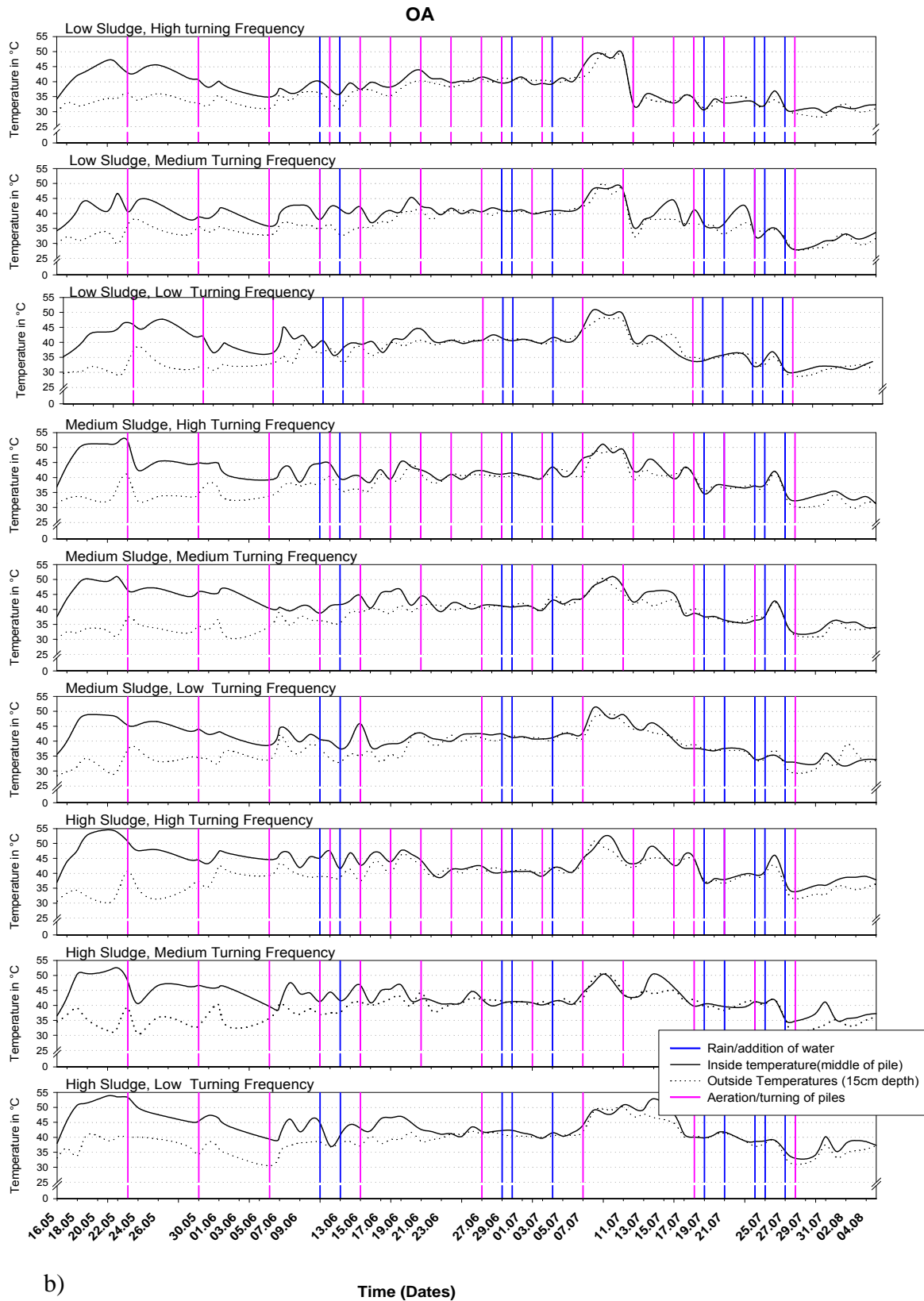


Figure 9: Daily mean temperatures during compost development

In the HS category, only the compost with MTF recorded two thermophilic phases with the first one lasting 4 days after the first 4 days of composting. The second thermophilic phase had temperatures between 46.5°C and 54.8°C that lasted 11 days between day 24 and 35 of composting. Temperatures declined in all treatments after two months of composting with the fastest decline in those composts subjected to the highest turning frequency.

All the composts in the category HS at OA had temperatures between 45.7°C and 54.6°C within the first 15 days of composting. Of the three compost piles in this category, the least frequently turned recorded temperatures in this range for 13 out of 15 days. In the category of MS composts, temperatures between 45.4°C and 52.3°C that lasted less than 7 days were recorded. Meanwhile, in the category of LS composts, temperatures were generally <48°C until the 47th day of composting when temperatures rose to between 48.1°C and 50.7°C, but this lasted less than 5 days. During the second month of composting, a second thermophilic phase was noticed for all compost categories at OA. The composts in the category HS still recorded the highest temperatures (up to 52.9°C) and for a comparatively longer period (between 5 and 7 days). Temperatures declined for all compost categories from this time until the end of the trial with a faster decline noticed in composts that were turned most frequently (HTF).

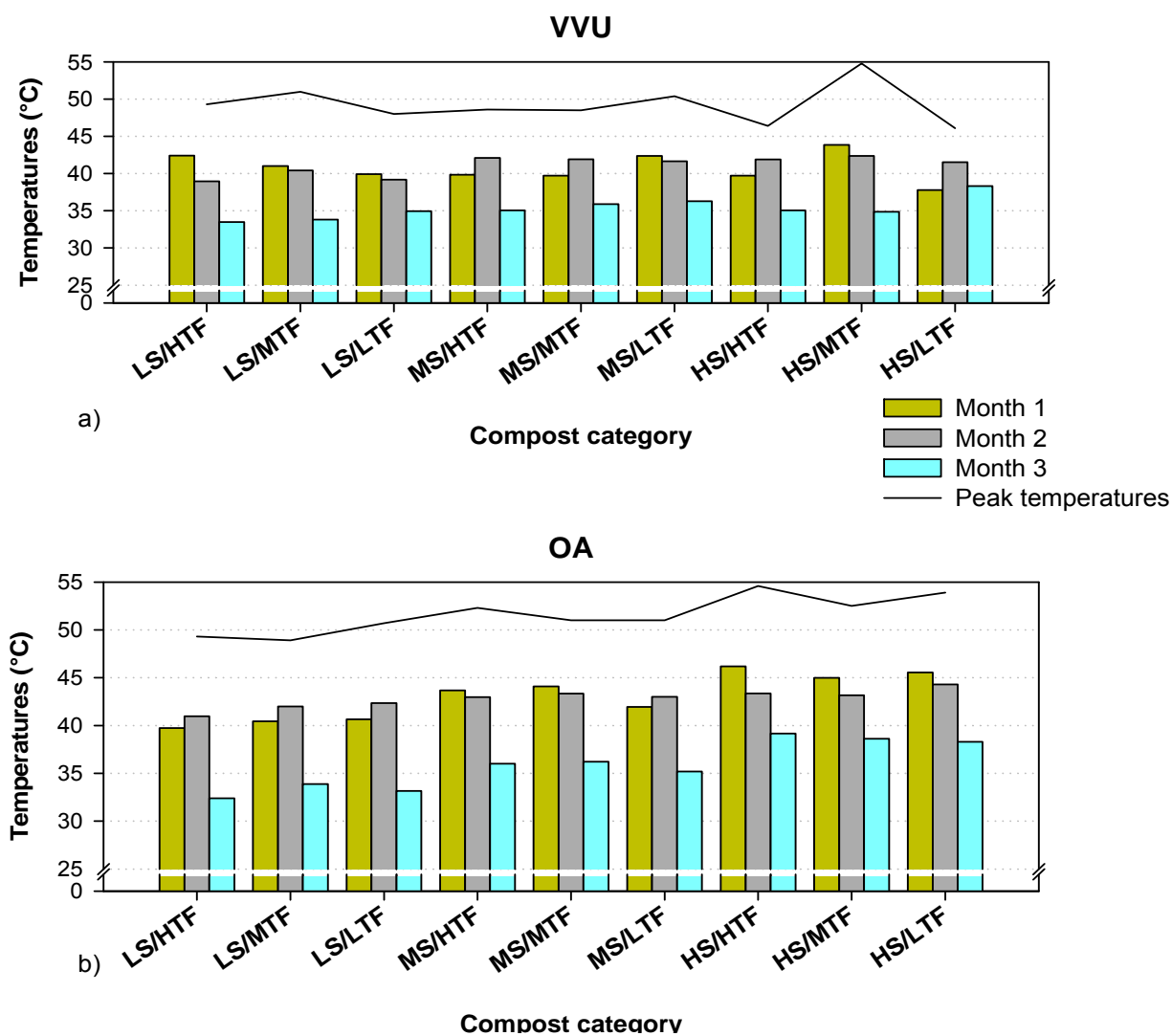


Figure 10: Monthly mean inner temperatures of compost categories

Peak temperatures for different categories of composts were higher at OA than VVU except for the compost pile with LS/MTF and HS/MTF). A monthly mean (core) temperature assessment also showed higher mean temperatures at OA than VVU (Figure 10). However, there was no significant effect of location. At VVU, the highest mean temperatures were recorded on two compost piles, namely, LS/HTF and HS/MTF after one month of composting. Mean temperatures were higher for composts with MS and HS except for two compost piles (MS/LTF and HS/MTF). This was consistent in the second month with 2 to 3°C higher averages for all composts in the MS and HS compared to the LS treatments. Mean

temperatures were about 8°C higher than ambient during the third month and this was similar for all categories. There was no statistically significant difference ($p>0.05$) in the mean inner temperature of the piles affected by sludge load or turning frequency. The time course of mean temperature showed no significant difference between the first and the second month. There was, however, a significant decrease ($p<0.05$) in temperatures for all compost categories at VVU between the second and the third month of the trial (Figure 10).

At OA, the HS compost recorded the highest mean temperatures ($\geq 45^{\circ}\text{C}$) during the first month of composting while the lowest mean temperatures were recorded in the LS compost piles. However, in the second month the mean temperatures for all categories were more or less the same. Compost piles in the MS and HS categories had mean temperatures above 43°C while those with LS loads were below this value. Lower mean temperatures (about 6.7°C higher than the ambient) were recorded in the third month for all piles. There was a significant difference ($p<0.05$) in mean inner temperature between compost with LS and HS, meanwhile, turning frequency had no significant effect.

3.1.2 Changes in pH

Compost pH decreased between days 27 and 54 and increased between days 54 and 84 for all categories at VVU. A similar pattern was observed at OA for three piles (LS/MTF, LS/LTF and MS/MTF) whereas the rest of the treatments had an increase during both periods (Table 4). After one month of composting, pH at VVU was between 7.12 and 7.60 (Table 4). Compost with LS had higher pH than the rest except the compost pile with MS/LTF (7.60). The decrease in pH between days 27 and 54 was significant for all compost categories. The increase between days 54 and 84 was also significant. The highest pH was recorded in the compost with LS/MTF the lowest pH was in the compost with HS/MTF. Sludge load and turning frequency had no significant effect on pH.

Table 4. Changes in pH of compost during composting

Location	Sampling Time (days)	Compost Category								
		LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
VVU	27	7.48	7.58	7.58	7.33	7.27	7.60	7.38	7.26	7.12
	54	7.18	7.13	7.36	7.00	7.08	7.05	6.99	6.86	7.00
	84	8.01	8.28	7.99	8.01	8.00	8.00	7.89	7.84	8.00
OA	27	7.51	7.71	7.85	7.79	7.70	7.89	7.68	7.60	7.68
	54	7.59	7.61	7.61	7.80	7.68	7.90	7.93	7.88	7.89
	84	8.24	8.33	8.39	8.61	8.52	8.60	8.63	8.68	8.73

There was a significant negative correlation between pH and electrical conductivity (EC) at $p < 0.05$. There was a strong positive correlation ($p < 0.01$) between pH and potassium while there were no significant correlations between pH and nitrogen or phosphorus concentrations. Results of correlation analyses for these parameters were similar at OA (Table 5).

Table 5. Pearson correlation coefficients (r-value) among pH, electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K) contents, *Salmonella* Spp. (Sal), faecal *Streptococci* (Strep), *Escherichia. coli* die-off, temperature (Temp) and time (months).

		VVU								
	pH	EC	N	P	K	Sal	Strep	E.coli	Temp	Time
pH	1	-0.43*	-0.12	-0.23	0.89**	-0.57**	-0.48*	-0.37	-0.81**	0.62**
EC	-0.41*	1	0.29	0.73*	-0.13	0.64**	0.57**	0.41*	0.47*	-0.54**
N	-0.27	0.50	1	0.86**	0.16	0.23	0.38*	-0.16	0.16	0.26
P	0.65	0.75*	0.80**	1	0.01	-0.56	0.55	-0.58	0.74*	NC
K	0.84**	0.91**	0.74*	0.88**	1	-0.05	0.54	0.09	-0.12	NC
Sal	-0.59**	0.05	0.37	-0.00	-0.22	1	0.82**	0.61**	0.73**	-0.87**
Strep	-0.69**	0.52**	0.54**	0.55	0.70*	0.61**	1	0.64**	0.64**	-0.94**
E. coli	-0.24	-0.05	0.36	-0.45	-0.32	0.53**	0.24	1	0.42*	-0.72**
Temp	-0.72**	0.68**	0.48*	0.78*	0.81**	0.46*	0.85**	0.09	1	-0.75**
Time	0.82**	-0.39*	-0.46*	NC	NC	-0.64**	-0.71**	-0.53**	-0.71**	1

OA

(n=27) except PK where, (n=9)

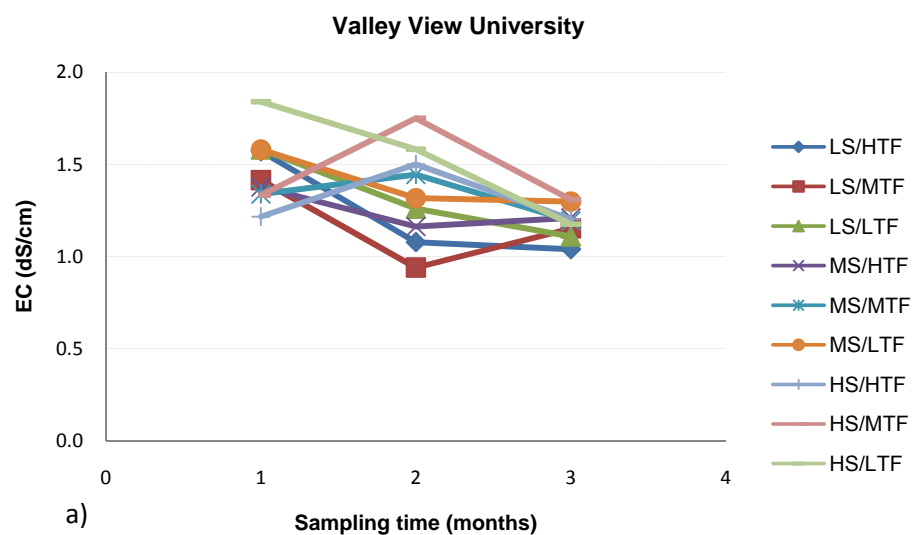
NC = Not Computed, *Significant at 0.05, **Significant at 0.01 (2-tailed)

At the end of the trial, pH was higher at OA than at VVU for all treatments except the compost category with LS/HTF (Table 4). The compost piles with HS load had a higher pH than those in the MS and LS treatments. However, this was not significant. After two months of composting, there was an increase in pH. A significant increase ($p < 0.01$) in pH was also recorded between days 54 and 84.

3.1.3 Changes in electrical conductivity (EC)

The EC of HS composts increased during the first two months of composting then decreased to levels almost equal to the composts with MS and LS during the last month (Figures 11a and 11b). The initial increase in conductivity was not statistically significant ($p > 0.05$) for the composts at VVU, but the decrease between the second and the third months was significant. Composts with lower sludge load also had significant reduction in EC during the second month. At the end of the trial (day 84), EC did not differ much between compost categories at VVU. Turning as well frequency had no significant effect on EC.

At OA, the increase and eventual decrease in EC was significantly different for compost in the categories of LS and HS. While compost with MS had an increase in conductivity, this increase was not significant ($p>0.05$). There was a significant decrease in EC during the last month of composting for this category. Compost conductivity was significantly different between sludge load treatments by the end of the trial, with compost in the HS category having higher conductivity. There was a positive correlation between EC, NPK and faecal *Streptococci* at OA while at VVU, EC was positively correlated with P, *Salmonella* spp., faecal *Streptococci* and *E. coli* (Table 5).



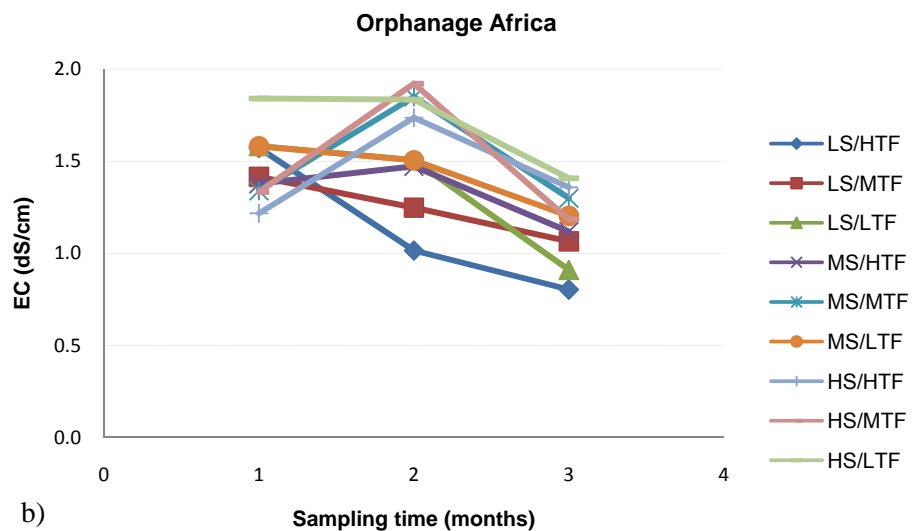
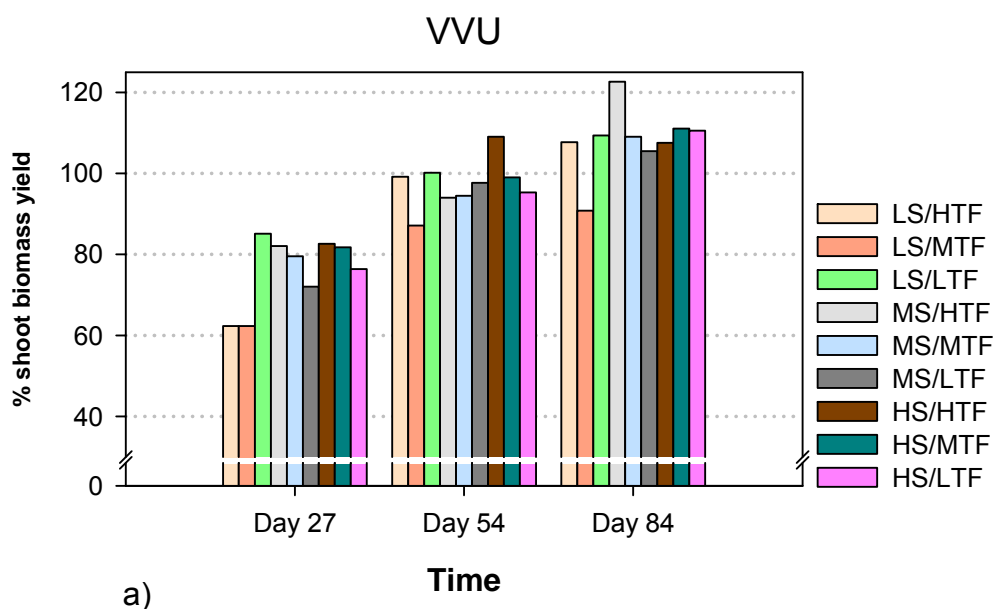


Figure 11: Changes in electrical conductivity during composting

3.2 Phytotoxicity

Phytotoxicity of compost was higher at OA than VVU after 27 days of composting (Figure 12). There was a significant increase in shoot biomass yield by day 54 of composting. By then, all compost categories had achieved more than 80 % of the control biomass yield at both sites. There was also a significant increase in biomass between days 54 and 84 of composting.



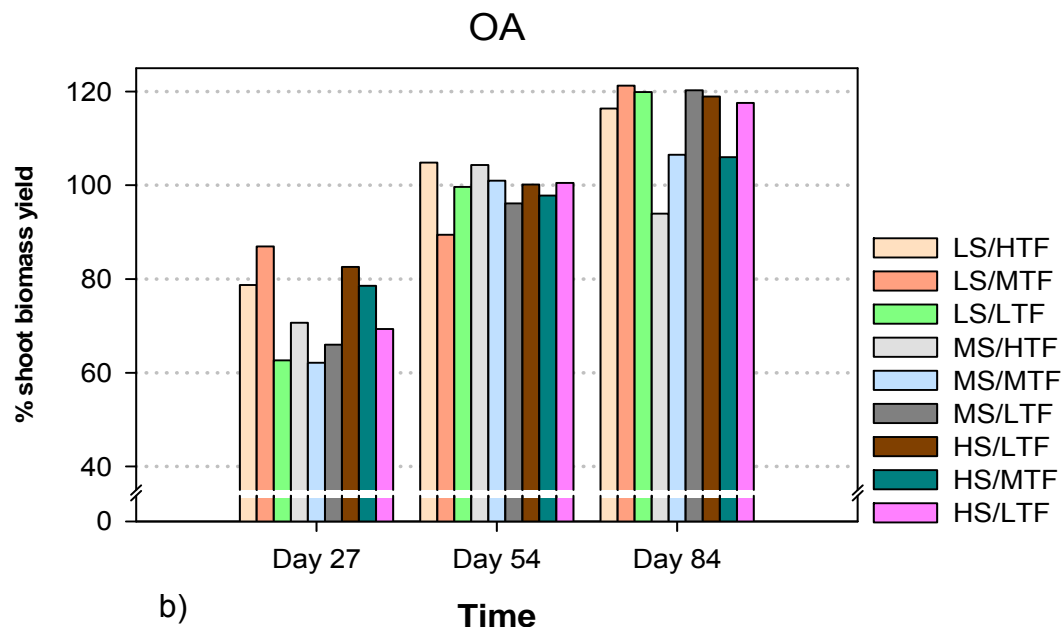


Figure 12: Bioassay of compost expressed as a percentage of control

At VVU as well as at OA, there was more shoot biomass in some of the HTF compost piles after 27 days. This was noticeable in composts with MS and HS at VVU and in HS load composts at OA. After 54 days, the difference in biomass yield was also noticed in composts with HS at VVU and MS at OA. However, this difference due to turning frequency was not statistically significant. Sludge load also did not show any significant effect on biomass yield at both sites. While there was a positive correlation ($p < 0.01$) between biomass and pH at OA, this was not the case at VVU.

3.3 Pathogen deactivation

3.3.1 Faecal bacteria

An initial assessment of the number of faecal bacteria in the sludge from both O A and VVU indicated significantly higher counts for all bacteria types at VVU (Table 6).

Table 6. Bacteria count in faecal matter before composting (cfu g⁻¹dw)

Bacteria type	VVU (n=3)	OA (n=3)
Salmonella spp.	3.6 x 10 ⁵	1.0 x 10 ⁵
<i>Range</i>	(2.0 x 10 ⁵ - 5.5 x 10 ⁵)	(0.5 x 10 ⁵ - 1.5 x 10 ⁵)
Faecal Streptococci	14.0 x 10 ⁵	0.6 x 10 ⁵
<i>Range</i>	(7.4 x 10 ⁵ - 14.0 x 10 ⁵)	(0.1 x 10 ⁵ - 1.4 x 10 ⁵)
Escherichia coli	1.8 x 10 ⁵	1.1 x 10 ⁵
<i>Range</i>	(0.8 x 10 ⁵ - 3.0 x 10 ⁵)	(0.7 x 10 ⁵ - 1.7 x 10 ⁵)

a) *Salmonella* spp.

At VVU between 2.3- and 3-log₁₀ reductions were achieved for all compost categories at the end of the trial. This was higher than the 1.6- to 2.7-log₁₀ unit reduction achieved at OA (Table 7). The highest die-off of *Salmonella* spp. at VVU was achieved in the composts with MS/LTF and HS/LTF. This was quite similar at OA where the highest reduction was in the categories of compost with MS/HTF and HS/LTF. A re-growth of *Salmonella* spp. of 0.3- and 0.6-log₁₀ for compost categories with HS/LTF and HS/HTF, respectively, was observed on day 54 of composting at VVU. This was also observed in composts with HS/LTF and LS/HTF at OA where re-growth was 0.3-log₁₀ and 0.4-log₁₀, respectively. While no re-growth was observed on day 84 at VVU, 0.1-, 0.08- and 0.04-log₁₀ re-growth for LS/HTF, LS/LTF, HS/HTF composts was observed at OA.

Table 7. Counts of *Salmonella* spp. (\log_{10} of cfu g⁻¹dw) at different times

Locat- ion	TIME	Compost Category								
	(days)	LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
VVU	0	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56
	27	5.38	5.34	4.68	4.62	5.18	4.81	4.62	5.12	4.29
	54*	3.26	3.56	3.58	3.76	3.38	3.51	4.89	4.86	4.84
	84**	2.78	3.15	3.26	3.00	3.00	2.60	3.20	3.00	2.60
OA	0	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03
	27	3.41	3.76	3.83	4.34	3.92	3.38	4.10	4.16	3.38
	54*	3.68	3.00	3.00	2.90	3.48	2.90	2.30	2.60	3.73
	84	2.78	3.41	3.08	2.30	2.60	2.90	3.34	2.60	2.30

* $p \leq 0.05$, ** $p < 0.001$ at 95% confidence limit; Day 0, $n=3$

There was no significant difference ($p > 0.05$) of die-off between the two sites or due to turning frequency or sludge load. However, there was a significant difference in the die-off of the bacteria between days 27 and 54, and between days 54 and 84 at VVU. There was also a significant decrease ($p < 0.05$) in the counts of *Salmonella* spp. between days 27 and 54 at OA. At OA, the survival of this bacterium was negatively correlated with pH and positively correlated with mean core temperatures. A negative correlation between *Salmonella* spp. and pH was also observed at VVU, while EC, mean inside temperatures and time (months) were positively correlated (Table 5).

b) Faecal *Streptococci*

A high die-off of faecal *Streptococci* was observed during the trial period. There was a higher decrease at VVU than at OA (Table 8).

Table 8. Counts of faecal *Streptococci* (\log_{10} of cfu $g^{-1}dw$) at different times

Locat- ion	TIME (days)	Compost Category								
		LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
VVU	0	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15
	27	4.58	4.41	4.88	4.97	4.34	4.53	4.98	5.12	5.17
	54**	2.30	3.41	3.15	2.30	2.78	3.45	3.41	3.08	3.08
	84*	1.60	2.08	1.30	2.08	1.90	2.26	2.34	1.60	2.26
OA	0	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81
	27	2.78	3.15	3.20	3.30	3.62	3.00	3.73	3.99	3.34
	54	3.38	2.60	3.20	2.60	4.08	3.08	2.78	2.90	3.15
	84**	1.60	1.90	2.00	2.26	1.90	2.15	2.48	2.51	2.93

* $p \leq 0.01$, ** $p \leq 0.001$ at 95% confidence limit; Day 0, $n=3$

There was no re-growth of this bacteria strain at VVU whereas at OA some re-growth was observed on day 54 in LS/HTF, MS/MTF, and MS/LTF categories. Higher re-growth occurred in the category with MS/MTF, $0.04\text{-}\log_{10}$. Log reduction of this strain was between $3.8\text{-}\log_{10}$ and $4.9\text{-}\log_{10}$ at VVU and $1.3\text{-}\log_{10}$ and $2.6\text{-}\log_{10}$ at OA. Reduction was higher in compost with low sludge than in those with medium and high sludge load. There were no significant effects of sludge load or turning frequency on faecal *Streptococci* die-off. The highest reduction was achieved between days 54 and 84 at OA ($p \leq 0.001$). A highly significant reduction of faecal *Streptococci* also occurred between days 27 and 54 at VVU, as well as between days 54 and 84.

c) *Escherichia coli* (*E. coli*)

Among the three bacteria monitored during the trial, *E. coli* had the most stagnant load (Table 9). \log_{10} reductions were between 0.5 and $0.8\text{ cfu }g^{-1}dw$ at VVU and OA. Some re-growth occurred in composts with MS/MTF and HS/MTF at VVU between days 27 and 54. This continued in the category with HS/MTF until day 84. During the same period, re-growth occurred in categories LS/HTF and HS/HTF at

OA. There were no significant effects of sludge load or turning frequency on the reduction of *E. coli*. There was a significant difference in the number of cfu g⁻¹dw between days 27 and 54 for compost categories at VVU and OA. Statistics also showed a significant difference ($p < 0.005$) in *E. coli* counts between days 54 and 84 at VVU.

Table 9. Counts of *E.coli* (log₁₀ cfu g⁻¹dw) at different times

Locat- ion	TIME (days)	Compost Category								
		LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
VVU	0	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
	27	5.11	4.96	5.13	4.88	4.78	4.85	4.97	4.58	4.86
	54*	4.77	4.82	4.74	4.66	4.98	4.75	4.74	4.63	4.76
	84**	4.57	4.74	4.66	4.61	4.56	4.42	4.64	4.68	4.39
OA	0	5.04	5.04	5.04	5.04	5.04	5.04	5.04	5.04	5.04
	27	4.51	4.56	4.96	4.87	4.75	4.56	4.48	4.15	4.66
	54**	4.57	4.29	4.28	4.23	4.26	4.06	4.30	4.41	4.33
	84	4.54	4.23	4.48	4.43	4.46	4.42	4.26	4.30	4.39

* $p \leq 0.05$, ** $p < 0.005$ at 95% confidence interval; Day 0, n=3

A significant negative correlation was observed between compost pH, time (months) and the die-off of *Salmonella* spp. and faecal *Streptococci* at VVU. There was no significant correlation between *E. coli* die-off and pH. Mean inner temperatures of composts were positively correlated with the reduction of *Salmonella* spp., faecal *Streptococci* ($p < 0.01$) both at VVU and OA. Die-off of *E. coli* was not correlated with temperatures at OA, but a weak positive correlation was observed at VVU. Like with the other two bacteria, there was a strong negative correlation between *E. coli* survival and time (months) (Table 5).

d) Comparative die-off rate of bacteria

The proportion of *Salmonella* spp. and faecal *Streptococci* inactivated by day 54 was higher at VVU than at OA. Higher proportions of deactivated *Salmonella* spp. were observed in HS compost piles at OA (Figure 13). More *E. coli* was destroyed at OA than at VVU during the same period. There were high rates of *Salmonella* spp. and faecal *Streptococci* destruction in all compost categories at both sites

although the die-off rate was higher at VVU than at OA (Figure 13). *E. coli* was more resistant to the conditions during composting at both locations.

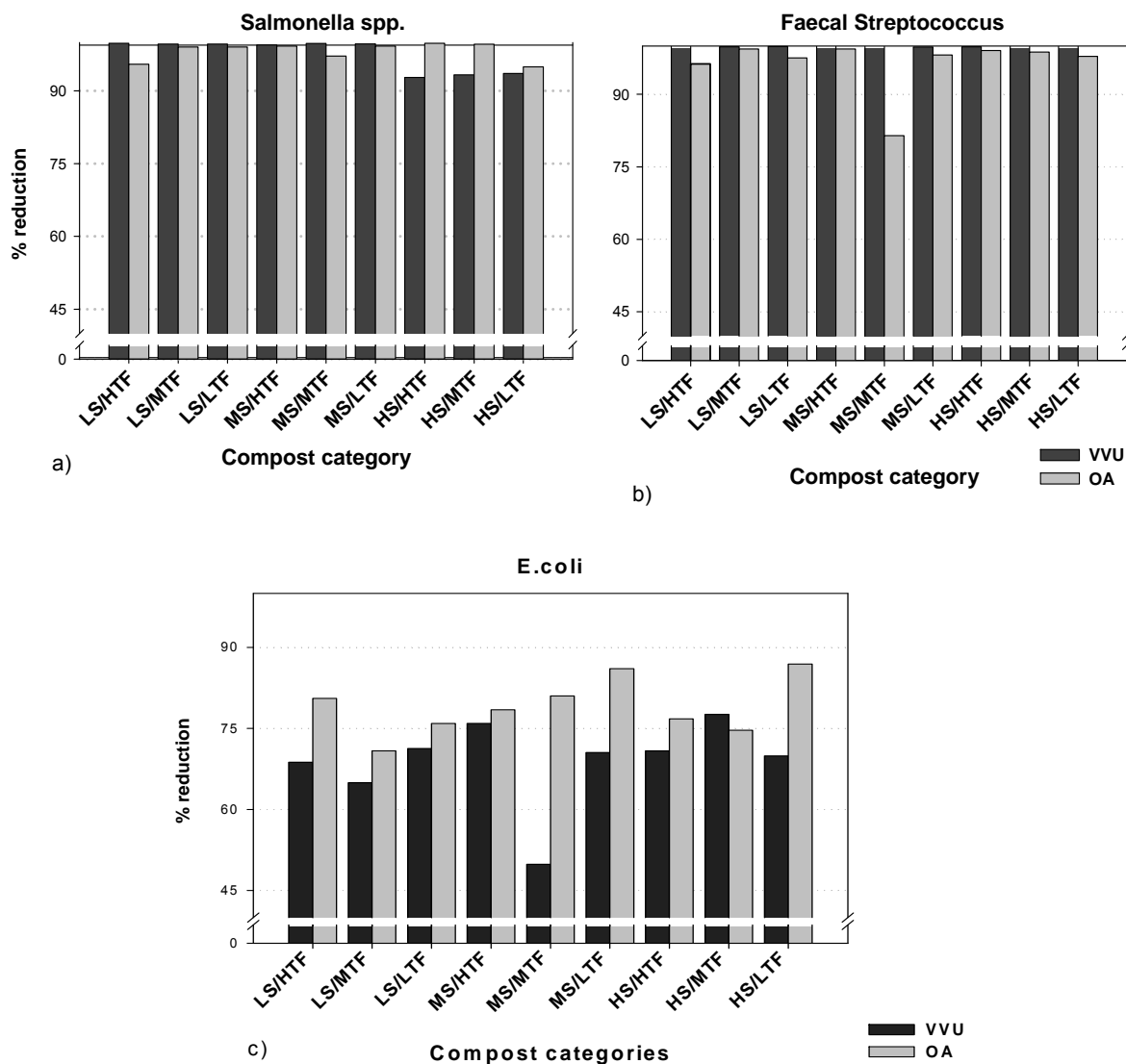


Figure 13: Die-off of faecal bacteria after 54 days

More than 99% of *Salmonella* spp. and *Streptococcus faecalis* had been deactivated by the end of the trial period (Figure 14). The proportion of these two pathogens deactivated was the same at both sites and in all compost categories except for HS/HTF in which deactivation of *Salmonella* spp. was higher (Figure 14b). Less than 90% of the *E.coli* were destroyed. Higher deactivation was

achieved at VVU than at OA except for composts with HS/HTF and HS/MTF, where there was 6 to 7% more deactivation at OA (Figure 14c).

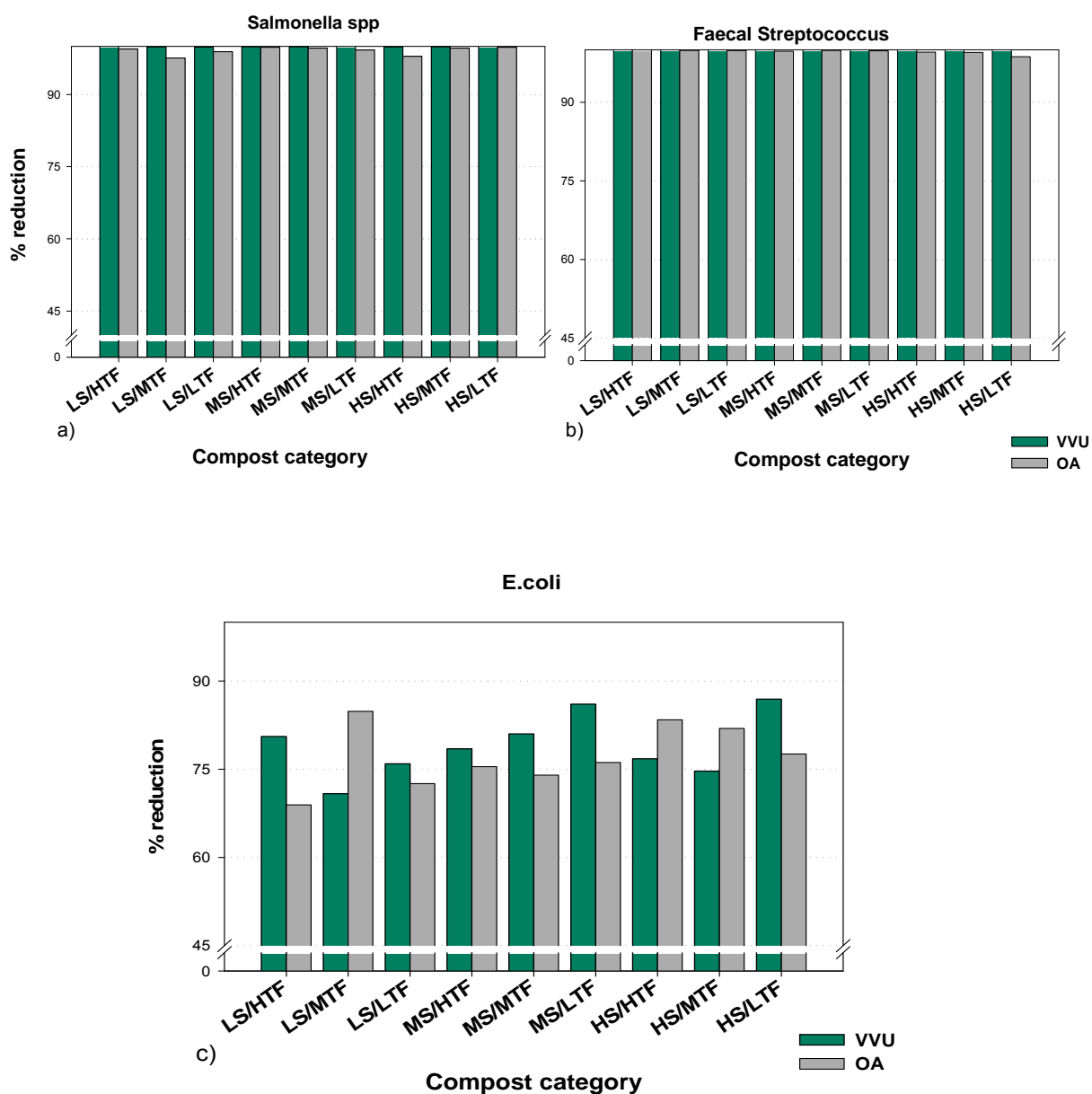


Figure 14: Die-off of faecal bacteria after 84 days

3.3.1 Helminth eggs (*Ascaris suum*)

A low percentage of the *Ascaris suum* eggs were recovered from the trial. At VVU, 40% of the egg probes recovered had eggs inside. No eggs were found in 43%, and empty egg shells were found in the remaining 13%. Of the recovered probes

that had eggs, 35% were from the middle of the compost, and all of them had >95% of the eggs deactivated by the end of the trial. The remainder (65%), that were ≤ 15 cm inside the compost during the trial had >90% viable eggs. No egg was found in 75% of the egg probes at OA. Of the remaining samples, 17% had eggs and 8% had empty eggshells. All the eggs recovered were from the colder zones of the compost pile (≤ 15 cm), and only 2 to 3% of them were not viable after breeding.

3.4 Nutrient composition

The proportion of NPK in the final compost at both sites reflected that of the respective feedstock. Table 10 shows that while nutrient composition and organic carbon content of biomass were similar for VVU and OA, N and P content of the sludge were two times higher in the faecal sludge at VVU, while K content was nearly three times higher at OA.

Table 10. Nutrient composition of compost feedstock

Locat- ion	Compost Feedstock	% DM Nutrients/Organic Carbon content (n=3)			
		N	P	K	C _{org}
VVU	Biomass*	1.34	0.06	2.56	37.59
	Range	(1.10-1.50)	(0.03-0.70)	(2.20-3.16)	(36.37-38.95)
	Faecal sludge (faeces + urine + paper)	3.27	3.78	1.45	21.89
	Range	(2.44-4.43)	(3.37-4.11)	(1.01-2.18)	(16.58-28.06)
OA	Biomass*	1.51	0.07	2.13	37.13
	Range	(1.51-1.60)	(0.06-0.07)	(1.75-2.36)	(34.91-38.71)
	Faecal sludge (faeces + urine + paper + wood ash + sawdust)	1.77	1.63	4.32	29.33
	Range	(1.66-1.85)	(1.55-1.71)	(3.96-4.39)	(26.72-32.15)

**Panicum maximum*, *Azadirachta indica* and *Mangifera indica* leaves and twigs

DM= Dry matter; C_{org} = Organic Carbon

At VVU, the amount of P was significantly higher in composts with medium compared to those with low sludge load. P was also significantly higher in HS than

in LS composts (Figure 15). There were no significant differences in NK and organic carbon composition with regard to sludge load. The frequency of turning had no significant effect on NPK and organic carbon contents.

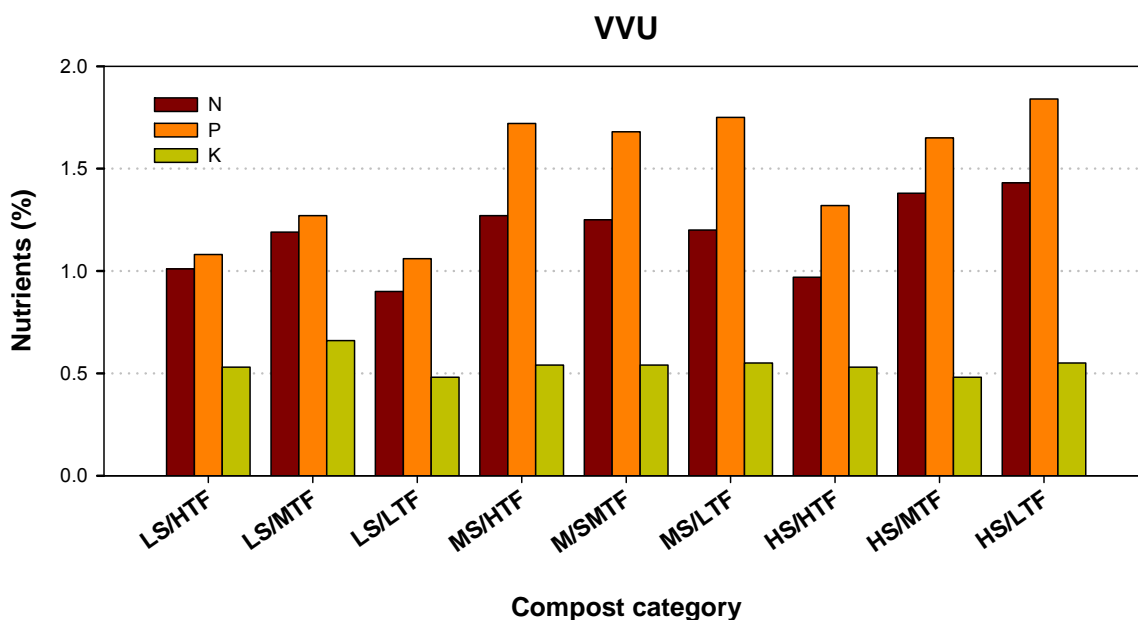


Figure 15: Nutrient contents in composts at the end of trial

On day 84 of composting at OA, the NPK content was significantly higher in HS than in LS composts (Figure 16). Organic carbon content was not affected by sludge load. Turning frequency also had no significant influence on NPK and organic carbon contents. Nutrient content varied according to compost sludge load. Percentage N and P were generally higher at VVU than at OA. Percentages of N and P were higher in composts with MS and HS except for the category HS/HTF. The compost K content was variable. N percentage decreased between days 27 and 54, but increased again towards the end of the trial (Table 12).

Percentage organic carbon decreased during composting for all composts to values lower than in each of the feedstock. From day 27 of composting, organic carbon content decreased by 8 to 11.8%. The carbon:nitrogen (C:N) ratio in the final composts ranged from 8.3 to 13.4 at VVU and from 11.3 to 22.1 at OA (Table 11). At the end of the trial, all compost categories at OA had a higher C/N ratio

than those at VVU except for the compost treatment MS/LTF with a C:N ratio of 13.4.

Table 11. C:N ratio at the end of the trial

Location	Compost category								
	LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
	C:N								
VVU	9.6	9.5	9.6	8.6	8.6	13.4	8.3	8.4	8.3
OA	11.6	12.1	14.3	22.1	11.3	13.3	12.5	11.8	11.7

Percentages of N and P at OA were <1.5% for composts with MS and HS (Figure 16). The composts with MS/MTF had the highest N content, 1.25%. K was less in composts with LS, but generally more in MS and HS compost. Except for the compost pile with LS/HTF at OA, the amount of K was higher in all composts at OA than in those at VVU. Between days 54 and 84, percentage N content did not increase.

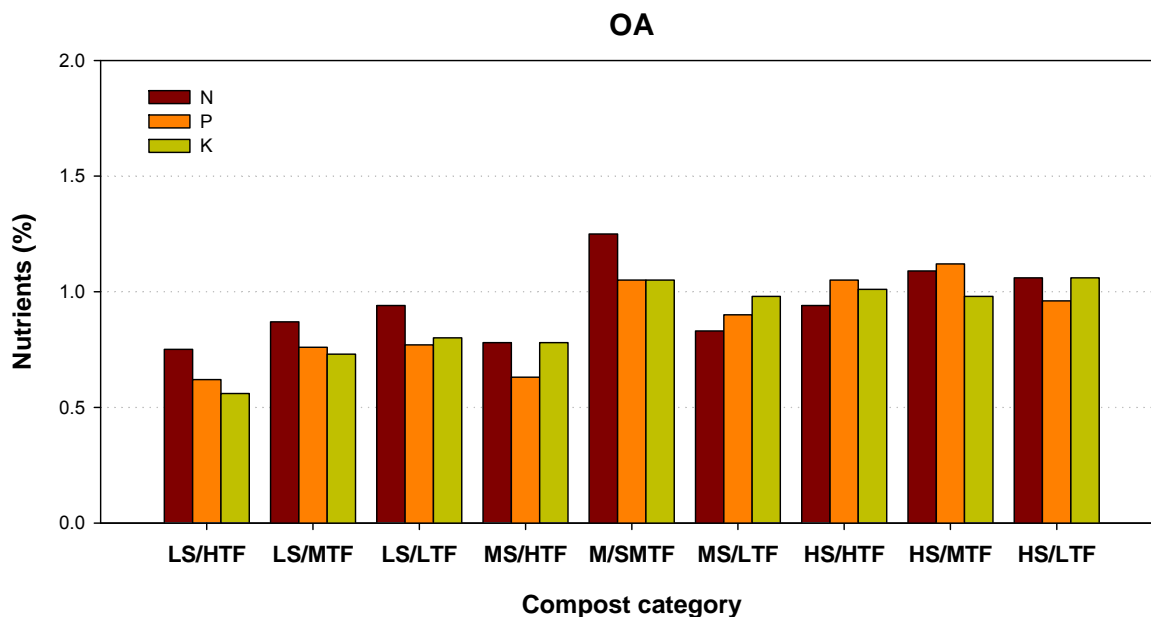


Figure 16: Nutrients in composts at the end of trial

The percentage of organic carbon also decreased. The compost with the highest turning frequency had the lowest organic carbon content.

Table 12. Changes of the nutrients and organic carbon content during composting

Location	Time (Days)	Nutrients & Carbon content *(%)	Compost Categories								
			LS/HTF	LS/MTF	LS/LTF	MS/HTF	MS/MTF	MS/LTF	HS/HTF	HS/MTF	HS/LTF
VVU	27	N	1.18	1.31	0.79	1.33	1.39	1.43	1.40	1.49	1.64
		P	ND	ND	ND	ND	ND	ND	ND	ND	ND
		K	ND	ND	ND	ND	ND	ND	ND	ND	ND
		C _{org}	17.87	21.13	12.60	18.74	20.40	13.81	18.23	17.50	21.73
	54	N	0.94	1.12	1.36	0.99	0.77	1.64	0.98	1.32	1.40
		P	ND	ND	ND	ND	ND	ND	ND	ND	ND
		K	ND	ND	ND	ND	ND	ND	ND	ND	ND
		C _{org}	7.14	11.79	12.44	9.98	6.03	12.16	9.00	12.52	10.68
	84	N	1.01	1.19	0.90	1.27	1.25	1.20	0.97	1.38	1.43
		P	1.08	1.27	1.06	1.72	1.68	1.75	1.32	1.65	1.84
		K	0.53	0.66	0.48	0.54	0.54	0.55	0.53	0.48	0.55
		C _{org}	9.73	11.25	8.65	10.91	10.80	16.06	8.09	11.58	11.83
OA	27	N	0.87	1.09	1.30	1.15	1.34	1.46	1.16	1.04	1.19
		P	ND	ND	ND	ND	ND	ND	ND	ND	ND
		K	ND	ND	ND	ND	ND	ND	ND	ND	ND
		C _{org}	15.53	20.35	22.36	19.03	21.49	20.52	19.32	17.66	22.50
	54	N	0.81	0.89	1.03	0.85	1.27	0.96	0.98	1.07	1.16
		P	ND	ND	ND	ND	ND	ND	ND	ND	ND
		K	ND	ND	ND	ND	ND	ND	ND	ND	ND
		C _{org}	9.73	9.72	12.48	10.41	14.35	10.72	11.93	14.07	15.39
	84	N	0.75	0.87	0.94	0.78	1.25	0.83	0.94	1.09	1.06
		P	0.62	0.76	0.77	0.63	1.05	0.90	1.05	1.12	0.96
		K	0.56	0.73	0.80	0.78	1.05	0.98	1.01	0.98	1.06
		C _{org}	8.74	10.52	13.47	12.27	14.07	11.04	11.76	12.85	12.40

ND = Not Determined, C_{org} =Organic Carbon, *Dry matter

4. DISCUSSION

4.1 Compost physiochemical parameters

a) Temperature

Except for one compost pile at VVU, composts in the HS category had only one thermophilic phase. This might have resulted from 'clogging' of faecal matter that allowed less contact of microorganisms with the organic matter in the biomass. At OA, where no such clogging was observed, the composts in these categories recorded two thermophilic phases. Although this parameter was not directly assessed, it could also be presumed that there was a higher population of microorganisms responsible for degradation that might have speeded up the process resulting in higher temperatures. Clogging of faecal matter might have been facilitated by the sandwich set-up. It allowed little room for the proper circulation of oxygen necessary for aerobic composting. Some heat might have also been lost in an attempt to mechanically disintegrate the clogged sludge with shovels and digging forks given that temperatures were already declining by the third week.

The occurrence of two thermophilic phases could be attributed to the fact that during the initial phase, when there was no turning of the piles, microbial degradation was high. Then it was reduced because access to non-degraded materials became increasingly difficult for microorganisms. This might have resulted in competition among the microorganisms resulting in a reduction of their population with a consequent reduction in temperatures. The thermophilic phase observed during the second month of composting might have resulted from the fact that undegraded material came more in contact with microorganism due to turning of the piles. Each turning, irrespective of sludge load, was followed by an increase in temperature, although this was not statistically significant between turning frequency treatments. This pattern was observed until the end of the trial when turning for all composts categories hardly raised temperatures to values

more than 5°C above the ambient, probably due to a decrease in organic matter upon which microorganisms could feed.

The number of days for which composts could sustain high temperatures may have been affected by frequency of turning and lack of insulation. Though there was no significant difference in pile temperatures due to turning frequency, there exist a potential for heat to be lost during each turning, and those composts turned the least in all categories had high temperatures sustained for a longer time. Higher temperatures and a distinct effect of turning frequency on temperature development might have been achieved if the compost piles were insulated. Vinnerås (2002) stated that sufficient insulation is required to maintain temperatures of 60°C and above for a long time to ensure an efficient disinfection of faecal matter during composting. It took between 2 to 4 hours for composts to attain the previous temperature after each turning. This lag time increased to an average 7 hours during the second month of composting. The time interval required for temperatures to rebuild after each turning implies that the activity of mesophilic and thermophilic microorganisms was affected by turning. Pinsem and Vinnerås (2003) stated that when composts are turned, new aeration pore and contact areas are constructed which enhances the microbial degradation of carbons and can result in an increase in temperature. However, more frequent turning might not be necessary once the organic matter content of the compost has been reduced.

At the initial phase of composting, there was no rainfall for at least one month. Compost moisture had to be regulated by addition of 12 to 24 litres tap water to each pile. However, when the rains came, they were often sporadic and heavy, rendering the compost soggy. This might have further reduced the chances of achieving higher temperatures. It took 2 to 3 hours for previous temperatures to be achieved after each rainfall event and after each watering. It is, however, unclear which factor (insulation or rainfall) played a greater role in reducing chances for achieving higher temperatures at both locations.

Higher mean temperatures were recorded during the second month and at OA, the increase was significantly higher for HS than for LS compost. This could be due to a smaller population of microorganisms in LS compost. Another possible reason might be that composts with HS could maintain high temperatures for a longer time due to larger size. The significant reduction in mean inner temperatures during the second month might be due to low microbial population resulting from a lack of suitable substrate.

b) pH and electrical conductivity

The pH and salt concentration of composts are important properties in determining the quality of the final compost (Alexander, 1992; Thomson et al., 2002). The required pH and EC however, depend on the characteristics of the soil on which the compost is to be applied, and on the type of crop to be grown. The application of compost to the soil can affect its pH and also the availability of nutrients (Tester, 1990; Tisdale, 1985). Too high or low pH in composts can reduce the activity of bacteria, further breaking down the organic matter in compost and releasing the nutrients. Besides, if pH is not within the desired range (Table 13), it may affect the plants' ability to take up nutrients. Low pH may severely limit nutrient uptake, too high pH may result in high nutrient uptake rate resulting in toxicity. Low EC may indicate low availability of nutrients while too high salt concentration may also result in plant toxicity through rapid uptake (Warncke and Krauskopf, 1983). Table 13 shows typical ranges of test parameters in compost quality.

Table 13. Typical ranges in compost quality test parameters (Alexander, 1992)

Test Parameter	Range
pH	6.8 – 7.3
Soluble salts	0.35 – 0.64 dS/m (mmhos/cm) (1:5 v/v method)
Nitrogen	1.0 – 2.0%
Phosphorus	0.6 – 0.9%
Potassium	0.2 – 0.5%
Moisture content	45 – 50%
Organic Matter	35 – 45%
Bulk density	400 – 450kg/m ³

Apart from its influence on the soil characteristic, germination and growth of plants, compost pH may also affect the growth and activity of microorganisms during composting. It has been reported that most bacteria grow well under neutral conditions, and the pH range of 6.0 – 8.0 is recommended for successful composting (Obeng and Wright, 1987). While compost pH is expected to fluctuate during composting, the degree of fluctuation may depend on the composition of the feedstock. The pH of the compost feedstock at OA was higher than at VVU. This could be due to the addition of wood ash to the toilets at OA. This practice has been reported to increase the pH of faeces (Vinnerås, 2007; Smår et al., 2002; Carlander and Westrell, 1999).

In all compost categories at both sites, pH decreased during the second month of composting. This may have resulted from the degradation of organic matter in the compost which led to the release of acids. For instance, the degradation of organic carbon can release CO₂ which can recombine with water in the compost to form carbonic acid. Other organic acids that may arise from the composting process include acetic, butyric and lactic acids. These can lower pH during the initial stage of composting (Sundberg, 2005; Beck-Friis et al., 2003; Himanen et al., 2006; Chanyasak et al., 1982) with a consequent decrease in microbial growth and activity (Cherrington et al., 1991). The subsequent increase in pH may have been due to the degradation of organic acids which became a valuable substrate for

some microorganisms. Similar findings have been reported by Sundberg (2005) and Beck-Friis et al. (2003). As the released acids could be volatile (Himanen et al., 2006; Chanyasak et al., 1982; De Vleeshauwer et al., 1982), turning the compost might facilitate the release of these acids with a subsequent increase in pH. Another possible reason for the increase in pH could be the release of ammonia (NH_3) resulting from the mineralization of nitrogen. Sundberg (2005) stated that NH_3 has a dissociation constant of 9.24 at 25°C, which is capable of increasing pH. There also was a significant correlation between pH and K, which could be an indication that there was an influence of K concentration.

Electrical conductivity is a measure of the soluble salts contained in a substance. A high conductivity in compost can suggest high salt availability (Sundberg, 2005). Most of the NPK in faeces has been reported not to be easily available to plants (Jönsson et al., 2004; Winblad and Simpson-Hébert, 2004). Composting could be a useful process through which these nutrients can be eventually released and become available upon application in the field.

Though not statistically significant, the observed higher levels of EC in HS composts could be due to higher concentration of unavailable salts than in LS composts. This would mean higher salt concentration upon degradation in composts with HS resulting in an increase in EC. The increase in EC might have resulted from the mineralisation of organic compounds containing NPK and sulphur (S). The eventual decrease could be because some of the mineralised compounds were eventually degraded or immobilized by microorganisms (Robertson and Groffman, 2007; Pearson et al., 2004). The decrease in conductivity may also have resulted from leaching of soluble salts like P and K from the compost as they were exposed to rather sporadic heavy rainfalls. This is consistent with the findings of Zhang et al. (2006) who found that the conductivity of the soil can decrease through leaching of salts. However, the conductivity of the composts is expected to decrease and eventually stabilize during the maturation phase (Wu et al., 2000).

There was a significant negative correlation between pH and EC. This was to be expected, because hydrogen ions could have been released from ammonium during nitrification processes in the compost which would have decreased pH. The accumulation of nitrates could eventually increase conductivity. Similar findings have been reported by Sánchez-Monedero et al., (2001).

4.2 Compost phytotoxicity

Compost stability is an important aspect that should be considered when composting faecal matter. Unstable and immature compost can have an inhibitory effect on the growth performance of plants as it may emit phytotoxic substances (Epstein, 1997; Elliot and Travis, 1975; Himanen et al., 2006). According to Taquia et al. (1996), a Germination Index (GI) above 80% is an indication of total disappearance of phytotoxic potential of compost. After 27 days of composting, all composts were just at the threshold of this phototoxicity limit. At this stage, the compost can still be considered active, as suggested by the high and fluctuating temperatures at both sites. This high activity might have resulted in the release of chemicals toxic to the growing seedlings of garden cress. Kakimolo et al. (2006) compared the toxicity of faeces from a 'healthy' person and compost extracts from a bio-toilet system. In the bio-assay, they found out that faeces were less toxic than compost and concluded that biological reactions during the composting process could have produced toxic chemicals.

Studies on the toxicity of composts at different stages of development have revealed that formic acids, butyric acid, propionic acids and acetic acid are released during the degradation of organic matter. These highly volatile acids were found to significantly increase phytotoxicity in various bioassays (Himanen et al, 2006; Chanyasak et al, 1982; De Vleeshauwer et al., 1982). The significant increase in fresh shoot biomass between days 27 and 54 and between days 54 and 84 could be from a reduction in the amount of the toxic elements released during the early stage due to the breakdown of organic matter in the composts. The period between day 54 and 84, when the highest biomass yield was achieved, coincides with the period of increased pH of the composts. This could be an

indication that toxicity of composts decreased with increasing pH which is in line with the previous assumption that the release of organic acids could be responsible for phytotoxicity. The fact that GI increased consistently over time implies that the toxicity of composts decreased. Araujo and Monteiro, (2005) also carried out a bioassay with 90 days old compost and achieved a GI of 100%.

Although not significantly different, the observed lower biomass (Figure 12) yield in composts turned the least frequently might be due to an accumulation of the above-mentioned acids while composts turned more frequently could have enhanced the release of these volatile acids and growth of garden cress (Himanen et al., 2006; Araujo and Monteiro, 2005). Results of a plant bioassay carried out by Himanen et al. (2006) with 3- and 6-month old compost showed that the high concentrations of formic and acetic acids in both composts were suppressive to plant growth.

4.3 Pathogens

While faecal composts can improve soil conditions through their nutrient and organic matter contents, pathogen concentration and the risk of infection may affect their use in agriculture. WHO (2006b) has recommended that no faecal *Streptococci* and *Salmonella* spp. should be found in finished faecal compost after treatment before use in agriculture. A tolerable amount of <1000/g total solid is given for *E. coli*. The pathogens monitored during this trial showed different deactivation rates. There was a lower count of faecal bacteria at OA than at VVU at the beginning of the trial. This might have resulted from the addition of wood ash and saw-dust to the toilet at OA. Wood ash addition can cause an increase of faecal pH during the collection phase in the toilets. Vinnerås (2007) reported that addition of wood ash to toilets could increase pH to levels unsuitable for bacterial growth. Carlander and Westrell (1999) found that up to 6log₁₀ reduction of *Salmonella* spp. was achieved after storing wood ash-treated faecal matter for 7 weeks. Since the users of the toilets were not the same in both areas, lower counts of bacteria number could also be associated with variations in the infection in both locations. The comparatively higher number of the assessed pathogenic bacteria

in the toilets at VVU could also be explained by the duration of the sludge in the collection chamber before composting. While some of the sludge at VVU was 15 years old at the time of collection for the compost trial, whereas at OA the oldest part of the sludge was only 2 years old. The period between collection and treatment of faecal matter can influence the number of pathogenic bacteria given that they have a potential to reproduce after they have been excreted (Schönning et al., 2002). Adding wood ash and sawdust to faeces can have a desiccation effect that negatively affects the growth of pathogens (Winblad and Simpson-Hébert, 2004; Austin, 2001). The addition of ash to the toilets at OA depended more on the availability than on the recommended handful or sufficient amount to cover the faecal matter and enhance pathogen deactivation. Faeces and urine were also collected in the same toilet chambers, and poor sealing of the collecting chamber allowed water intrusion into it, making the water content of faecal sludge here higher than it should have been.

During the trial, faecal *Streptococci* had the highest decrease in numbers at both sites. This could mean that the bacteria were most sensitive to the composting conditions, especially temperatures and pH. The significant reduction in the assessed faecal bacteria after two months of composting at both sites and for all compost categories could be due to the increase in compost temperature during this period. Mean monthly temperatures for the different compost categories were 12°C ($\pm 4^\circ\text{C}$) above the ambient. Although there was no significant difference between LS and MS composts, the highest \log_{10} reduction of *Salmonella* spp. and faecal *Streptococci* after the first month of composting was achieved in them both at VVU and OA. This could be due to the lower concentration of their lower concentration considering that both of them received relatively low amounts of sludge.

Escherichia coli was the most resistant of the three pathogens assessed, and at the end of the trial, less than 80% of the initial load of the bacteria had been killed. This might be because the temperatures achieved were not high enough for its deactivation. On the other hand, > 99% of the initial load of *Salmonella* and faecal

Streptococci had been deactivated by the 54th day of composting. The significant correlation ($p < 0.005$) between the mean inner temperatures during this period and the die-off of *Salmonella* spp. and faecal *Streptococci* seems to indicate that these two bacteria are sensitive to temperatures between 45°C and 55°C, which were achieved during composting. In various experiments, different pathogen survival times have been identified by different authors. The temperature, pH, moisture content, storage and length of time within which different pathogenic bacteria are deactivated may differ with composting method and scale. Droffner and Brinton (1995) found that *E. coli* could survive for 59 days at 60°C, indicating that it is highly thermo-tolerant though it could be killed after 9 days at temperatures between 60 and 70°C. Larney et al. (2003) on the other hand, achieved >99% reduction of total coliform and *E. coli* after 7 days of windrow composting with mean temperatures between 33.5°C and 41.5°C. The USEPA (1992) has recommended minimum temperatures of 55°C for at least 15 days of composting to ensure that pathogens in sludge are completely deactivated. This, however, requires further investigation for an in-depth understanding of the behaviour of this pathogen during composting.

The significant decrease of *Salmonella* spp. and faecal *Streptococcus* during the last 30 days of composting at both sites may have resulted from the slight increase in pH which might have negatively affected the growth of these faecal indicators. Faecal bacteria tend to be highly sensitive to pH above 9 (Smår et al., 2002). However, this factor interacts with the compost temperatures. Höglung et al. (2002) reported that there was no reduction in *Salmonella typhimurium* 28b phages at 5°C in a pH of 9.0 but more than 90% reduction was achieved within 71 days when temperatures were 20°C. Studies carried out by Carlander and Westrell (1999) and Vinnerås (2007) have also shown that an increase in pH can enhance the reduction of faecal pathogens at temperatures between 4°C to 35°C. The significantly negative correlation between pH and survival of *Salmonella* spp., faecal *Streptococci* could indicate that increasing pH has a negative effect on their survival. This may not be the case with *E. coli*, for which this correlation was not significant. This speculation is, however, not conclusive and further investigation is

therefore needed. At mesophilic temperatures during composting, with a pH range between 6.8 and 7.3, Larney et al. (2003) achieved a significant reduction of faecal pathogens. Microorganisms more adapted to aerobic compost processes might have also been responsible for pathogen reduction through predation and competition for nutrients during composting (Faechem et al., 1983; Hussong et al., 1985).

Pietronave et al. (2004) have observed that low levels of pathogenic bacteria such as *Salmonella* spp. achieved during composting may re-grow and pose a health risk in agricultural application. Re-growth manifested during composting might have resulted from recontamination of sanitised compost during turning. Since the sludge formed 'clogs' which prevented uniform temperatures to be achieved in all parts of the compost piles at the same time, each turning might have caused a recontamination of the portions of the composts already sanitised. Jones and Martin (2003) have reported that poorly stabilised composts with organic matter remains might enhance the re-growth of *E. coli* and *Salmonella* spp. Sidhu et al. (2000) and Pietronave et al. (2004) have stated that all composted products still have the risk of pathogen re-growth and as such should never be taken as a sufficient guarantee for compost safety. Re-growth has also been reported to be enhanced by the moisture content of the compost. The addition of water to meet the required optimum for composting microorganisms and irregular rainfall during the trial period might have increased the moisture content of composts, favouring the pathogen re-growth. According to WHO (2006b), application of moisture to faecal matter can enhance the re-growth of bacterial pathogens if easily metabolisable organic compounds are present. The higher tendency of re-growth of *Salmonella* spp. and faecal *Streptococcus* observed at OA compared to VVU could be due to the relatively higher manure content and C:N ratio of the composts at OA (Table 11). Russ and Yanku (1981) have reported the potential for *Salmonella* spp. re-growth in composts with C:N ratio >15 and manure content >20%. *E. coli* has also been found to re-grow when sanitised compost still contains sufficient amounts of nutrients (Soares et al., 1995).

There was a low recovery of the *Ascaris suum* eggs that were inserted into the piles to monitor the deactivation of helminth eggs. Perhaps some of the eggs were already at the early stage of development at the time of extraction; nonviable embryonated eggs were found after breeding for 5 weeks. Since excreted eggs can only develop in their secondary hosts, it can be assumed that the embryo had started developing in the pig before the eggs were extracted. This could be an indication that some of the eggs might have passed their resistant stage of development before they were subjected to treatment. This could render them more susceptible to slightly elevated temperatures. Black et al. (1982) when studying the survival rates of parasite eggs in sludge also found that embryonated eggs were less resistant to aerobic and anaerobic digestions. The eggs used for this trial were extracted from the uteri of worms and might not have undergone the necessary physiochemical stages, such as tanning, necessary to render them resistant (Black et al., 1982; Cheng, 1974). This might also be the reason for the high percentages of broken and empty eggshells found during analyses. Eggs extracted from the uteri of worms could be at different stages of development and this could render different resistances to temperatures and physical pressure exerted on them. Physical pressure during field handling which involved removal of bags from the composts and washing the probes before preservation for analyses may have also accounted for the proportion of broken eggshells found during analyses of viable eggs. Brownell and Nelson (2006) have reported that physical forces exerted on eggs may result in a high number of empty eggshells of *Ascaris suum*.

However, of the recovered eggs, those in the middle of the pile had more than 95% non-viable eggs at the end of the trial. This could be because the temperature achieved in this zone was high enough to deactivate the eggs. Besides, assuming that some of the eggs had started developing before extraction, it is likely that they may become more susceptible to deactivation at temperatures less than the optimal requirement (>55°C for at least 1 hour) for composting (Jones and Martin, 2003). Those which were about 15cm into the pile had only 2 to 10% non-viable eggs at the end of the trial probably because the temperatures here were too low.

Helminths eggs are highly thermo-resistant and can survive in the environment for up to one year at temperatures less than 40°C (Brownell and Nelson, 2006; Faechem et al., 1980). Strauss and Blumenthal (1990) have estimated the survival time of helminth eggs to be > 1 year at temperatures between 20°C to 30°C. During the trial, temperatures above 45°C were achieved at least once and for more than 3 days and for at least two months temperatures were above 40°C for all compost categories at both sites. This time might have been sufficient to deactivate the viable eggs. Barret (1976) reported that once subjected to protracted thermophilic temperatures, the eggshells of *Ascaris* could become less resistant and susceptible to destruction by osmotic effects of dissolved chemicals.

4.4 Nutrients

Apart from the organic matter content, retaining the nutrients in compost is of agronomic importance. Most of the nutrients in raw faecal matter are in organic form, implying they may not be available to plants in the short term. These nutrients can be made plant-available during composting (Frossard et al., 2002). The rate at which they become available may depend on the rate at which the microorganisms degrade them (Hadas and Portnoy, 1994). The amount of nutrients that in compost may be influenced by the compost feedstock (Thomson et al., 2002) and by turning frequency. Feedstock with high plant nutrient content can result in composts rich in nutrients. However, this is only possible if the composting process is managed in a way that minimizes losses due to volatilization and leaching. Pisem and Vinnerås (2003) stated that during composting some of the nitrogen could be lost in the form of NH₃. The relatively high content of N and P in the final composts at VVU could be associated with the amounts in the feedstock. The low concentration of N in the faecal matter at OA may due to volatisation losses during the collection phase in the toilet chamber. The lids were made of aluminium and painted black to augment temperatures in favour of increased ventilation (in through the toilet bowl and out through the ventilation pipes). Increased temperatures and ventilation can increase gaseous emission of N. Though there is a similar system at VVU, it does not function well

due to thick concrete slabs used as lids. The poor ventilation here could be recognised from the strong smell inside the toilet building. Discrepancy in the number of users and frequency of use may also be responsible for the differences in the percentage N content in the sludge. At VVU the number of people who use the toilets for both defecation and urination is approximately 3 times more than OA. The concentration of N from urine is likely to be higher too in the faecal sludge. Besides relatively smaller number of users, dry-urinals at OA reduce the potentials for collecting most of the urine which could increase the content of N in the faecal matter if they were not used separately.

Turning intervals of composts in a pile setup could have considerably influence on the final composition of some of the plant macronutrients. N and sulfur are volatile, and significant losses may occur if the composts are turned frequently (Mang et al., 2007; Pisem and Vinnerås, 2003). The amount of N lost from composting is difficult to quantify due to fixation of free atmospheric N by some microorganisms (e.g. *Nitrosomonas-Nitrobacter* communities) (Gazi, et al., 2007; Robertson and Groffman, 2007) which may also be present in the compost.

The content of N decreased during the second month but increased again by the end of the trial at VVU. The decrease of N could have resulted from leaching of nitrate-N formed during the decomposition process (Robertson and Groffman, 2007) or volatilisation of ammonia formed during the mineralisation of organic nitrogen by microorganisms (Pisem and Vinnerås, 2003). Similar changes in N content have been reported by Sánchez-Monedero et al. (2001) during organic waste composting. The later increase might be due to mineralisation of organic N which came more in contact with bacteria during turning. At OA, there was a continuous decrease in N until the end of the trial. This might be due to leaching resulting from frequent rainfall that occurred here during the maturation phase. Also, the final compost at OA had a higher C:N ratio. Though this was not tested at the beginning of the trial, it could be assumed that C:N ratio was higher at OA than at VVU from the beginning due to the relative high N content of the feedstock. This could result in a high N demand by microbes to degrade carbon in the composts.

Robertson and Groffman (2007) have reported that a high C:N ratio could cause microorganisms to scavenge for N in their surrounding resulting in a low N content in soil. Such an inference could also be applied to composts.

K was significantly higher in the final compost at OA than at VVU, probably due to the application of wood ash to the toilets. Mang et al. (2007) stated that the addition of wood ash can increase the K content of composts. There was no significant change observed in the contents of P and K during composting but the observed slight decrease could be due to leaching. The comparatively higher P content in the sludge and final compost at VVU than OA might have been due to its accumulation over a long time.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Achieving high temperatures, which is considered very important for pathogen deactivation in open pile faecal composting constitutes a challenge. However, under semiarid conditions, it is possible to reduce by 99% faecal bacteria such as *Salmonellas* spp. and faecal *streptococci* within one month of composting with temperatures about 45°C (\pm 5°C) and pH above 7. *E. coli* shows higher resistance in these conditions and may require other treatment options. Pre-treated faecal (wood ash and sawdust) matter did not have any effect on the final load of the faecal bacteria.

Turning frequency has a minimal effect on temperature development and hence on pathogen deactivation. Composts that are turned more frequently especially at the early stage of composting could lead to heat loss that can lower the deactivation of thermo-resistant pathogens such *E. coli*. Compost toxicity could be substantially reduced within 54 days irrespective of turning frequency and sludge load.

A sandwich setup with wet faecal sludge enhanced clogging which could favour anaerobic conditions. Properly mixed feedstock could reduce the need for aeration within the first two weeks of composting which is the period when potentially high temperatures could be achieved.

The sludge load could influence temperatures in the piles. Larger piles (HS) could sustain temperatures above 45°C for a relatively longer time than LS piles. The nutrient concentrations in the final compost were influenced by compost feedstock and faecal sludge load.

Addition of water and sporadic rainfall lowered the temperatures in compost which could reduce microbial activity with a consequent reduction in the compost quality. Moreover, excess water may lead to leaching and loss of nutrients.

The final composts may look like soil but could still carry pathogenic bacteria as there exist a potential for re-growth. Therefore, subjecting composted faecal matter to further treatment could reduce pathogens and eliminate the risk of infection during application.

5.2 Recommendations

Frequent turning of composts may not be necessary during composting as this may increase heat loss. Thorough mixing of feed stock is required so that compost could be turned only once a week after the first 7 to 10days of composting and this period could be reduced to once in a fortnight during the maturation or stabilisation phase.

For a proper mixture and easy handling, faeces from urine diverting toilets should be used. This might reduce the risk of contact when taking out sludge from pit latrines such as the VIPs. Besides, comparably drier faecal matter could reduce clogging that might necessitate early turning of the compost.

Providing some form of insulation through the use of compost palettes or bigger piles could help to ensure a uniform temperature development which in turn could enhance pathogen die-off. Moisture losses through evaporation and the need to irrigate which may affect the temperature development in the compost could be reduced. The risk of compost getting soggy due to sporadic heavy rainfall could also be reduced by covering.

For a proper validation of the die-off rate of helminth eggs, only eggs shed by the worms should be used as their shells would have developed the properties necessary for their resistance in the environment.

5.3 Further Research

The die-off of faecal bacteria due to the effect of indigenous microorganisms is still speculative and could be investigated to have a proper understanding of why pathogen numbers still continue to decrease during the maturation and

stabilisation stage when temperatures are relatively low. It would also be of interest to investigate the optimum combination of pH, temperature and indigenous microbial population necessary for sanitising faeces compost.

SUMMARY

In Ghana soils are generally poor in organic matter and nutrient content, agricultural productivity is low and there is little use of mineral fertiliser. This research aimed at developing a composting process apt to sanitise faecal matter from public toilets in a simple way that can be easily adopted by local communities. Therefore, the compost as a product must be able to increase soil organic matter and nutrient content, while being hygienically and environmentally safe in its production and use.

To facilitate the initial building of the compost piles, a sandwich setup of faecal sludge and plant materials (*Panicum maximum*, *Azadirachta Indica* and the leaves and twigs of *Mangifera Indica*) was chosen. The experiment was carried out at Valley View University (VVU) with a pseudo-replicate at Orphanage Africa (OA) in Greater Accra. The layout was constituted of 9 treatments at each site. Treatments differed in the plant material to faecal sludge ratio and/or turning frequency. Ratios 1:1, 1:2, 1:3, were categorised as Low Sludge (LS), Medium Sludge (MS) and High Sludge (HS) respectively. Each pile in these categories was turned every 3rd, 5th and 10th day, starting 14 days after pile building; respectively classified as High Turning Frequency (HTF), Medium Turning Frequency (MTF) and Low Turning Frequency (LTF). Temperatures in the core and 15cm depth of each treatment were recorded twice a day and the courses of pH and electrical conductivity (EC) were monitored as well. Die-off of faecal indicators (*Salmonella* spp., faecal *Streptococci* and *Escherichia coli*) was assessed from homogenised samples collected on days 27, 54 and 84 of composting and analysed at International Water Management Institute (IWMI) Accra, Ghana. The inactivation of helminth eggs was validated with *Ascaris suum* eggs that were inserted into the compost after the piles had been set up at two depths; core of the pile and ≤ 15 cm depth. A plant bioassay with garden cress (*Lipidium sativum*) was carried out three times at a monthly interval to test phytotoxicity of compost at different stages. Above-root biomass yield of each treatment was expressed as a percentage of the control

(with garden soil). Changes in percentage nutrient nitrogen (N), phosphorus (P), potassium (K), and organic carbon (C_{org}) contents were also assessed, at Institute for Agricultural Chemistry at the University of Hohenheim, from air-dried compost material sampled three times during the trial.

Compost piles in the MS and HS categories recorded relatively higher temperatures at both sites. Temperature courses were slightly different at both sites with characteristic two peaks. Thermophilic temperatures were recorded earlier at OA than VVU. The pH of all categories at both locations decreased during the second month of composting and then increased during the third. However, it was in the range of 7.0 to 8.5 throughout the composting period. EC was distinctly higher at both sites for HS compost category though it decreased to slightly the same level in all treatments at the end of the trial. There was no clearly observed treatment or site effect on deactivation of faecal indicators. More than 99.9 % die-off of the initial load of *Salmonella* spp., and faecal *Streptococci* was achieved within 54 days of composting at temperatures less than 55 °C. *Escherichia coli* were more resistant at the attained temperature and pH. However, >75 % of the bacteria had been deactivated by the end of the trial. Slight re-growth for all bacteria was observed during the second month. Deactivation of *Ascaris suum* eggs was >90 % at the core of the compost and <30 % at 15 cm depth.

There was no observed influence of treatment on compost phytotoxicity. However, a significant reduction of toxicity was achieved after 54 days. All treatments at both locations achieved > 80 % above-root biomass yield of the control. Treatment effect on compost phytotoxicity was minimal. Nutrient balances indicated significantly higher percentage N and P at VVU while K and C_{org} were higher at OA. Lack of insulation and a proper mixture of the composts piles might have negatively affected the temperature increases during composting and the consequent effect on pathogen deactivation rate.

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