Human Excreta Treatment Technologies – prerequisites, constraints and performance

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Abstract

This thesis investigates treatment technologies for human excreta for safe recycling of the plant nutrients present as fertilizers.

The thesis consists of three papers, the first of which investigates incineration of faecal matter as a treatment and sanitation method using a locally fabricated incinerator made of steel sheets. The second and third papers investigate composting of faeces and food waste at two size scales, using 78-litre and 216-litre wooden reactors.

Incineration of faeces containing ash added during the collection phase showed that faeces/ash mixtures with ash content >80% caught fire when the temperature exceeded 800°C. Thereafter, temperatures in the range 800-1000°C were recorded. Incineration reduced mass almost instantly by 15-36%, organic matter by 78-99%, total nitrogen by 90-94% and available phosphorus by 70-94%. Incinerating faeces/ash mixtures with dry matter (DM) content <90% resulted in a strong smell that lessened when DM was higher. Incineration disinfects human excreta almost instantly and reduces their mass, while the ash produced can be used as a toilet additive, which is advantageous in urban areas where access to ash is limited.

Composting of faeces-to-food waste (F:FW) in wet weight ratios of 1:0, 3:1 and 1:1 was studied in 78-litre reactors. Styrofoam insulation (25 mm thick) around the compost reactors and compost turning every three days enabled sanitising temperatures (>50°C) to be reached and sustained for over a week in the F:FW = 1:1 compost, giving a reduction of >3$\log_{10}$ for *E. coli* and >4$\log_{10}$ for *Enterococcus* spp. Composting of faeces/ash mixtures (F:FW = 1:0) with food waste (F:FW = 1:1 and 1:3) was also studied in 216-litre reactors insulated with 75 mm styrofoam and in non-insulated control units with faeces/ash. Composts that attained sanitising temperatures (>50°C) had high initial pH (8.5-9.7), moisture content between 43-63% and initial ash content up to 77%. *E. coli* and total coliforms decreased below detection in composts with temperatures above 50°C for at least six days. With no food waste, the time above sanitising temperatures was short.

Disadvantages of incineration and composting, *e.g*. possible environmental pollution, risk of contamination and disease when handling initially unsanitised material and lack of social acceptance, can be overcome by improved design, use of protective wear and community training.

Key words: Composting, faeces, food waste, incineration, sanitation, temperature.

Contents

Appendix

Papers I-III

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Niwagaba, C., Nalubega, M., Vinnerås, B. & Jönsson, H. 2006. Incineration of faecal matter for treatment and sanitation. *Water Practice & Technology* 1, 2. Online ISSN: 1751-231X.

II. Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C. & Jönsson, H. 2006. Composting of source separated faecal matter for treatment and sanitation. In: Kraft E., Bidlingmaier W., de Bertoldi M., Diaz F.L. & Barth J. (Eds.), Proceedings of the ORBIT Waste Management Conference, Weimar, Germany, September 2006: Part 2. *Composting – Quality, Application and Benefit, Life Cycle Analysis, Sludge and Soil*. ISBN 3-935974-09-4.

III. Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C. & Jönsson, H. 2007. Composting of source separated human faeces.
Submitted to *Bioresource Technology*

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Notes on the authorship of papers:

In Paper I, Jönsson and Niwagaba planned the investigation. Niwagaba performed the experiments, Jönsson and Niwagaba performed the calculations, Niwagaba did the writing with revisions by Vinnerås, Nalubega and Jönsson.

In Paper II Niwagaba and Jönsson planned the investigation. Niwagaba and Magumba performed the experiments, Niwagaba analysed the data and did the writing with revisions by Vinnerås, Nalubega, Sundberg and Jönsson.

In Paper III, Niwagaba, Vinnerås and Jönsson planned the investigation. Niwagaba performed the experiments, data analysis and the writing with revisions by Vinnerås, Nalubega, Sundberg and Jönsson.

Background

When people lived in small groups as hunter-gathers, their refuse and human wastes decomposed naturally in the environment (www.ashland.or.us). As societies moved from nomadic cultures to concentrated settlements, waste (solid and wastewater) disposal became an important concern. The problem increased as cities developed and mechanisms became necessary to address waste issues. Human excreta management has been dealt with in many different ways and knowledge has been gained, some lost and regained.

Globally, at least 2.6 billion people in the world lack access to improved sanitation (WHO, 2004a; EcoSanRes, 2005a) and more than 90% of the sewage in the developing countries is discharged untreated (Esrey, 2001; Werner *et al*., 2004a; Langergraber & Muellegger, 2005). Sewage discharges from centralised water-borne collection systems potentially pollute surface waters and seepage from sewers, septic tanks and pit latrines contaminate groundwater (Esrey *et al*., 1998). The lack of access to improved sanitation, together with the lack of clean drinking water (faced by about one billion people) accounts for daily deaths of between 10,000-30,000 people. Approximately 6,000 children die every day from diarrhoeal diseases only and about 88% of diarrhoea diseases are caused by unsafe water and inappropriate sanitation (WHO, 2004a; Rosemarin, 2004). WHO (2004a) estimated that improved sanitation can reduce diarrhoeal diseases worldwide by 32%. In Uganda, about 440 children die from diarrhoea every week (National Sanitation Guidelines, 2000) and evidence suggests that improving the sanitation could reduce diarrhoeal diseases by 35-40%, and child mortality by half (National Sanitation Guidelines, 2000).

Millennium Development Goal (MDG) 7, Target 10, requires that the proportion of the world's population without safe drinking water (taking 1990 as the base year), should be halved by 2015 (UN, 2000). This goal was supplemented at the UN World Summit for Sustainable Development in Johannesburg, South Africa, with the formulation of a demand for access to basic sanitation (UN, 2002). Extreme poverty eradication is number one of the Millennium Development Goals. Recognising the risk that the MDG target on sanitation may not be achieved due to the slow progress so far, and the understanding that sanitation affects all other MDGs directly or indirectly, the UN has declared 2008 to be the International Year of Sanitation (IYS), in order to raise sanitation awareness amongst governments, donor agencies, UN agencies and civil society. The British Medical Journal (2007), in a survey of 11,000 global respondents, reported that sanitation engineering represented a health breakthrough greater than the discoveries of antibiotics, anaesthesia, vaccines and DNA, and declared public sanitation the greatest 'medical breakthrough' since 1840, giving sanitation recognition in saving human lives and reducing poverty. According to VISION 21 of the Water Supply and Sanitation Collaborative Council, WSSCC (2000), sanitation is a basic human right, and one of the major components of poverty eradication. VISION 21 also states that new approaches to meet future demands

on water and sanitation should be based on the principle that human faeces and urine are not waste products, but rather resources to be recycled in safe ways.

Today, poor people in rural and urban areas in the developing countries are often impoverished due to lack of food. The consequences of this are malnutrition, usually of small children, hunger and death. The total global health burden due to malnutrition is actually more than twice as large as that due to diarrhoeal diseases (Murray & Lopez, 1996). Poverty amongst urban communities can be linked to poor sanitation, since in times of sickness it is possible that the meagre financial resources may be spent nursing the sick, who contract diseases due to poor sanitation (Maforah, 1994). One way to contribute to the solution of this problem could be to recover safe nutrients from excreta and to use them to grow food for domestic consumption and for sale. This is potentially promising because there is a nutrient mass balance over the human body for adults (Jönsson & Vinnerås, 2004). Essentially all of the nutrients taken in as food appear in excreta. Hence the plant nutrients taken up in the production of food for a given population are found in its excreta, and if recycled, can improve food security and help eradicate famine and poverty.

Human urine and faeces are products of body metabolism that are rich in plant nutrients. In most of today's sanitation systems, these nutrients are not captured for use in growing food. Instead, the nutrients in urine and faeces, which have been removed from fields by the crops, eaten by people as food and excreted, mainly end up, via latrines and wastewater systems in deep pits and recipient waters, potentially causing groundwater and surface water pollution. Wastewater systems in urban areas account for a very large proportion of the plant nutrient flows to surrounding waters. In wastewater effluents, the nutrients are undesirable because of their potential to cause eutrophication in recipient waters, while they are required on land for sustainable production of food. Currently, this requirement, when met, usually is fulfilled by chemical fertilizers produced by use of non-renewable resources. Poor people often cannot afford to buy chemical fertilizers, and even more important, the long-term sustainability of today's use of chemical fertilizers is questionable. It is estimated, for example, that the lifetime of global economical phosphorus reserves is between 60 to 130 years (Steen, 1998). Production of nitrogen-based fertilizers relies heavily on non-renewable resources, oil and gas, for reduction of dinitrogen to ammonia (Greenwood & Earnshaw, 1998). These resources are estimated to reach their global peaks in about 10 years for gas and approximately 20 years for oil (Bentley, 2002). Hence, for sustainable availability of nutrients for food production, the nutrients in excreta should be recycled.

In addition, the high urban population growth taking place in informal settlements in cities in the developing countries is not matched with provision of services, including sanitation (Redlinger *et al.*, 2001). Municipal authorities are either unable or unwilling to provide sanitation, often considering it a private issue (Nakiboneka, 1998). Approximately 60% of the population of Kampala (>1,000,000 people) resides in informal settlements, most of them in low-lying areas with high groundwater table (WSP/NWSC, 2000). In all of these areas, the

plots are small and the housing density is high. Furthermore, there is no sewerage and some places also lack piped water. The residents rely on pit latrines for excreta disposal. Pit latrines offer neither a practical nor a safe sanitation solution because of the space required for pits and the high groundwater table. Pathogens from pit latrines directly pollute the shallow groundwater, the drinking water source for a great majority of the residents in most informal settlements (Barrett *et al*., 1999; Kulabako *et al*., 2004).

In this work, the effort to understand treatment systems for human faeces derives from the present status of sanitation in Uganda. Sanitation in Uganda, especially in difficult conditions (areas with rocky or collapsing formations as well as those with high groundwater table) is undergoing a period of transition, in which dry urine diverting ecological sanitation (ecosan) toilets are considered a potentially safe and sustainable sanitation system for these areas (Tushabe *et al*., 2004; Niwagaba & Asiimwe, 2005). There is an increasing realisation that waterborne sewerage systems are beyond the reach of most of the population and that there is need to recycle nutrients from excreta to increase crop production (Tushabe *et al*., 2004). Consequently, implementation of ecosan systems started in Uganda in 1997 under the South Western Towns Water and Sanitation (SWTWS) project. In addition, Kampala City Council is in the final stages of completing a Sida-financed ecosan project targeting slum areas in Kampala (in which at least 80 dry urine diverting ecosan toilets have been constructed in Kampala's slums); and NGOs, notably AMREF, BUCADEFU, CIDI, Water Aid (Uganda) and SSWARS are implementing and promoting ecosan in various parts of the country. At least 6,000 dry urine-diverting ecosan toilets have been constructed countrywide (M. Oketch, pers. comm. 2005).

Dry urine diverting toilets collect urine and faeces separately. When collected separately, the two fractions, *i.e*. urine and faeces, constitute nutrient resources in relatively undiluted form that can be easily recycled. Approximately 80% of the nitrogen, about 50% of the phosphorus and nearly 60% of the potassium otherwise to be found in household wastewater fractions can be recycled from urine, and about 11% of the nitrogen, 25% of the phosphorus and 21% of the potassium from the faeces (Vinnerås *et al*., 2006). The heavy metal content in faeces is higher than in the urine, but the cadmium concentrations are lower than in chemical fertilizers, and the chromium and lead concentrations are lower than in farmyard manure (Jönsson *et al*., 2005). Hormones, endocrine disruptors and pharmaceutical residues may be present in urine and faeces, but the concentrations of these compounds are usually extremely low and to date only effects on animals in direct contact with polluted water have been demonstrated (WHO, 2006). The major concern in the recycling of plant nutrients from urine and faeces is that these fractions are associated with pathogens. Urine contains few pathogens and can be easily disinfected by storage (Höglund, 2001). Faeces consist mainly of undigested food residues, mucus and cells shed from the intestines, bile, fats and unabsorbed intestinal secretions (Feachem *et al*., 1983; http://www.colonic-association.co.uk). From a hygiene risk perspective, faeces should always be considered to contain pathogens (Stenström, 2001; WHO, 2006; Schönning *et al*., 2007). The actual species and densities of pathogens in faeces depend on the

health of the person excreting them and may vary substantially at different times (Feachem *et al*., 1983). Health risks from sanitation systems are mainly associated with faeces, and therefore the collection, containment and treatment of faeces is of the utmost importance in protection of the health of any community. Safe treatment is even more important in societies re-using human excreta in agriculture. To date, well documented, simple, reliable and cost-effective methods for treating human faeces for safe reuse are lacking.

Objectives

The main objective of this research was to increase the knowledge on simple and robust treatment technologies for faeces aimed at achieving safe recycling of plant nutrients. The overall aim was to find a cheap, robust, environmentally friendly and resource efficient method (Papers I, II & III). Specific objectives were to find well functioning compositions and to determine the amount of insulation needed when composting faeces at small scale (78 L) for production of safe fertiliser or soil conditioner (Paper II) and to verify this at slightly larger scale (216 L) experiments (Paper III). Another objective was to investigate incineration as a treatment method for faeces for safe fertilizer production and also as a means of reducing the volume of material to be disposed of (Paper I).

Literature and Theory

What is human excreta?

Human excreta consists of faeces and urine. The two are waste products of the bodily metabolism. The appearance, physical and chemical characteristics of urine or faeces depend largely on the health of the person excreting the material, as well as on the amount and type of food and liquid consumed (Lentner *et al*., 1981; Feachem *et al*., 1983). Therefore, the excreta generated by healthy people eating a similar diet are quite similar in both physical and chemical composition. In a study on the composition of human excreta, it was reported that age, sex, occupation or religion did not affect the chemical composition of the different fractions (Schouw *et al*., 2002). However, a significant variation was that older people excreted larger amounts of total wet matter than younger, which was linked to a larger water intake intended to reduce the risk of constipation (Schouw *et al*., 2002).

Urine

Urine is the excreta fraction that is filtered from the blood and combined with excess water by the kidneys (Guyton, 1992). At excretion, urine is usually yellow and does not have a foul smell (Drangert, 1998; www.madsci.org) but when stored it acquires a pungent odour as the urea breaks down to ammonia and carbon dioxide due to bacterial action (www.madsci.org). Urine largely consists of water,

approximately 93-96% (Polprasert, 1995; Vinnerås *et al*., 2006), and large amounts of nutrients that are mainly in water-soluble form (Jönsson *et al*., 2004).

Generation rate

Urine is used by the body as a balancing medium for liquids and salts and the amount of urine excreted by a person therefore varies (Jönsson *et al*., 2004). The quantity excreted depends on how much a person drinks and sweats, and also on other factors such as diet, physical activity and climate (Lentner *et al*., 1981; Feachem *et al*., 1983). Excessive sweating results in concentrated urine, while consumption of large amounts of liquid dilutes the urine. Feachem *et al*. (1983) reported that the urine generation rate for most adults is between 1.0 and 1.3 kg per person and day (kg/p,d). Vinnerås *et al*. (2006) suggested a design value for urine generation to be 1.5 kg/p,d based on measurements in Sweden. Del Porto and Steinfeld (1999) reported a urine generation rate of 1.2 kg/p,d, which is also quoted by EcoSanRes (2005a) while Winblad *et al*. (2004) report 1.1 to 1.4 kg/p,d. Schouw *et al*. (2002) measured human excreta generation rates in Southern Thailand and found that between 0.6-1.2 L/p,d of urine was produced.

Nutrients in urine

Urine contains the largest proportion of plant nutrients found in the household waste fractions (Fig. 1). The amount of plant nutrients excreted via urine per person and year has been measured at 2.5-4.3 kg nitrogen (N), 0.4-1.0 kg phosphorus (P) and 0.9-1.0 kg potassium (K) (Lentner *et al*., 1981; Guyton, 1986; Jönsson *et al*., 2005; Vinnerås *et al*., 2006).

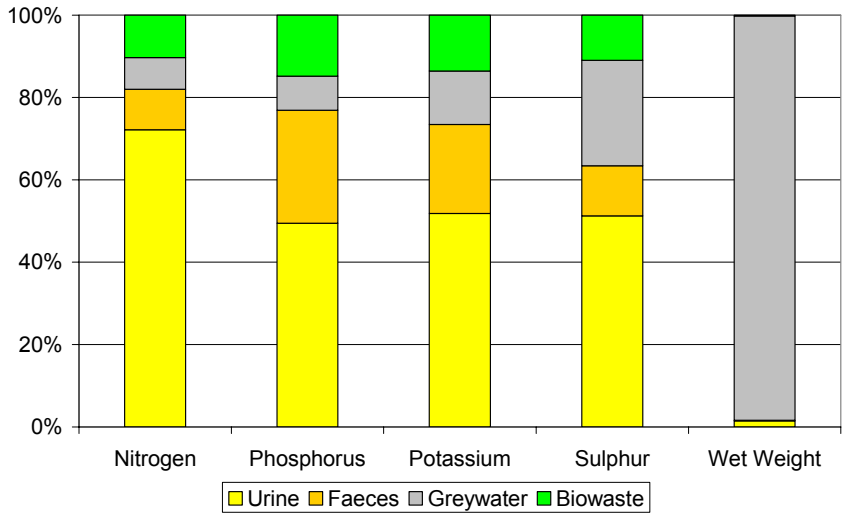


Fig. 1. Proportions of nutrients found in household wastewater fractions. Source: Jönsson *et al*., 2005.

Vinnerås *et al*. (2006) combined their own measurements on the nutrient content of urine with previous studies and found that the annual excretion rate per person

in Sweden was about 4000 g N, 365 g P and 1000 g K, corresponding to 11 g N/p,d, 1.0 g P/p,d and 2.7 g K/p,d. Jönsson *et al*. (2005) evaluated previously published studies on urine and on food consumption and arrived at similar values, except for phosphorus, which was estimated at 0.9 g/p,d. Together, the nutrients in urine and faeces in Sweden add up to some 4.5-4.6 kg N, 0.5 kg P and 1.4 kg K per person and year (Jönsson *et al*., 2005; Vinnerås *et al*., 2006). Of the excreted nutrients, urine contains about 80-90% of the N, 50-65% of the P and 50-80% of the K (Schouw *et al*., 2002; Jönsson *et al*., 2005; Vinnerås *et al*., 2006).

In the growing human body, nitrogen mainly accumulates as proteins in muscles, phosphorus in bones and muscles, and potassium in nerves and muscles (Nationalencyklopedin, 1993). In healthy adult persons, the amounts of plant nutrients in the body mass are approximately constant (Jönsson & Vinnerås, 2004). Therefore in the long term, the plant nutrients are in mass balance over the grown body. All plant nutrients consumed are excreted over time, mainly via the urine and faeces (Guyton, 1992), even though small fractions of N, P and metals can also be found in sweat (Schroeder & Nason, 1971). Therefore the nutrients in excreta can be estimated from the amounts of food consumed. According to Jönsson & Vinnerås (2004), the nutrients N and P in excreta are related to the food supply via the following empirical relationships;

N = 0.13*Total food protein Eqn. (1)
P = 0.011*(Total food protein + vegetal food protein) Eqn. (2)

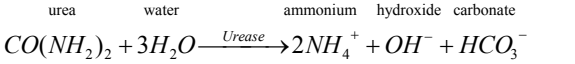
where the flow of proteins come from the FAO statistics on food supply (FAO, 2003).

From the flow of N and P in excreta, estimated with Eqns. 1 and 2, the flows of nutrients in urine and faeces can be estimated. Eqns. 1 and 2 (Jönsson & Vinnerås, 2004) use the following relationships:

a) The amount of nitrogen in food is linearly correlated with the protein in the food provided.
b) Vegetal food stuffs on average contain approximately twice as much P per gram of protein as animal foodstuffs.

Plant availability of nutrients in urine

Total N excretion is closely related to the protein intake. With a high protein diet, up to 90% and with a protein-free diet, 50-60% of the urinary N consists of urea (Lentner *et al*., 1981). In the presence of urease, urea is quickly degraded to ammonium and carbon dioxide with the formation of hydroxide ions, which increase the pH to about 9-9.3 (Jönsson *et al*., 2004) according to Eqn. 3.



Eqn. (3)

The ammonium, when applied to arable soil, is transformed (by microbial activity) to nitrate within a few days via the following equations:

$$NH_4^+ + 1.5O_2 \Rightarrow NO_2^- + 2H^+ + H_2O \quad \text{Eqn. (4)}$$

$$NO_2^- + 0.5O_2 \Rightarrow NO_3^- \quad \text{Eqn. (5)}$$

$$NH_4^+ + 2O_2 \Rightarrow NO_3^- + 2H^+ + H_2O \quad \text{Eqn. (6)}$$

The N in urine is an excellent plant-available fertilizer, as has been confirmed in agronomic studies, for example, by Kirchmann & Petterson (1995), Simons & Clemens (2004) and Richert-Stintzing *et al*. (2001).

The P, K and sulphur (S) in the urine are excreted as ions, the same form in which they are present in chemical fertilizers. The ions are directly plant-available and the fertilizer value of P, K and S in the urine should be the same as in chemical fertilizers, as has been confirmed for P by Kirchmann & Petterson (1995).

The presence of plant available nutrients has given rise to studies on the possibility for nutrient recovery as solids from human urine by struvite [Mg (K, NH_4) (PO_4)*6H_2O], which is formed by reaction of magnesium with phosphate in the presence of ammonium (Harada *et al*., 2006; Ganrot *et al*., 2007a, 2007b; Ronteltap *et al*., 2007; Wilsenach *et al*., 2007). Other processes that have been investigated for recovery of solid nutrients from human urine include freezing and adsorption to zeolite and active carbon (Ganrot *et al*., 2007b). Interesting results from the above and future studies on solid nutrient recovery from human urine may give rise to future production of human urine based commercial fertilizers.

Faeces

Faeces consist of material that passes through the intestines undigested, mixed with material extracted from the blood stream or shed from glands and the intestines (Guyton, 1992). Faeces are malodorous and consist, in addition to the undigested material, of mucus and cells shed from the intestines as well as bile, which gives them their characteristic brown colour (http://en.wikipedia.org). Faeces contain mainly water, bacteria, nutrients and food residues (Lentner *et al*., 1981). They can also contain large concentrations of pathogenic viruses, cysts of protozoa and eggs of helminths (Faechem *et al*., 1983).

Generation rate

Approximately 30-45 kg (wet weight basis) of faeces are produced per person and year in developed countries, corresponding to 10-15 kg of dry matter (Lentner *et al*., 1981; Feachem *et al*., 1983; Schouw *et al*., 2002; Jönsson & Vinnerås, 2004; Jönsson *et al*., 2005; Vinnerås *et al*., 2006). Del Porto & Steinfeld (1999) compiled data from several studies and reported an average faecal excretion rate of 150 g/p,d. The amount of faeces produced depends on the composition of the food consumed. Foods low in fibre such as meat and other products result in smaller amounts (mass and volume) of faeces (Guyton, 1992). Faecal excretion rates in developed countries are lower than those in developing countries, with excretion rates for Americans and Europeans estimated at between 100 and 200 g/p,d. while for developing countries estimates are on average 350 g/p,d in rural areas and 250

g/p,d in urban areas (Feachem *et al*., 1983). In China, Gao *et al*. (2002) measured 315 g/p,d while Pieper (1987) measured 520 g/p,d in Kenya. In measurements by Schouw *et al*. (2002) in Southern Thailand, wet faecal generation rates were found to be 120-400 g/p,d. Vinnerås *et al*. (2006), using measurements from two blocks of flats in Sweden, estimated faecal excretion rate at 140 g/p,d amongst the Swedes, and water content at about 78%. At faecal excretion rates between 100 and 150 g/p,d, water content is about 75%, but this increases with increasing weight, and is approximately 90% at faecal weights of 500 g/p,d (Feachem *et al*., 1983). Faecal excretion is on average one stool per person and day, but it may vary from one stool per week up to five stools per day (Lentner *et al*., 1981; Pharmacia, 2000).

Nutrients in faeces

Like urine, the nutrient content of faeces originates from the food consumed. For P, calcium (Ca) regulates the amount of P available for uptake by the digestive system (Fraústo da Silva & Williams, 1997). It is estimated that the food nutrient content is distributed to the faecal fraction in the proportions: 10-20% N, 20-50% P and 10-20% K (Berger, 1960; Lentner *et al*., 1981; Guyton, 1992; Fraústo da Silva & Williams, 1997). About 20% of the faecal nitrogen is ammonia, biochemically degraded from proteins, peptides and amino acids, some 17% is found in living bacteria and the remainder is organic nitrogen combined in molecules such as uric acid and enzymes (Lentner *et al*., 1981). According to Vinnerås *et al*. (2006), the nutrients contained in faeces in Sweden are 550 g N/p,yr, 183 g P/p,yr and 365 g K/p,yr, which agrees well with Jönsson *et al*. (2005), who reported 1.5 g N/p,d, 0.5 g P/p,d and 1.0 g K/p,d in Swedish faeces.

Plant availability of nutrients in faeces

Faeces contain both water-soluble nutrients and nutrients that are contained in larger structures not soluble in water (Jönsson *et al*., 2004). About 50% of the N and majority of the K in fresh faeces are water soluble (Berger, 1960; Guyton, 1992; Fraústo da Silva & Williams, 1997), while P is primarily found as calcium phosphate particles that are slowly soluble in water (Fraústo da Silva & Williams, 1997). The plant availability of nutrients from human faeces is slower than that from urine. This is explained by the fact that a large proportion of both faecal N and P originate from undigested matter, which means that this matter has to be degraded in the soil before the nutrients become water soluble and available to plants. The total plant availability of the calcium phosphates in the faeces is probably comparable to that of chemical fertilizers (Jönsson *et al*., 2004). The K in faeces is mainly in ionic form that is directly plant-available, just as in chemical fertilizers (Jönsson *et al*., 2004).

Thus in conclusion, faecal P and K are plant-available at total rates comparable to those in chemical fertilizers. Faecal N, however, is less plant-available than in chemical fertilizers, as much of this is in organic form (Jönsson *et al*., 2004). However, the faecal organic matter when applied on agricultural land has the following potential advantages: improvement of the soil structure and of its water-holding and buffering capacities (Oades, 1984; Lal, 1986; Lavelle, 1988), and it is

also a source of energy for soil microorganisms (van Veen & Kuilman, 1990; Jönsson *et al*., 2004).

Other constituents in urine and faeces

Human faeces and to a small extent urine contain trace metals, which if present in excess concentrations may be harmful to man and to the environment. The amounts of harmful heavy metals in the urine are miniscule (WHO, 2006). This is a result of the biological uptake being small and their excretion being even smaller (Vinnerås, 2002). However, non-essential metals, for example cadmium (Cd), are to some extent also taken up, especially those that are similar in size and charge to metals used in biochemical reactions. Uptake of heavy metals occurs by two main pathways, ingestion and inhalation. The percentage uptake is higher for inhaled metals than for ingested metals (Kehoe *et al*., 1940; Vahter *et al*., 1991; Kim & Fergusson, 1993).

Schouw *et al*. (2002) reported the following metal contents per person and day in human excreta in Southern Thailand: 9-16 mg zinc (Zn), 1.4-1.5 mg copper (Cu), 0.3 mg nickel (Ni), 0.02-0.03 mg Cd, 0.07-0.14 mg lead (Pb), 0.01 mg mercury (Hg) and 0.8-1.1 mg boron (B). The metal content and mass flows in faeces are usually reported to be far higher than in urine. In the study by Schouw *et al*. (2002), the amounts of Zn, Cu, Ni, Cd, Pb and Hg were larger in faeces than in urine, while amounts of the non-metal elements S and B were larger in urine than in faeces. The measurements by Schouw *et al*. (2002) were performed on 15 adults (drawn from three areas, *i.e*. 5 persons per area) for one week duration. In Swedish source-separated fractions, Vinnerås *et al*. (2006) measured (/p,d) 11 mg Zn, 1.1 mg Cu, 0.07 mg Ni, 0.02 mg chromium (Cr), 0.02 mg Pb, 0.01 mg Cd and 0.01 mg Hg in faeces, and lower flows in urine (/p,d): 0.04 mg Zn, 0.1 mg Cu, 0.01 mg Ni, 0.01 mg Cr, 0.002 mg Pb, 0.001 mg Cd and 0.001 mg Hg. The data by Vinnerås *et al*. (2006) were obtained from a total of 3095 person-days taken from three locations in Sweden. Generally, all the metals are excreted in larger amounts in faeces than in urine (Jönsson *et al*., 2005). However, the metal flows in the faecal fraction are generally smaller than in greywater (Jönsson *et al*., 2005). Essentially all the heavy metals in the excreta come from the food ingested and a large proportion of the metals in the crop will have been removed from the fields. Thus, it is possible to recycle excreta fertilisers, provided that they have not been polluted when handled, without threatening the sustainability of the agricultural soil.

Pathogens in faeces and faecal indicators

The faeces of a healthy person contain large numbers of bacteria of many non-pathogenic species. These bacteria are referred to as normal intestinal microbiota. Gastrointestinal pathogenic microorganisms do not occur as a natural part of normal intestinal microbiota (Feachem *et al*., 1983). Their presence in faeces is an indication of infection amongst the population contributing to the faeces analyzed. However, on occasion, some of the commensal bacteria otherwise referred to as normal intestinal microbiota may give rise to disease. This situation is likely to

happen when the immune system of the human being has been compromised, for example, during sickness or old age, giving rise to opportunistic infections (Madigan & Martinko, 2006).

Most pathogenic or potentially intestinal pathogenic microorganisms enter a new host by ingestion (water, food, fingers, dirt on lips, aerosols caught in the nose and swallowed) or through the lungs (after inhalation of aerosol particles) or through the eye (when eyes are rubbed with contaminated fingers) (Feachem *et al*., 1983), while others may also enter through the skin or wounds. After infecting the host, large numbers of pathogens may be excreted. Depending on the health of the population, several species of pathogenic bacteria, viruses, parasitic protozoa and helminths may be found in the faeces from the population (Table 1) and thus also in its mixed wastewater. From a hygiene point of view, any exposure to faeces constitutes a risk (Feachem *et al*., 1983; Stenström, 2001; WHO, 2006). Pathogens that can be found in faeces, as well as their importance in disease transmission, are listed in Table 1. The majority of faecal pathogens cause gastrointestinal symptoms such as diarrhoea, vomiting and stomach cramps, while some also cause symptoms involving other organs and severe consequences (Schönning & Stenström, 2004).

Some bacteria ubiquitous in faeces from healthy individuals are often used as indicators of faecal contamination. The main constituent of the enterobacteria group of the normal intestinal microbiota, the faecal coliform *Escherichia coli* (*E. coli*) has traditionally been the mostly widely used indicator of faecal contamination (Feachem *et al*., 1983). An indicator of faecal contamination is a normal intestinal organism, whose detection in a sample should denote the presence of faecal material and thus the possible presence of relevant pathogens (WHO, 1984). As such, indicators should be abundant in excrement but absent, or present only in small numbers, in other sources; they should be easily isolated, identified and enumerated and should be unable to grow in the sample under investigation (WHO, 1984). *Escherichia coli* is more sensitive to treatment processes and environmental stress than many pathogens (Feachem *et al*., 1983) and its suitability as a sole indicator of hygiene quality of reuse products is therefore questionable. Hence, *Enterococcus* spp. or faecal streptococcus, which is more tolerant to environmental stress, is sometimes preferred to *E. coli* (Feachem *et al*., 1983). In addition, *Enterococcus* spp. is a good indicator for the die-off and potential occurrence of enteric viruses, particularly in sludge and sea water (Bitton, 1994). Other indicators of faecal contamination that have been used in pollution control and pathogen die-off studies include *Clostridium perfringens*, *Bacteroides fragilis* and *Bifidobacterium* for bacteria (Feachem *et al*., 1983; WHO, 1984) and bacteriophages for viruses (Feachem *et al*., 1983).

Table 1. *Selected pathogens that may be excreted in faeces, disease and symptoms they cause (adapted from Schönning & Stenström, 2004)*

Group	Pathogen	Disease symptoms
Bacteria		
	Aeromonas spp.	Enteritis
	Campylobacter jejuni/coli	Campylobacteriosis-diarrhoea, cramping, abdominal pain, fever, nausea, arthritis, Guillain-Barré syndrome
	Escherichia coli (EIEC, EPEC, ETEC, EHEC)	Enteritis. For EHEC there are also internal haemorrhages that are sometimes lethal
	Salmonella typhi/paratyphi	Typhoid/paratyphoid fever – headache, fever, malaise, anorexia, bradycardia, splenomegaly, cough
	Salmonella spp.	Salmonellosis – diarrhoea, fever, abdominal cramps
	Shigella spp.	Shigellosis – dysentery (bloody diarrhoea), vomiting, cramps, fever; Reiter´s syndrome
	Vibrio cholerae	Cholera – watery diarrhoea, lethal if severe and untreated
Virus		
	Adenovirus	Various; respiratory illness, here added due to enteric types (see below)
	Enteric adenovirus 40 and 41	Enteritis
	Enterovirus types 68-71	Meningitis; encephalitis; paralysis
	Hepatitis A	Hepatitis – fever, malaise, anorexia, nausea, abdominal discomfort, jaundice
	Hepatitis E	Hepatitis
	Poliovirus	Poliomyelitis – often asymptomatic, fever, nausea, vomiting, headache, paralysis
	Rotavirus	Enteritis
Parasitic protozoa		
	Cryptosporidium parvum	Cryptosporidiosis – watery diarrhoea, abdominal cramps and pain
	Cyclospora histolytica	Often asymptomatic; diarrhoea; abdominal pain
	Entamoeba histolytica	Amoebiasis – often asymptomatic, dysentery, abdominal discomfort, fever, chills
	Giardia intestinalis	Giardiasis – diarrhoea, abdominal cramps, malaise, weight loss
Helminths		
	Ascaris lumbricoides	Generally no or few symptoms; wheezing; coughing; fever; enteritis; pulmonary eosinophilia
	Taenia solium/saginata	Taeniasis
	Trichuris trichura	Trichuriasis - Unapparent through vague digestive tract distress to emaciation with dry skin and diarrhoea
	Hookworm	Itch; rash; cough; anaemia; protein deficiency
	Schistosoma Spp. (blood fluke)	Schistosomiasis, bilharzia

Source-separation of urine and faeces

Source-separation of urine and faeces involves the collection of these fractions separately at source. The easiest way to achieve this is by use of a urine-diverting toilet. In fully functioning source separation systems, the greywater and solid waste fractions, which together constitute the larger fractions of the wastes generated in a household (Vinnerås *et al*., 2006), are also collected separately. The focus in this thesis is on treatment of the faecal fraction. However, in the composting process, mixtures of faeces and kitchen food waste were used in the experiments.

The advantage of separately collecting the urine and faeces is that the treatment method can be tailored to the specific composition and need for treatment of each fraction (Vinnerås, 2001), which depends upon the use of the treated material, as well as the need to protect the environment from pollution. The literature shows that for most parameters, the faeces are more polluted than urine, while the latter contains most of the plant nutrients found in household waste. Thus, in source separating systems, the less polluted and nutrient-rich urine can be sanitised by a relatively simple and inexpensive treatment, storage, whereas the faecal fraction, potentially containing a high concentration of pathogens, has to be subjected to more rigorous treatment to ensure safe sanitation (Schönning & Stenstrom, 2004; WHO, 2006).

Urine and faeces can be collected separately using single or double-flushed toilets (Fig. 2) or non-flush dry toilets (Fig. 3).

Fig. 2. Double flush urine diverting toilets of different designs, Sweden (photos: C. Niwagaba, 2005).

When dry urine diversion toilets are used, the faecal matter and toilet paper (if used) are collected in a container or vault directly beneath the toilet. The diverted urine is collected in a separate container or is infiltrated into the soil in a soakaway. No data have been found on the separation efficiency of the urine fraction in dry urine-diverting squatting toilet systems, the types that are mainly used in Uganda. However, both sexes excrete faeces and urine separately and the toilets seem to separate fairly well for both men and women when used correctly,

even though it is reported that some urine droplets can be misplaced into the faecal vault, especially by women (H. Jönsson, pers. comm. 2006).

Fig. 3. Dry urine-diverting toilets, Left: Squatting type; Right: Pedestals, Uganda (photos: C. Niwagaba, 2004).

Ecological sanitation

Ecological sanitation is a term not yet well defined. However, authors tend to agree that ecological sanitation systems are those that include safe handling and treatment of excreta, to produce a safe fertilizer and re-use the excreta nutrients for production of food (Winblad *et al*., 2004; EcosanRes, 2005b; Morgan, 2005; Schönning & Stenström, 2005). Ecosan systems utilize the nutrients present in human excreta in an attempt to close the nutrient loop. Ecosan systems range from dry urine diverting toilets with simple faecal composts, to wet systems with separate low flush systems for urine and faeces, and to high-tech vacuum systems (Otterpohl, 2004; Langergraber & Muellegger, 2005).

In ecosan systems, human excreta and wastewater from households are considered a resource and not a waste. The ecosan paradigm in sanitation is based on ecosystem approaches and the closure of material flow cycles. According to Werner *et al*. (2004a), ecosan systems:

- Reduce health risks related to sanitation, contaminated water and waste.
- Prevent pollution of surface waters and groundwater.
- Prevent the degradation of soil fertility.
- Optimise the management of nutrients and water resources.

The features described below are common with dry urine diverting ecosan toilets, the products of which are investigated in this thesis. A dry urine diverting ecosan toilet consists of a superstructure similar to that of most toilets (Fig. 4). However, the excreta are separated at source using the urine diverting toilet features shown in Fig. 3.

In dry urine-diverting ecosan toilets, an additive or cover material is normally applied on top of the faeces after each defecation. The purpose of this additive is to cover the faeces (Fig. 5), *i.e*. to seal them from the air and thus minimize the smell and prevent flies from accessing the moist faeces (Winblad *et al*., 2004).

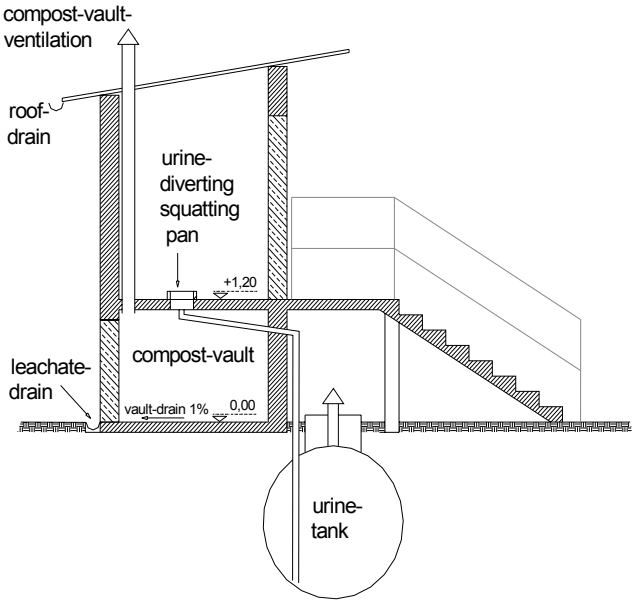


Fig. 4. Typical cross-section through a dry urine diverting ecosan toilet (adapted from Kyomugisha, 2007)

Additives commonly used include lime, ash, dry soil and sawdust and mixtures of these. Depending on the additive applied, the pH of the material may be elevated, thereby creating unfavourable conditions for pathogens and thus speeding up their reduction (Schönning & Stenström, 2004).

Fig. 5. The faecal collection chamber of a dry urine-diverting toilet showing the heap formed by the faeces, cover material and wiping material (photo: C. Niwagaba, 2004).

In urine diverting ecosan toilets, separately collected urine can, without any dilution, be applied as a fertilizer to all types of crops (Jönsson *et al*., 2004). Some people who use urine in Uganda prefer to apply it after dilution with water in 1:2-

5 ratios of urine:water for fear of scorching crops due to high concentration (M. Oketch, pers. comm. 2005). However, in most of the dry urine diverting ecosan toilet systems in Uganda, the urine is infiltrated into the soil. This system still has the advantages compared to pit toilets of less smell and no flies, and also of taking a long time to fill, since the faeces are only a small volume. Furthermore, the chambers are re-usable, and the toilets therefore conserve space.

All parts of the dry urine diverting toilet can be constructed above ground. This makes it feasible to construct hygienic toilets even in areas with hard rock, collapsing soils and high groundwater table.

The conditions in the faecal collection beneath a urine-diverting ecosan toilet result in initial pathogen kills during storage (Winblad *et al*., 2004; Schönning & Stenström, 2004). However, the inactivation of pathogens in stored faeces is generally slow, and storage times ranging from months for sufficient bacterial reduction and to years for helminths are needed to achieve safe sanitation (Strauss & Blumenthal, 1990; Schönning & Stenström, 2004; Moe & Izurieta, 2004; WHO, 2006). This necessitates sanitation of the source separated faeces, even if they have been separately contained (*i.e*. without any new faeces being added) for 6 to 8 months in the toilet chamber (design retention time used in Uganda), before being used as fertilizer (Schönning & Stenström, 2004). A secondary treatment is necessary. Faeces may be sanitised by heat treatment or chemical treatment with *e.g*. urea (Vinnerås, 2002; Schönning & Stenström, 2004). Anaerobic digestion is another method that can be used to treat faeces. This method suits wet organic material but is sensitive to settling solids, *e.g*. ash, and normally does not sanitize the substrate, making it inappropriate as treatment for faeces from dry urine diverting toilets.

Heat treatment is probably one of the most common processes for killing microorganisms (Madigan & Martinko, 2006). For faeces, sludge from wastewater treatment plants and other domestic waste, the most used heat treatment process is probably thermophilic composting. Thermophilic composting for a few days is known to kill pathogens (Haug, 1993; WHO, 2006). Incineration is another possible heat treatment process for faeces. Heat treatment (incineration and thermal composting) as sanitation methods for source separated faeces from dry urine diverting ecosan toilets are investigated in this thesis.

Factors affecting die-off of microorganisms

From the time of excretion, the concentration of microorganisms in human faeces usually declines with time. Bacteria may multiply outside of the host under favourable environmental conditions, but will normally decline in numbers (Schönning & Stenström, 2004). Protozoa and viruses are unable to grow in the environment outside the host and thus their numbers will never increase. Helminths may need a latency period after excretion and before being infective, but will usually decrease in numbers with time outside the host, *i.e*. after excretion.

The major factors affecting the survival of microorganisms in the environment are time and prevailing environmental conditions (Feachem *et al*., 1983; Schönning & Stenström, 2004; Winblad *et al*., 2004). These factors interact with organism-related factors, yielding survival specific characteristics in any particular situation. Important factors that play a crucial role in the reduction of enteric microorganisms are listed in Table 2.

Table 2. *Physiochemical and biological factors that affect the survival of pathogenic microorganisms in the environment (adapted from Schönning & Stenström, 2004)*

Factor	Reaction
Temperature	Most pathogenic microorganisms survive well at low temperatures and rapidly die off at high temperatures (>40°C-50°C). This is the case in water, soil, sewage and on crops. To ensure inactivation in *e.g*. composting processes, temperatures around 55-65°C are needed to kill all types of pathogens (except bacterial spores) within hours (Haug, 1993).
pH	Many pathogenic microorganisms are adapted to neutral pH (7). Highly acidic or alkaline conditions will have an inactivating effect. Addition of lime to excreta in dry latrines and to sewage sludge increases pH and can inactivate microorganisms. The speed of inactivation depends on the pH value, *e.g*. it is much more rapid at pH 12 than at pH 9.
Ammonia	In natural environments, ammonia (NH_3) chemically hydrolysed or produced by bacteria can be deleterious to other organisms. Added ammonia-generating chemicals also facilitate the inactivation of pathogens in *e.g*. excreta or sewage sludge (Ghiglietti *et al*., 1997; Vinnerås *et al*., 2003).
Moisture	Moisture is related to organism survival in soil and faeces. A moist soil favours the survival of microorganisms and a drying process will decrease the number of pathogens, *e.g*. in latrines.
Solar radiation/UV-light	UV-irradiation reduces the number of pathogens. It is used in processes for the treatment of both drinking water and wastewater. In the field, the survival time is shorter on the surface of soil and crop, where sunlight can affect the organisms.
Presence of other organisms	The survival of microorganisms is generally longer in material that has been sterilised than in an environmental sample containing other organisms. Organisms may affect each other by predation, release of antagonistic substances or competition
Nutrients	If nutrients are available and other conditions are favourable, bacteria may grow in the environment. Enteric bacteria adapted to the gastro-intestinal tract are not always capable of competing with indigenous organisms for the scarce nutrients, limiting their ability to reproduce and survive in the environment.
Other factors	Microbial activity is dependent on oxygen availability. In soil, the particle size and permeability influence the microbial survival. In soil, as well as in sewage and water environments, various organic and inorganic chemical compounds may affect the survival of microorganisms.

An understanding of environmental factors that affect the survival or die-off of pathogenic microorganisms, as highlighted in Table 2, is important in order to devise means for their inactivation. For safety reasons, it would be preferable if all

pathogens were killed before the faeces were handled and used as a fertilizer. The state of total die-off is the level of sterility, which for most organisms is set at 12 $\log_{10}$ reduction (Madigan & Martinko, 2006). However, it is usually not possible to measure, or verify, total die-off, but only to determine a state where no viable organisms can be detected (Madigan & Martinko, 2006). An example of this is the EU legislation for sanitation of manure in composting and biogas treatment. This requires a reduction of viability/infectivity by at least $5\log_{10}$ for *Enterococcus* spp. and *Salmonella Senftenberg* and $3\log_{10}$ for heat-resistant viruses to attain the state of no viability of these organisms (EC No 208/2006).

There may be a risk of re-growth of bacteria if favourable conditions are re-established, even if only one single bacterium survives (Schönning & Stenström, 2004). Pathogens surviving in treated faecal products applied to soils are eventually out-competed by the more resistant soil microbes and thus are reduced within the terrestrial environment, but for some pathogens, long survival times are reported in soils (WHO, 2006).

Survival of microorganisms under extreme conditions

For every organism, there is a minimum temperature below which no growth occurs, an optimum temperature at which growth is most rapid and a maximum temperature above which growth is not possible (Madigan & Martinko, 2006). These three temperatures are often referred to as the cardinal temperatures. The optimum temperature for each microorganism is always closer to the maximum temperature than the minimum temperature (Fig. 6).

In Fig. 6, A corresponds to the minimum temperature where growth occurs. Below this temperature, membrane gelling occurs and the cell transport processes are so slow that growth does not occur. As temperature increases, chemical and enzymatic reactions in the cells proceed at more rapid rates and growth becomes faster (A-B).

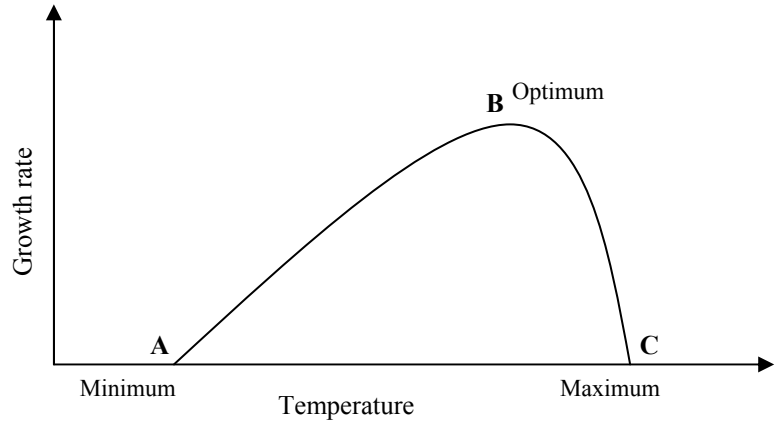


Fig. 6. The cardinal temperatures for microorganisms (minimum temperature A, optimum temperature B and maximum temperature C) (adapted from Madigan & Martinko, 2006).

At the optimum temperature B, enzymatic reactions occur at rates resulting in the fastest possible growth and any additional increase in temperature results in reduced growth. At the maximum growth temperature C, protein denaturation occurs at the same rate as cell reproduction, resulting in no net growth at all. Above temperature C, cytoplasmic membranes collapse and thermal lysis of the microbial cells takes place at such a fast pace that a total reduction of bacteria eventually occurs (Madigan & Martinko, 2006). In temperature treatment, it is not the killing of all of the microorganisms that is essential, but rather the killing of all the pathogens.

From the hygiene perspective, it is the mesophilic and thermophilic groups of microorganisms that are usually encountered in real life situations, which interact with man and hence are relevant in disease transmission (Madigan & Martinko, 2006). Their growth temperature range is normally between ~10-50°C for mesophilic microorganisms and ~30-70°C for thermophilic microorganisms (Madigan & Martinko, 2006). Pathogenic microorganisms grow within about 0-50°C even though a few organisms are reported to grow up to about 52°C (USFDA, 2007). Temperatures higher than 50°C are unfavourable for the survival of most pathogens.

Microbial resistance to environmental factors

Whereas nearly all of the mesophilic and thermophilic microorganisms are unable to survive excessively harsh conditions, some have developed defence mechanisms that enable them to withstand difficult situations (Madigan & Martinko, 2006). Under extreme conditions (such as very low nutrients, high temperatures, *etc*.), the vegetative cells sporulate to form a non-vegetative dormant structure called the endospore. The endospore is a tiny differentiated cell structure, highly resistant to heat and difficult to destroy even by harsh environments, chemicals or radiation (Nicholson *et al*., 2000; Madigan & Martinko, 2006). Some highly resistant bacterial endospores survive heating to temperatures as high as 150°C, although an autoclave operating at 121°C should kill the endospores of most species (Madigan & Martinko, 2006). Endospores can be easily spread in the environment by wind, water or through the animal gut. They can remain dormant for extremely long periods (Gest & Mandelstam, 1987; Cano & Borucki, 1995). Isolation of endospores aged up to 250 million years has been reported (Vreeland *et al*., 2000). Once better conditions are re-established, the endospore reverts to the vegetative form, and the growth and multiplication cycle begins. The predominant endospore-forming bacteria, the genera Bacillus and Clostridium, are found most commonly in soils. Some species of Clostridium (*e.g. C. perfringens, C. paraputrificum*) and Bacillus (*e.g. Bacillus subtilis*) are part of the normal microbial flora of the small intestine and can therefore be found in excreted faeces (Benno *et al*., 1984).

The high resistance and long survival times of endospores defeat most faecal treatment processes and will probably also defeat composting, even though high temperature incineration should kill them. It can also be argued that the moist and cosy conditions in the composts may lure potentially formed spores to revert to

vegetative cells, where they can be easily destroyed, even though no data on this have been reported. According to Smith (1985), the vegetative forms of spore-forming bacteria are no more resistant than those of non-spore-forming bacteria. Moist heat is effective in killing pathogens (Madigan & Martinko, 2006) and this is the heat experienced in well operated composts. The risk of persistence of endospores in the faecal treatment processes investigated in this thesis (*i.e.* composting and incineration) might be lower than with other alternative methods such as prolonged storage and/or anaerobic digestion. Besides, the question of destruction of endospores in composting or other faecal treatment processes may not be very relevant since most of the spore-forming bacteria such as *Clostridium* spp. and *Bacillus* spp. are not pathogenic (Smith, 1985). WHO (2006) does not list spore-forming bacteria among important human excreta pathogens.

Treatment of faeces

Introduction

After faeces are excreted, their microorganism concentration, including any pathogens that may be present, decreases with time in the natural environment (Schönning & Stenström, 2004; WHO, 2006), during storage, handling or treatment sanitation facilities. Faecal treatment includes storage for specific periods, alkaline and other chemical treatment, and heat treatment (Vinnerås, 2002; Schönning & Stenström, 2004; Jönsson *et al*., 2004).

Storage

Storage of faeces for a specific time results in a reduction in pathogenic microorganisms due to natural die-off (WHO, 2006). The degree of reduction depends on the storage conditions and type of microorganisms present. Ambient temperature, pH, moisture and biological competition all affect inactivation. Some of the factors depend on the conditions in the natural environment. Therefore, changes in the external environment, for example seasonal shifts in temperature and humidity, can even result in an increased number of pathogenic organisms as a result of re-growth, especially the bacteria.

Storage is more efficient in killing pathogens in dry, hot climates, with desiccation of the material and low moisture contents aiding the pathogen inactivation. Storage at low moisture levels, 5-25%, results in rapid pathogen destruction (Feachem *et al*., 1983) and reduces odour and fly breeding (Carlander & Westrell, 1999). In areas where ambient temperatures reach up to 20°C, a total storage time of 1.5 to 2 years (including the time stored during primary treatment) will eliminate most bacterial pathogens (if kept dry) and will substantially reduce viruses, protozoa and parasites (Schönning & Stenström, 2004; WHO, 2006). In areas where higher ambient temperatures (up to 35°C) are attained, a total storage period of one year will achieve the same result, as pathogen die-off is faster at higher temperatures (Schönning & Stenström, 2004; WHO, 2006). This agrees well with Strauss & Blumenthal (1990), who suggested that one year was sufficient for inactivation under tropical conditions (28-30°C) whereas 18 months would be needed at lower temperatures (17-20°C). However, longer survival times

of 2-3 years have also been reported for different types of faecal pathogens at 22-37°C (Moe & Izurieta, 2004). Vinnerås *et al*. (2007) reported that storage of faecal matter at 20°C did not reduce *Enterococcus* spp. and at 4°C *Salmonella* spp. was not reduced in 50 days of treatment. Thus, it hard to ascertain when sufficient sanitation has been attained by storage.

Chemical treatment

Chemicals used for treatment of faeces include acids (*e.g*. phosphoric acid), bases (*e.g*. ammonia and lime) and oxidising agents (*e.g*. chlorine). According to Vinnerås (2002), chemicals for disinfection of sewage products that take into account an additional advantage of the agronomic value of the substances in the disinfectants, such as $Ca(OH)_2$, NH_3, KOH and PO_4^{-3}, are preferable for substrates that are to be recycled as fertilizers, as the nutrient content of the disinfectant increases the fertilizing value of the product. Two such materials are wood ash, rich in K and Ca, and lime, which are usually applied as cover material on the faeces during toilet use.

The sanitation of faeces by application of lime and wood ash as additives has been studied in South Africa. In toilet vaults where wood ash and lime were applied, the pH was in the range 8.6-9.4. Weekly turnings of the faecal heap resulted in a high reduction in pathogen numbers, even though *Salmonella* was found in the stored faeces after one year, which was linked to possible re-growth in the system as a result of partial wetting (Austin, 2001). A combination of high pH and temperature was suggested to account for 1.5 $\log_{10}$ reduction of a conservative viral indicator after six weeks of storage of faecal material (moisture 10%, pH around 8, temperature, 24°C) in Mexico (Franzén & Skott, 1999). Most organisms thrive around the neutral pH range of 6-8, and may be inactivated by more acidic or alkaline environments (Prescott *et al*., 1996). The pH affects the activity of microbial enzymes and the ionisation of chemicals and thus plays an important role in the transport of nutrients and toxic chemicals into the cell (Bitton, 1999). In a study of 156 double vault, urine diverting and solar toilets in El Salvador, the combination of high pH, temperature and storage time contributed to microbial inactivation (Moe & Izurieta, 2004). The average pH in vaults with soil additives was 8.8; in vaults with ash 9.4 and in vaults with lime additives 10.5. Moe & Izurieta (2004) performed multiple regression and survival analyses that revealed pH to be the most critical parameter for inactivating the bacteria indicators (faecal coliforms and *Clostridium perfringens*) and somatic coliphages, while high pH and temperature were the most critical factors for inactivation of *Ascaris*.

Urea has also been investigated for sanitation of faecal matter (Vinnerås, 2002), blackwater (Vinnerås & Svensson, 2005), manure (Vinnerås, 2005a) and pig manure (Vinnerås, 2005b). During treatment, the urea degrades to form ammonia and the pH increases simultaneously. Studies have shown that the undissolved ammonia at high pH may act as an inactivating agent for viruses (Pesaro *et al*., 1995), *Cryptosporidium* oocysts (Jenkins *et al*., 1998) and *Ascaris* eggs in sewage sludge (Ghiglietti *et al*., 1997).

According to Vinnerås (2002), addition of urea at a dosage of 30 grams ammonia per kilogram (3% N) is sufficient for the material to be considered generally safe after 2 months at room temperature (approximately 20°C). However, spore-forming bacteria were not affected by this treatment. In the study by Vinnerås (2002), addition of urea to faecal matter resulted in a pH increase to approximately 9.3. This produced an efficient disinfection of *E. coli*, *Enterococcus* spp. and *Salmonella* spp. within 3 weeks (>6$\log_{10}$ reduction) and a reduction of the chemical resistant phage *Salmonella* Typhimurium 28B, corresponding to a decimal reduction within 7.5 days, or 45 days for 6$\log_{10}$ reduction. Peracetic Acid (PAA) was also investigated. This reduced all of the indicator organisms within 12 hours of application. Between 0.5-1% of PAA was found to be sufficient to disinfect faecal material with a dry matter content of approximately 10% to achieve the state of no detectable organisms. However, while no bacterial re-growth occurred when urea was used for disinfecting faecal matter, there was a high rate of bacterial re-growth 5 days after the treatment with a 0.15% PAA dosage.

Composting

Composting is the biological degradation of organic material to a humus-like stable product under aerobic, moist and self-heating conditions. The process is often performed under controlled conditions for: 1) Conversion of potentially degradable waste into a beneficial product; 2) disinfection of material that might be contaminated with pathogens; and 3) bioremediation of hazardous waste (Steger, 2006). The compost product from a well functioning thermophilic process is usually free of pathogens and plant seeds and can be beneficially applied to land, supplying nutrients for plant growth, organic matter for soil improvement and agents for plant disease suppression (Sundberg, 2005).

Although most organic materials can be composted, successful thermophilic composting of raw materials (substrates) usually requires mixing them with amendments, a process called feed conditioning (Haug, 1993). The amendment is added to improve the process structurally or chemically and/or to add energy for the process. Structural amendments are organic materials that are added to reduce the bulk weight and increase air voids, allowing for proper aeration. Energy or fuel amendments are organic materials that are added to increase the proportion of biodegradable organics in the mixture and thereby increase the energy content of the mixture. Amendments often used in composting operations include sawdust, straw, peat, rice hulls, cotton gin trash, manure, refuse fractions, yard wastes, wood chips and a variety of other wastes (Haug, 1993). Inorganic amendments *e.g*. lime, ash or soil can be added to acidic substrates to increase their pH to improve composting.

When a well conditioned substrate is composted, aerobic degradation of the wastes occurs. The process is exothermic, *i.e*. heat is generated, resulting in increased temperature. The heat produced either remains in the compost mass or escapes by conduction and radiation, or is lost with the outgoing gas. To keep the compost hot and thereby sanitize it, the heat generated should be kept in the

compost matrix. This requires, at least on the small and medium scale, that the compost is well insulated.

The degradation of the organic waste is a biochemical process performed by microorganisms. Factors that influence microbial growth affect the compost process. These factors relate to substrate composition, including *e.g*. C/N ratio, pH, oxygen, moisture content and temperature (Miller, 1993; Haug, 1993; Del Porto & Steinfeld, 1999).

C:N ratio: The C:N ratio is considered among the important factors affecting the compost process and compost quality (Golueke, 1977; Michel *et al*., 1996). Huang *et al*. (2004) investigated the effect of initial C/N ratio on the composting of pig manure and found that when composting at a lower initial C/N (15), it took 63 days longer to reach compost maturity than when the initial substrate had an initial C/N of 30. Compost maturity was measured by DOC, soluble NH_4-N, C/N_{solid} and $C/N_{aqueous}$ and seed germination index. Microorganisms require digestible carbon as an energy source for cellular growth and nitrogen for cell synthesis (Epstein, 1997). During aerobic metabolism, microbes use about 15 to 30 parts of carbon for each part of nitrogen, *i.e*. C/N = 15 to 30 (Haug, 1993). A C/N ratio of 15 to 30 is recommended because in this range, nitrogen is present in excess and no rate limitation should be imposed (Haug, 1993). If the initial C/N ratio is greater than 35, the microorganisms must go through many lifecycles, oxidising off the excess carbon until a convenient C/N ratio for their metabolism is reached (de Bertoldi *et al*., 1983). In compost substrates with low C/N ratios, nitrogen loss occurs via ammonia volatilisation at high pH and temperature (de Bertoldi *et al*., 1983; Eklind *et al*., 2007). The loss of N reduces the value of the compost as a fertilizer. For optimum composting, C/N ratio of the starting substrate should be about 25 (de Bertoldi *et al*., 1983).

pH: In the initial phases of the composting process, pH usually declines due to the formation of organic acids. This is especially so if the moisture content is high and the substrate contains lots of easily degradable organics. The pH development in a normal composting process is shown in Fig. 7. Organic acids are initially produced through fermentation of easily degradable organic matter. During such processes, the main product is normally lactic acid or acetic acid but longer-chained butyric or propionic acids are also produced. Acetic acid is mainly produced anaerobically, but it can also be produced when oxygen is present, *e.g*. when *E. coli* is subjected to high concentrations of glucose (Enfors & Häggström, 2000). The bacteria take up more glucose than they can oxidize aerobically and acetate is formed. Organic acids interfere with microbial cellular functions by entering the cells when they are in their undissociated form, *i.e*. when the pH is low. During the initial phases of composting, the organic acids reduce the pH, but the carbonic and ammonia systems balance this with varying success, depending on the substrate. The pH rises later, because the acids are consumed and ammonium is produced (Beck-Friis *et al*., 2003), and the pH usually stabilizes around 7.5-8.5 (Jeris & Regan, 1973; Beck-Friis *et al.*, 2003).

Oxygen: To properly function, the microorganisms involved in composting of substrate organic matter should be supplied with oxygen. Oxygen is used as electron receptor in metabolism by the aerobic microorganisms. Oxygen can be supplied to composts by mechanical aeration, convective air flow (passive aeration), diffusion and physical turning of the compost mass (Epstein, 1997).

Moisture: Moisture is important for the proper functioning of the compost process as the active bacteria live in a water film. The moisture in the composting blend provides a medium for the transport of dissolved nutrients required for the metabolic and physiological activities of microorganisms (Stentiford, 1996; McCartney & Tingley, 1998). The maximum rate of transfer of nutrients and waste products takes place in a liquid environment (100% MC) (Stentiford, 1996), but in these conditions operating an aerobic composting system, *i.e.* liquid composting, requires much energy for the mechanical aeration. Optimum moisture for successful composting of various types of wastes is reported to be in the range 25-80% (Ahn *et al*., 2007), 50-60% (Bishop & Godfrey, 1983) and 50-60% (Suler & Finstein, 1977; McKinley *et al*., 1984; Tiquia *et al*., 1998). The availability of nutrients for microorganisms becomes limited when compost moisture is low. At low initial moisture (*e.g.* <25%), early dehydration of the compost easily occurs (Liang *et al*., 2003), which arrests the biological process, thus giving physically stable but biologically unstable composts (de Bertoldi *et al*., 1983). High moisture may produce anaerobic conditions through waterlogging, which prevents and halts compost activities (Schulze, 1962; Tiquia *et al*., 1996). At moisture contents exceeding 60% the free air space (FAS) often start to decrease, reducing the oxygen diffusion through the compost matrix (Haug, 1993). The free air space is related to the moisture content and physical structure of the composting substrates (Schulze, 1962). Jeris & Regan (1973), estimating the consumption of oxygen required for the composting of a wide variety of residues with different moisture contents, concluded that 30-36% FAS is required to obtain optimum speed composting.

Substrate conditioning for moisture and energy: Feed conditioning is an important aspect that determines how successful the compost can be in attaining sanitising temperatures. Since a faeces/ash mixture may not contain enough organics to ensure that sanitising temperatures (>50°C) are kept for a sufficiently long duration (at least one week) to attain sanitation, there may be a need to co-compost with food waste or other organic waste. Haug (1993) has developed rules of thumb that can be used to roughly estimate whether the energy in the material is sufficient for thermal composting. Since the largest energy usage in composting is that for the evaporation of water, it is possible to use the ratio of water to the mass of biological volatile matter (W) to determine whether the energy is sufficient to evaporate the water. The water ratio, W, is calculated according to Eqn. 7.

$$W = \frac{(X_s - X_s S_s)}{k_s V_s S_s X_s} \qquad \text{Eqn. (7)}$$

where k_s is the fraction of the substrate volatile solids degradable under composting; V_s is the volatile solids content of the dry solids; S_s is the fractional

solids (dry matter) content of the substrates; X_s is the wet weight of the feed substrate.

The calculated W is compared to the recommended literature value to check whether the compost substrate has sufficient energy for temperature elevation and water evaporation (W<8). If W>10, normally insufficient energy is available to achieve temperature elevation and sufficient water evaporation. Another important parameter, energy ratio (E) is calculated according to Eqn. 8:

$$E = \frac{k_s V_s S_s X_s H_s}{(X_s - S_s X_s)} \qquad \text{Eqn. (8)}$$

where H_s is the heat released per gram of biodegraded volatile solids. An estimate of H_s = 23.24 MJ/g degraded V_s (5550 cal/g degraded V_s) is given by Haug (1993). As a rough rule of thumb, composts with E>700 theoretically posses sufficient energy for composting and drying and with E<600 lack sufficient energy (Haug, 1993).

Temperature: Temperature is an important factor in composting efficiency. From the start of the composting process, the temperature increases due to microbial metabolism. Temperature increase within composting materials is a function of initial temperature, metabolic heat evolution and heat conservation (Miller, 1993). The temperature affects the rate of decomposition, which can be defined as the rate of carbon dioxide evolution. Temperatures below 20°C have been demonstrated to slow or even stop the composting process (Mosher & Anderson, 1977). The temperature at which maximum decomposition occurs probably depends on the type of substrate composted (Haug, 1993) and is reported to be in the range 50-67°C (Suler & Finstein, 1977; Haug, 1993; Miller, 1993; Richard & Walker, 1999); Eklind *et al*., 2007). At higher temperatures, the activity of the microbial community declines as the thermophilic optimum is surpassed (Miller, 1993). If the temperature reaches 82°C, the microbial community is severely impeded (Nell & Wiechers, 1978; Finstein *et al*., 1986; Fermor *et al*., 1989).

At temperatures (>50°C), pathogen inactivation occurs (Schönning & Stenström, 2004; WHO, 2006). High temperatures cause protein denaturation, leading to destruction of the cells (Madigan & Martinko, 2006). The temperature of a composting pile is usually such that it is hotter at the centre than at the edges (Haug, 1993). To attain high temperatures in the majority of the pile, insulation should be provided to prevent heat loss. Even then, there will still be parts of the compost that experience low temperatures, for example, near the inlet (where ambient air enters). To expose the material in such low temperature zones to high temperatures, the compost should be sufficiently mixed (Epstein, 1997; Vinnerås *et al*., 2003).

Based on temperature development, the composting process can be divided into three main phases (Fig. 7). The mesophilic phase is characterised by increasing temperatures up to about 40°C. The transition from mesophilic to thermophilic takes place at about 40-45°C. The thermophilic phase is defined by temperatures

from 45°C to 70°C (Miller, 1996) and the curing phase is characterised by temperatures again sinking below 40-45°C (Chiumenti *et al*., 2005).

The mesophilic phase is characterized by growth and activity of mesophilic organisms, bacteria, fungi and yeast (Finstein & Morris, 1975; Miller, 1993; de Bertoldi, 1998; Ryckeboer *et al*., 2003). As mentioned earlier, the activity of the acid-producing bacteria is initially high and results in a decrease in pH (Fig. 7). During this phase, temperature increases.

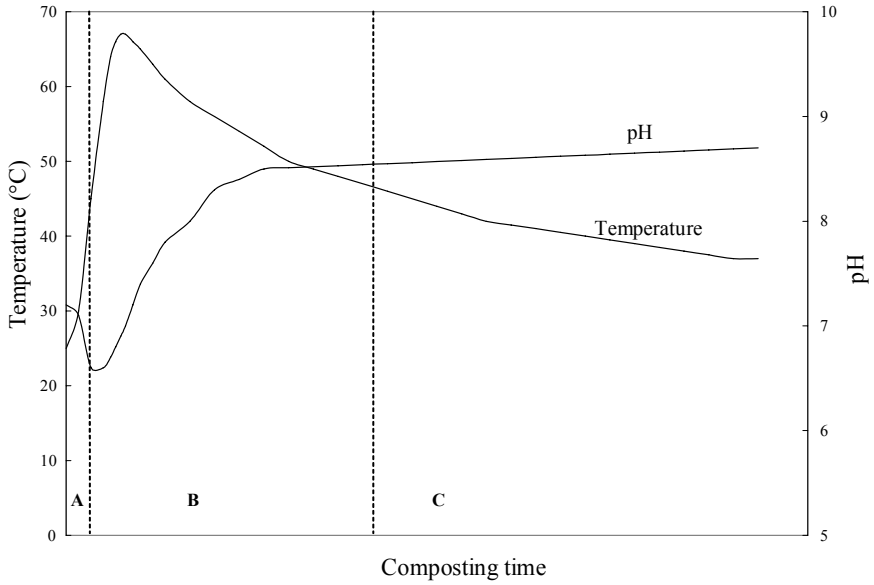


Fig. 7. Schematic description of different phases of a well functioning composting process based on the development of temperature and pH: A – Mesophilic, B – Thermophilic, C – Curing (adapted from Steger, 2006).

In the thermophilic phase, the temperature rises beyond 45°C. At these temperatures, the growth and activity of non-thermotolerant organisms including pathogens and parasites is inhibited. The organisms adapted to temperatures above 45°C dominate the thermophilic composting process (Strom, 1985). During, or just before this phase, the pH rises and stabilises as the supply of short-chain organic acids is exhausted (Beck-Friis *et al*., 2001).

As the temperature declines again, the curing stage sets in and mesophilic microorganisms including fungi and actinomycetes normally reappear. There seems no doubt that temperature is one of the most important factors in the succession of composting microorganisms, and it is relatively easy to ascertain the microbial succession from mesophiles to thermophiles, or conversely from thermophiles to mesophiles, by using different incubation temperatures (Nakasaki *et al*., 2005). Nutritional factors are also important in the transition (Steger, 2006). In the curing stage, most of the easily degradable compounds have been depleted. The microorganisms in this phase must therefore be able to degrade more complex

compounds less susceptible to mineralisation, such as cellulose, hemicellulose and lignin. Actinobacteria (Actinomycetes) normally play an important role in this last phase of the composting process (Steger, 2006).

Pathogen die-off in composts

In composting, pathogens are killed as a result of elevated temperatures and also by competition with the more resistant compost and/or soil microbes (Feachem *et al*., 1983). Under thermophilic composting, the temperature effect on pathogen die-off probably dominates, and thus the temperature and the time of exposure at high temperature together govern the pathogen inactivation (Feachem *et al*., 1983; Haug, 1993).

As different parts of the compost do not heat up to high temperatures at the same time, an important factor in ensuring sanitation of all of the compost material is mixing. Mixing during the high temperature phase of the compost increases the fraction of the compost matrix that is exposed to high temperatures. The following relationship (Eqn. 9), assuming that each mixing is random, can be used to determine the number of turnings/mixings required to safely sanitise the compost (Haug, 1993).

$$n_t = n_o (f_1)^N \qquad \text{Eqn. (9)}$$

n_t = number of surviving organisms,
n_o = number of organisms initially present,
N = number of pile turnings, the turnings are assumed to be random, N≥0
f_1 = fraction of compost material in low temperature zones where no organism destruction occurs, f_1 is such that $f_1 \leq 1$ but $f_1 \neq 0$, *i.e*. there will always be a low temperature zone, however sufficiently the compost might be insulated, for example near the inlet or outlet where temperatures are usually around ambient. It is assumed that organism die-off in the high temperature parts of the compost is complete between each turning.

Eqn. 9 does not include the die-off before the first mixing. To take this into account, Eqn. 9, which is according to Haug (1993) is re-written to Eqn. 10 below:

$$n_t = n_o (f_1)^{N+1} \qquad \text{Eqn. (10)}$$

By frequently turning the compost, a state of no viable pathogenic organisms can be attained, provided that the high temperature zone is hot enough to kill off the pathogens. The mixing potentially mimics a tyndalisation process that can even kill spore-forming bacteria, which are known to survive at high temperatures (Stanbury *et al*., 1985). However, Eqn. 10 assumes that there is no re-growth of organisms in the compost. This is true for helminths, protozoa and viruses, which cannot multiply outside of their host, but certainly not absolutely true for bacteria, which have this potential. However, it has been shown that re-growth of pathogenic bacteria in material that contains active microorganisms such as composted matter is small (Sidhu *et al*., 2001). Therefore, the equation can be used to give a good indication of the safety margins that can be achieved during composting, even for pathogenic bacteria.

Using data from a number of studies, Feachem *et al*. (1983) presented diagrammatically the duration of treatment as a function of temperature where no viable organisms of several kinds of pathogens should be detected above a critical temperature. Vinnerås *et al*. (2003) assumed a logarithmic die-off for pathogens during composting, and used the diagrams by Feachem *et al*. (1983) to derive equations for the required duration (t) of treatment at a given temperature (T) to attain a state of no viable organisms (Table 3).

Table 3. *Equations derived from Feachem* et al*. (1983) for the time in hours (t) required to attain no viable organisms (equal to 12log$_{10}$ inactivation) of different pathogens at different temperatures (T) in ℃ (according to Vinnerås* et al*., 2003)*

Organism	Type	Equation
Enteroviruses	Virus	$t = 55.9 * 10^{-0.101(T-45)}$
Salmonella	Bacteria	$t = 75.4 * 10^{-0.1466(T-45)}$
Enteric *Hystolica*	Protozoa	$t = 21.3 * 10^{-0.2806(T-45)}$
Schistosoma	Helminth	$t = 10.0 * 10^{-0.1844(T-45)}$
Ascaris	Helminth	$t = 177 * 10^{-0.1922(T-45)}$

Vinnerås *et al*. (2003) considered that when the time of treatment is shorter than that needed to achieve no viable organisms, a partial inactivation will be attained, which can be calculated as the fraction of the total inactivation. The sum of all partial inactivations will then give a quantified measure of the theoretical safety margin of how many times the inactivation was obtained during the treatment according to Vinnerås *et al*. (2003) (Eqn. 11).

$$\sum X = \frac{t_1}{E_{d1}(T_1)} + \frac{t_2}{E_{d2}(T_2)} + \frac{t_3}{E_{d3}(T_3)} + \ldots\ldots \frac{t_i}{E_{di}(T_i)} \ldots\ldots \frac{t_n}{E_{dn}(T_n)} \qquad \text{Eqn. (11)}$$

$\sum X$ = number of times total die-off is achieved; E_d is the time for total die-off at the average temperature T during the time interval t, calculated from the equations in Table 3, according to Vinnerås *et al*. (2003); and t is the time interval (h) for the temperature T.

Vinnerås *et al*. (2003) used the above calculation to show that calculated safety margins of more than 37 times the total die-off of Enteroviruses and some 550 times that of *Ascaris* were achieved when composting faeces/food waste mixture at pilot scale, where the temperature reached 65°C and stayed above 50°C for about 8 days.

Several authors have studied the temperature-time relationships that result in a safely sanitised compost. Beauford & Westerberg (1969) reported that *Salmonella newport*, poliovirus type 1, *Ascaris lumbricoides* ova and *Candida albicans* were effectively killed in aerobic composting of sewage sludge at 60-70°C within 3 days. According to Feachem *et al*. (1983), the time-temperature combinations lethal to all pathogens excreted in faeces including the most resistant *Ascaris* (with

the possible exception of hepatitis A virus at short retention times) are: 1 hour at ≥62°C, 1 day at ≥50°C, and 1 week at ≥46°C. Deportes *et al*. (1998) reported that faecal streptococci and *Salmonella* spp. are good candidates for assessing municipal solid waste compost hygienisation. The findings by Deportes *et al*. (1998) were based on studies of microbial disinfection capacity of municipal solid waste composting by following the composting process from raw material to mature compost and long-term storage, in which no re-growth of faecal streptococci and *Salmonella* spp. was encountered. In other studies, *Salmonella* spp. and *E. coli* became undetectable within 24 hours of composting at temperatures higher than 50°C (Lung *et al*., 2001; Hess *et al*., 2004). Schönning & Stenström (2004) recommend thermophilic composting of source separated faeces at temperatures >50°C for more than one week to ensure safe sanitation. Grewal *et al*. (2006) found that composting dairy manure at 55°C killed off *E. coli*, *Listeria* and *Salmonella* spp. within 3 days. Using data on survival and inactivation times of pathogens in compost or manure collected from numerous studies, Cornell Waste Management Institute (2005) concluded that: 1) *Salmonella* and *E. coli* are generally unlikely to survive in compost where temperatures exceed 50°C over a period of several days to 2 weeks; and 2) faecal coliforms and streptococcus may be more resistant to temperature in compost than either Salmonella or *E. coli*.

Incineration

Literature on incineration of faeces is limited, as the process has not been investigated. Incineration offers a treatment method that not only aims at destruction of pathogens, but is also a compact and rapid process, *i.e*. inactivation is achieved quickly. In addition, the amount of material is reduced to a large extent. The possibility to re-use the ashes as additive material during the collection phase means there is little additional need for disposal. Thus the frequently encountered problem of providing additive material for the collection phase can be solved.

Incineration increases the temperature to high levels (>800°C). Therefore even short exposure should be enough for inactivation of any pathogens present. Low-cost small-scale incinerators made of steel sheets have been promoted by international agencies, mainly for disposal of health care waste. In most of these applications, incinerators are used to prevent health risks arising out of possible scavenging of sharps, with the associated possibility of transmission of diseases *e.g*. hepatitis, HIV/AIDS (WHO, 2004b).

The product of the incineration is ash. Fly ash containing furans, dioxins *etc*. is contained if the facility includes flue gas cleaning (Shaaban, 2007). Shibamoto *et al*. (2007) performed studies on the formation of dioxins from small-scale waste incineration by using various waste-simulated samples, including different kinds of paper, various kinds of wood, fallen leaves, food samples, polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyvinylidene chloride, polyethylene tetraphthalate (PET) and various kinds of plastics. In these studies, samples with either inorganic or organic chlorides produced much more dioxins than the samples without chlorides when incinerated under similar conditions. When the

same sample was incinerated at different temperatures, the sample burnt at low temperatures (>450°C) yielded a higher toxicity equivalence quantity (TEQ) than did the sample burned at higher temperatures (>850°C). From this, Shibamoto *et al*. (2007) concluded that combustion temperature plays an important role in dioxin formation in exhaust gases from the incineration of waste materials. Dioxin formation occurred at temperatures above 450°C and was reduced significantly at temperatures above 850°C (Shibamoto *et al*., 2007). This also is in accordance with EU directives (89/429/EEC and 2000/76/EU) discussed in Nasserzadeh *et al*. (1995), which state that air pollution is minimised when the combustion chamber temperature reaches at least 850°C and the gases are exposed to this for two seconds or more in the presence of at least 6% oxygen.

Partridge & Hodgkinson (1977) estimated that a total loss of N and S and no loss of P and K are achieved when straw was burnt. Heard *et al*. (2000) obtained an N and C loss of more than 90% from the burning of different types and sources of straw. In their studies, an average of 24% of the P, 35% of the K and 75% of the S were lost in the smoke and particulate matter that drifted away. It thus appears that the hygienic ash from successful incineration should contain most of the P and K, which, like plant ash, can fertilize the soil for agricultural purposes (Jönsson *et al*., 2004).

Environmental impacts of faecal treatment methods

Composting

Composting has beneficial impacts but it also has potential negative impacts, especially if the process is not well managed. The beneficial impacts are sanitation of faecal matter (Vinnerås *et al*., 2003; Niwagaba *et al*., 2006b), volume reduction (Ciavatta *et al*., 1993; Vinnerås *et al*., 2003), production of material (compost) with valuable nutrients and organic matter for soil improvement and suppression of plant pathogens (Haug, 1993; Eghball & Lesoing, 2000). Degradation of organic matter (mainly into CO_2 and water) of up to 75% was reported in 35 days of composting of faecal matter, food waste and amendments (Vinnerås *et al*., 2003), while Ciavata *et al*. (1993) reported that about 30% of organic waste material can be decomposed to CO_2 within 2 months of composting. Together these data show the importance of a well managed process. Composting is a flexible technology in terms of size, time frame for planning and construction and pay-back time for investment, and it can be performed at any scale, from household to regional (Sundberg, 2005). It is potentially a cheap sanitation method for excreta. If the collection and composting systems are well managed, they reduce environmental pollution by removal of inadequately treated human excreta. Composting can also offer opportunities for poverty alleviation, by increasing the yields of agricultural activities, thus increasing food security and consumption, as well as the possibility of selling the surplus (Ali, 2004).

One potentially negative impact of composting faecal matter is the risk of handling initially unsanitised human excreta (Vinnerås *et al*., 2003). Furthermore, ammonia emissions can be large (Beck-Friis *et al*., 2001), and ammonia contributes to

acidification and eutrophication (Sundberg, 2005). Furthermore, the greenhouse gases methane and nitrous oxide are formed during composting, even though the amounts are usually small in well managed systems (Beck-Friis *et al*., 2001; Zeman *et al*., 2002). However, potentially high amounts of these can be formed when a composting system is not managed properly (Beck-Friis *et al*., 2001). In addition, there is a potential for bad odours in composting systems, especially if they are not properly designed and operated (Haug, 1993). Furthermore, when the substrate has a high moisture content (>60%) and is without a strong structure, it can become waterlogged and turn anaerobic, producing bad odours and environmentally hazardous emissions, *e.g*. methane and nitrous oxide. In many fresh substrates, water is stored in intact cells, and it is not easy to determine visually or by use of the fist test whether the material has suitable initial moisture content or a moisture content that is too high and that will inhibit the composting process. As the cells start to disintegrate due to decomposition, they release the water, and the material can prove to be too wet. Starting the process dry and adding water as the composting progresses is therefore often a wise strategy.

Incineration

Potentially positive impacts of incineration are that the process is able to attain disinfection almost instantly. Incineration greatly decreases the amounts of material to be finally disposed of (Danish EPA, 2005; Niwagaba *et al*., 2006a; Shaaban, 2007). Well managed incineration produces sanitised ash containing the incoming amounts of P and K, which can fertilize the soil for agricultural purposes (Jönsson *et al*., 2004). However, the plant-available P in ash from the incineration process is generally low (Jakobsen & Willett, 1986; Zhang *et al*., 2002).

From an environmental point of view, incineration is often associated with emissions of air pollutants such as dioxins, furans and other toxic air pollutants (Ketlogetswe *et al*., 2004; WHO, 2004b). Other deficiencies often reported are incomplete destruction of waste, high smoke emissions, and fugitive emissions (WHO, 2004b; Schuhmacher & Domingo, 2006). These deficiencies are linked to low temperatures in the incinerator (WHO, 2004b) and can be well controlled in large- and small-scale processes. User acceptance of small-scale incinerators appears to be generally high and the use of incinerators is preferable to the disposal of waste in unsecured pits or landfills, or (uncontrolled) burning in drums or pits (WHO, 2004b).

Summary of Papers

Paper I

Incineration of faecal matter for treatment and sanitation

Faeces (including toilet paper and ash added during toilet use) were collected from urine diverting toilets at St. Charles Lwanga Girls' Secondary School. The school

has a population of 350 students and 50 staff. The faeces used in the experiments were collected from the students' toilets, where woven papyrus baskets are used for faecal collection in the toilet chambers. The faeces from the faecal chambers had been emptied in a drying shed. One batch of the faeces had stayed on the concrete floor of the drying shed for 2 months, whereas the other had stayed there for 6 months. Without mixing the contents from the different batches in the drying shed, the faeces were packed into separate 50 kg bags.

A pre-trial incineration experiment showed that the large amount of loose ash in the faeces extinguished the fire from the stove placed under the metallic grating for starting the incineration. Thus, to decrease the amount of loose ash and to increase the proportion of organic matter in the faeces, the samples were sieved using a quarter-inch (6.35 mm) aperture sieve. Faeces as collected from the toilet (*i.e.* containing toilet paper and ash) were placed on the sieve. The sieve was shaken manually until no more ash was seen dripping from the bottom of the sieve. The remaining material, the faeces, toilet paper and faecal-bound ash, were spread out on a polythene sheet and dried in the open in strong sun at an average ambient air temperature of about 28°C for 2-3 days to become sufficiently dry for incineration.

A locally fabricated incinerator was used for burning the faeces. It was made out of steel sheets, and consisted of a metallic grating on which a perforated steel sheet was mounted for supporting the dried faeces (Fig. 8).

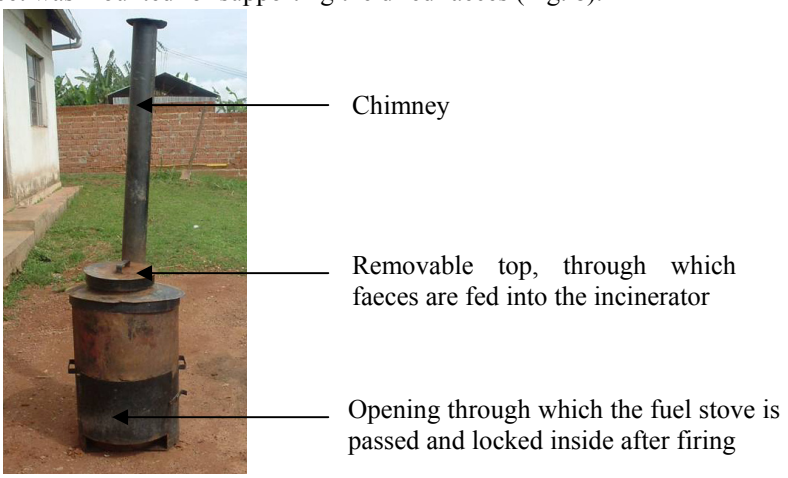


Fig. 8. Incinerator used in the experiments (Paper I).

The fire was driven by a sawdust fuelled stove underneath the metallic grate. The experiments were monitored and the highest temperatures attained during each experiment recorded. Sawdust was used to fire up the stove, and within 45 minutes to 1 hour, the sieved faeces on the metal grate ignited at temperatures of 800°C and beyond.

Samples were collected before and after incineration and analyzed for moisture and organic matter content (Table 4), plant nutrients (N, P, and K), and bacteria. Analysis was performed on crushed samples, *i.e*. faeces and toilet paper were crushed to get a homogeneous sample.

Table 4. *Moisture (MC) and organic matter (OM) content in the different trials*

Expt. No.	Time in drying shade	Before Incineration		After Incineration	
		MC (%)	OM (%)	MC (%)	OM (%)
1	6 months	12.4	8.8	4.3	1.9
2	2 months	5.3	14.6	4.2	0.1
3	6 months	22.8	18.7	1.4	0.4

Using the moisture and organic matter content of the material before and after incineration, the mass loss was calculated (Table 5). A mass balance of the dried faecal matter over the incineration was carried out. The mass losses by percentage are shown in Table 5.

Table 5. *Mass balance for sun-dried faeces over the incineration*

Expt. No.	Time in drying shade	Initial mass (kg)	Final mass (calculated) (kg)	Mass Loss (kg)	Mass loss (%)
1	6 months	14.7	12.5	2.2	15
2	2 months	16.0	13.5	2.5	15
3	6 months	17.5	11.2	6.3	36

Total losses of incinerated material, as shown in Table 5, were low due to its high initial ash content. However, for the organics the mass loss was >90%. Due to the mass losses achieved after incineration, this treatment process for faecal matter may be useful where mass reduction of final products is very important, such as in peri-urban dense settlements where space for excreta re-use and disposal is limiting. A further advantage is that the ash from the incineration of faeces can be used as an additive in the toilets without risk of disease transmission since the pathogens have been destroyed.

Comparing the plant nutrients before and after the incineration, the loss of nutrients was calculated. Calculated nutrient losses of total N and available P are shown in Table 6.

Table 6. *Losses of total N and plant-available P in the incineration experiments*

Expt. No.	Total N			Available P		
	Before incineration (g/kg ash)	After incineration (g/kg ash)	Loss (%)	Before incineration (g/kg ash)	After incineration (g/kg ash)	Loss (%)
1	1.56	0.14	91	0.21	0.06	70
2	1.69	0.10	94	0.33	0.08	75
3	2.34	0.23	90	0.49	0.03	94

From Table 6, total N and available P are lost in the range 90-94 % and 70-94% respectively. The results on the loss of N agree well with Heard *et al*. (2000).

Paper II

Composting source separated human faeces for treatment & sanitation

Composting was performed in three wooden compost reactors, each of internal dimensions 405x405x475 mm^3 and wall thickness of 25 mm. Three experiments (I, II and III) were performed successively, integrating into each experiment the knowledge attained in the previous ones. Fig. 9a shows the compost reactors in Experiment I (without insulation); Fig. 9b compost boxes in Experiments II and III (insulated with 25 mm styrofoam).

(a) Non insulated compost reactors (b) Insulated compost reactors

Fig. 9. Non-insulated compost reactors (left) and insulated compost reactors (right).

To reduce the amount of ash, and thereby increase the organic fraction, the material was sieved on a quarter-inch (6.35 mm) aperture sieve prior to composting. Sieved faeces were mixed with food waste to give compost substrates containing faeces:food waste (F:FW) in wet weight mix ratios of F:FW = 1:0, 3:1 and 1:1. The substrates were used in Experiments I, II and III, which were performed successively according to Table 7. Table 8 gives the different substrates mixes used in the three successive compost Experiments I, II and III by wet weight and type.

Table 7. *Description of experiments and substrates (Paper II)*

Experiment	Experiment I (December 04)	Experiment II (Jan-Feb 05)	Experiment III (March- May 05)
Insulation	No insulation	25 mm styrofoam	25 mm styrofoam
Food waste components	Maize meal (*posho*) and beans	Maize meal (*posho*), beans and fruit peelings of orange, avocado, lemon, jackfruit, tangerine, watermelon and passion fruits.	Peas, rice, bananas, beans, banana leaves, maize meal (*posho*), sweet potatoes, cassava, potatoes
Inoculation	500 mL yoghurt per unit	1 kg old compost per unit	1 kg old compost per unit
Initial preparation	Material placed in compost reactors and mixed within the reactors by spade while sprinkling water.	Material placed in compost reactors and mixed within the reactors by spade while sprinkling water.	Material placed on a polythene sheet and mixed by spade while sprinkling water before being placed in compost reactor.
Mixing	Once every 7 days	Once every 7 days	Once every 3 days

Table 8. *Mixtures of Faeces (F), Food waste (FW) and sawdust used in the three compost experiments (Paper II)*

Ratio	Experiment I			Experiment II			Experiment III		
	F (kg)	FW (kg)	Sawdust (kg)	F (kg)	FW (kg)	Sawdust (kg)	F (kg)	FW (kg)	Sawdust (kg)
1:0	60	0	3	45	0	2.25	45	0	2.25
3:1	45	15	3	33.75	11.25	2.25	33.75	11.25	2.25
1:1	30	30	3	22.5	22.5	2.25	22.5	22.5	2.25

Temperatures were measured daily using a portable digital thermometer (Model 307, Taiwan). Grab samples were handpicked from different parts and depths of the compost boxes and mixed by hand to get a representative sample of about 400 g which was divided and distributed to four laboratories for analysis of pH, moisture content, total N, total organic carbon, *Escherichia coli* (*E. coli*) and *Enterococcus* spp.

The maximum temperature increase (all three boxes taken into consideration) above that of the surrounding air was approximately 14°C in Experiment I, about 25°C in Experiment II and over 35°C in Experiment III.

In Experiment III, temperatures in all three compost boxes increased faster than in the previous experiments, reaching a maximum of 67°C on Day 2 in the F:FW = 3:1 compost, while a maximum of 62°C was reached in the F:FW = 1:1 compost on Day 9 (Fig. 10). Throughout the experiments, temperatures in F:FW = 1:0 compost were always low, and mostly below 50°C (Fig. 10).

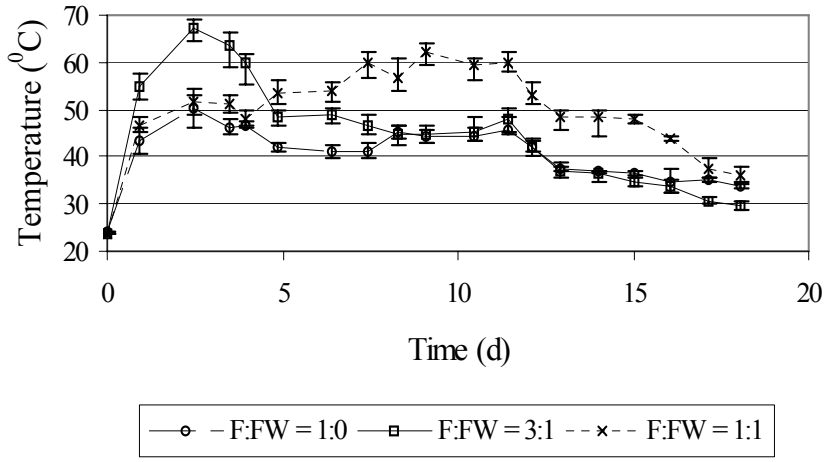


Fig. 10. Changes in temperature in Experiment III (mean, maximum and minimum temperature of the five measurement shown).

In all experiments the measured pH values were between 6.9 and 9.4. In general, the pH increased with increasing fraction of faecal material in the mix and with increasing degree of stabilisation of the compost.

Composts in Experiments I did not heat up to sanitising temperatures (>50°C). Although sanitising temperatures were reached in Experiment II, they were not sustained. In Experiment III, sanitising temperatures were reached and *E. coli* was below detection level in all of the samples taken from mixtures on Day 7 (Fig. 11). On Day 15 in the F:FW = 1:0 compost, *E. coli* were again detected, $4\log_{10}$ c.f.u/g but not in the other composts, which maintained above 50°C for more than 3 days.

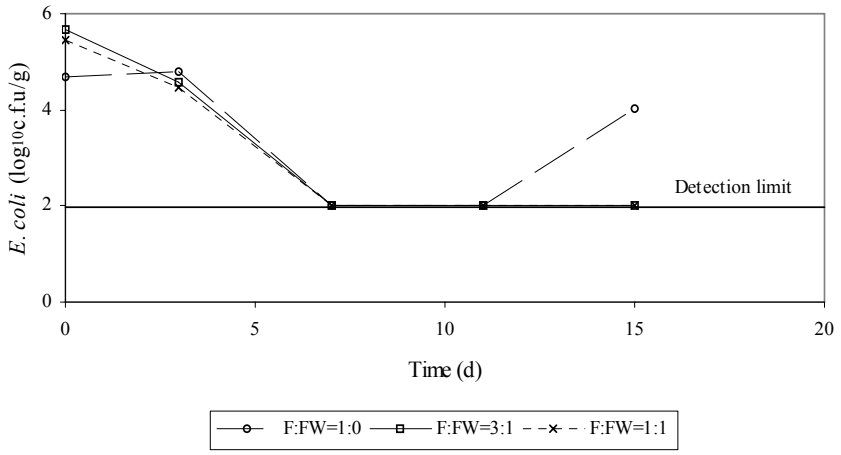


Fig. 11. Changes in *E. coli* (log_{10} c.f.u/g) over time in Experiment III.

In Experiment III, *Enterococcus* spp were detected in all samples taken from the F:FW = 1:0 compost and the count increased between Days 11 and 15 (Fig. 12). Thus, re-growth seems to have occurred after Day 11 as the count increased from $3log_{10}$ on Day 11 to $5.5log_{10}$ on Day 15, even though there could also have been survival as a result of non-homogeneity in temperatures over the entire compost mass and lack of achievement of complete mixing to expose all areas of the compost to a high temperature due to the hand mixing method with a compost agitator tool.

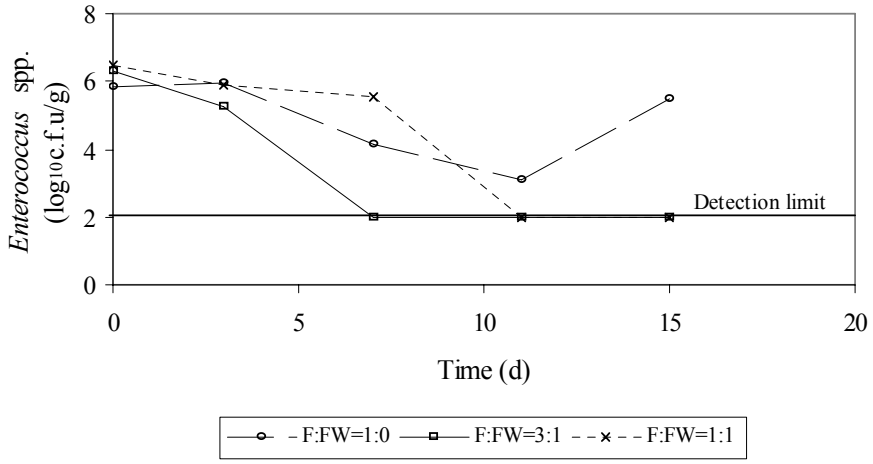


Fig. 12. Changes in *Enterococcus* spp (log_{10} c.f.u/g) over time in Experiment III.

For the F:FW = 3:1 and F:FW = 1:1 composts, there was a decrease in *Enterococcus* spp. with time until there was no detection on Day 7 and 11 respectively.

Paper III

Composting of source separated human faeces

The faeces were collected from school toilets as in Experiment II, but because the quantities were not sufficient, additional faeces/ash mixture from two public toilets in Kampala were also collected and mixed with those from school toilets. In both toilets, generous amounts of ash were applied as cover material during toilet use. To increase the proportion of organic matter, the amount of loose ash was decreased by sieving in the same manner as in Paper II.

Compost substrates containing faeces:food waste (F:FW) = 1:0, 1:1 and 1:3 by volume were used in Experiment A and = 1:0, 1:1 and 1:3 by weight in Experiments B and C. Sawdust and old compost were added to each substrate to provide the structure and inoculum to start up the compost process (Table 9). Faeces/ash mixture or and faeces/ash mixture together with food waste were mixed and composted in 216-L plywood compost reactors insulated with 75 mm styrofoam (Fig. 13). An uninsulated control, containing faeces/ash mixture (without food waste) was used in Experiments B and C. The food waste composition is described in Table 9.

Fig. 13. Preparation of material (faeces and food wastes) for composting (left). Compost boxes used in the experiments (right) (photo: P. Kiyaga, 2006).

Compost temperatures were monitored using a portable digital thermometer (Model 307, Clas Ohlson, Taiwan). Grab samples were handpicked from three locations in the compost reactor (near the top, in the middle and close to the bottom) and mixed by hand to get a representative sample of about 200 g from each reactor, which was distributed to three different laboratories for analyses of pH, moisture content (MC), ash content; total organic carbon, total N and microbiological parameters, *E. coli*, total coliforms and *Enterococcus* spp.

The degraded material was calculated from the increasing proportion of ash in the dry matter of the compost material according to Haug (1993) (Eqn. 12).

$$k_m = \frac{(Ash_p\% - Ash_m\%)100}{Ash_p\%(100 - Ash_m\%)} \qquad \text{Eqn. (12)}$$

where k_m is the percentage of organic matter degraded during the treatment; Ash_p is the ash content of the product (%); and Ash_m is the ash content of the feed substrate mixture (%).

Table 9. *Characteristics of substrates and composts and of the process in Paper III (Experiments A, B and C)*

Parameter	Experiment A[a]			Experiment B[b]					Experiment C[c]				
	F:FW = 1:0	F:FW = 1:1	F:FW = 1:3	F:FW = 1:0	F:FW(u) = 1:0	F:FW = 1:1	F:FW = 1:3	F:FW(f) = 1:3	F:FW = 1:0	F:FW(u) = 1:0	F:FW = 1:1	F:FW = 1:3	F:FW(f) = 1:3
Wet weight (ww), kg	165	169	190	170.5	173	161	185	203	172	173.5	167	199	208
Bulk Density, p_s, kg/m^3	782	801	900	789	801	813	934	1025	796	803	843	1005	1051
Initial DM, % ww	55	48	43	52	53	37	30	28	57	57	33	31	27
$pH_{initial}$	9.8	7.9	7.3	9.3	9.5	7.7	6.4	6.0	9.7	9.7	8.6	8.5	7.6
pH_{min}	9.1	7.9	7.3	9.3	9.3	7.0	5.0	4.8	9.1	9.1	6.1	5.4	5.5
$T_{max, mean}$, °C	60.9	67.4	73.2	60.0	40.3	71.3	41.0	42.5	65.9	48.6	37.2	36.5	39.0
$Ash_{initial}$, % TS	43	33	31	77	77	61	54	54	68	68	59	51	54
Degraded OM (k_m), %	30	61	72	36	27	71	25	19	40	17	34	36	30
Energy ratio (E), Cal/g	1174	2104	2093	501	382	903	276	189	943	409	382	442	281
Water ratio (W)	5	3	3	11	15	6	20	29	6	14	15	13	20

[a] Compost in Experiment A included 10 L sawdust and 1 L old compost in each reactor

[b] Compost in Experiment B included 2 kg sawdust and 1 kg old compost in each reactor

[c] Compost in Experiment C included 5 kg sawdust and 2 kg old compost in each reactor

$T_{max,mean}$ = maximum mean temperatures taken at 5 points in the reactor, DM = dry matter, OM = organic matter, TS = total solids

In calculating E, the heat value (H_s) was estimated at 23.24 MJ/g of degraded V_S (=5550 Cal/g of degraded V_S) (Haug, 1993). In calculating E and W, measured degradation was used. Food waste in Experiment A = peas, rice, bananas, beans, bones (some meat), banana, maize meal (*posho*) and potatoes; in Experiments B and C = maize meal (*posho*), some rice and beans. Experiment A was conducted April-June 2005; Experiment B July-September 2006 and Experiment C October-December 2006. The food wastes reflected the foods eaten at schools during collection. FW(f), fresh food waste (collected and used on the same day); FW, food waste collected over a period of two weeks and mixed. In Experiments B and C, composts with just faeces/ash mixture were repeated twice, F:FW = 1:0 which was insulated and F:FW(u) = 1:0 which was non-insulated. n.d. = not determined.

The energy ratio E was calculated from the ratio of the heat released to the weight of water (Eqn. 8) and the water ratio W was calculated as the ratio of the weight of water to that of degraded organics (Eqn. 7), both according to Haug (1993).

Temperature changes in Experiment III

Temperatures increased rapidly in all composts reactors in Experiment A as shown in Fig. 14 and discussed in Paper III.

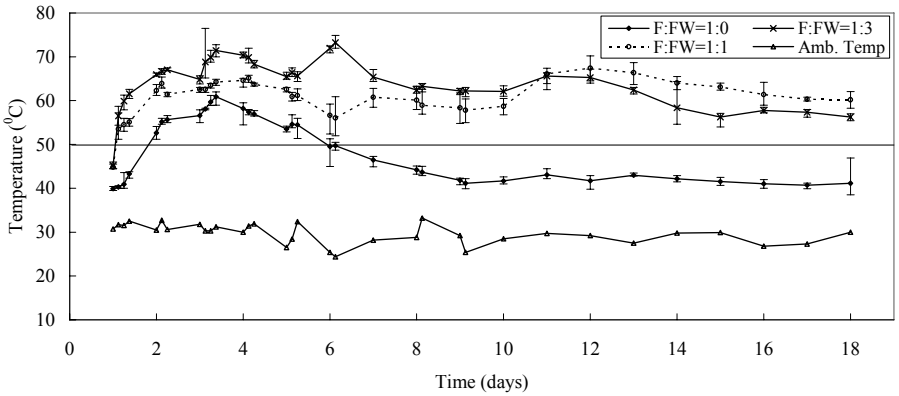


Fig. 14. Temperature changes in the three composts [mean, maximum and minimum of five measurement points shown].

Temperature variation in Experiment B is shown in Fig. 15 and discussed in Paper III. In this experiment, temperature change in F:FW = 1:0 was fast, in F:FW = 1:1 slow and in the F:FW = 1:3 and F:FW(f) = 1:3 (not shown), never increased to sanitising temperatures (>50°C).

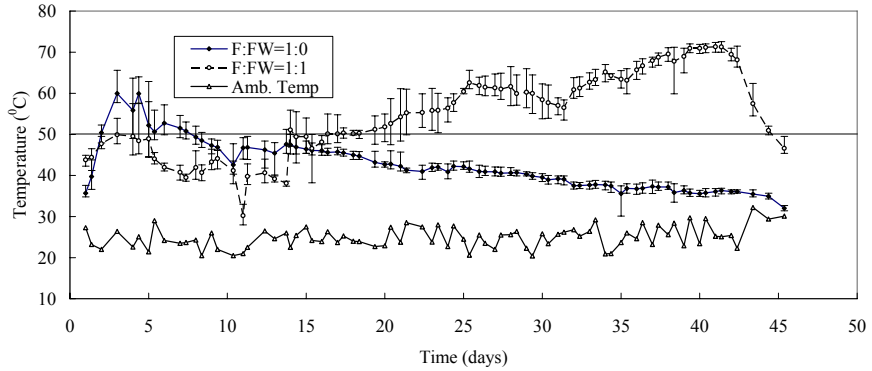


Fig. 15. Temperature changes in the composts reaching sanitising temperatures in Experiment B [mean, maximum and minimum of five measurement points shown].

In Experiment C, only the F:FW = 1:0 compost heated to sanitising temperatures (Fig. 16). Other compost mixtures did not attain 50°C, and were occasionally colder than ambient air (Data not shown).

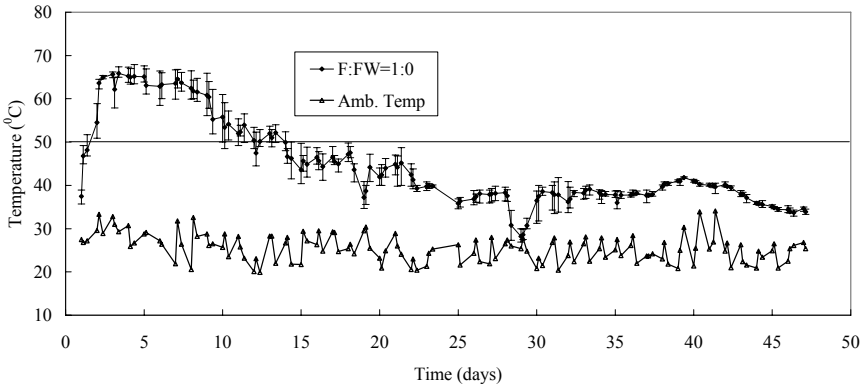


Fig. 16. Temperature development of the compost reaching sanitising temperatures in Experiment C [mean, maximum and minimum of five measurement points shown]

Insulation

Only insulated composts reached sanitising temperatures and the highest temperatures did not always occur along the centre-line (Table 10). The corners sometimes and during start periods were slightly hotter than the centre-line. Only insulated compost runs reaching sanitizing temperatures had centre temperatures on average 0.3°C-2°C higher than in the corners (Table 10). Therefore, insulation is important for achieving sanitising temperatures, minimising low temperature zones and attaining rapid temperature rise and disinfection of the material (Haug, 1993; Epstein, 1997; Vinnerås *et al*., 2003).

Table 10. *Temperatures and periods when temperatures above 50°C were maintained in Experiments A, B and C*

Exp.	Compost mix	[a]$T_{C,\,max}$ (°C)	[b]T_{max} (°C)	[c]Mean 4T (°C) (T_C - $T_{corn,Av}$)	t (days) when T_{av}>50°C[d]	Ambient temp. (°C)
A[e]	F:FW = 1:0	61.6	62.0	0.8	4	Min 24.4, mean 29.6, max 33.2
	F:FW = 1:1	67.1	70.2	0.3	>18	
	F:FW = 1:3	72.5	76.5	0.5	>18	
B	F:FW = 1:0	65.6	65.6	1.9	6	Min 20.4, mean
	F:FW = 1:1	72.0	72.6	1.8	25	24.9, max 32.2
C	F:FW = 1:0	67.9	67.9	1.5	12	Min 24.4, mean 29.6, max 33.2

[a]$T_{C,\,max}$ is the maximum centre-line temperature recorded during the measurement period
[b]T_{max} is the highest of the five temperature measurements taken in the compost over the measurement period
[c]Mean 4T (T_C - $T_{corn,Av}$) is the mean of the differences between centre-line temperature and mean corner temperature
[d] 50°C is the sanitising temperature. Mixing was carried out twice a week when temperatures were above 50°C
[e] Continuous temperature measurement in Experiment A was carried out over 18 days only

Moisture content

In Experiments A, B and C, composts with initial moisture in the range 38 to 57% rapidly achieved self-heating to sanitising temperatures. None of the composts with initial moisture content above 63% reached sanitising temperatures. At 63% initial moisture content, sanitising temperatures were reached, but slowly.

Energy ratio E and water ratio W

In all composts in Experiment A, in the F:FW = 1:1 compost in Experiment B and in the F:FW = 1:0 compost in Experiment C, E was >700 cal/g and W was <10, meaning that the composts met the thermodynamic rules of thumb for well functioning composting (Haug, 1993). In the F:FW = 1:0 compost in Experiment B, E was <600 cal/g (E = 500 ca/g), and W was 11 (>10) meaning that this compost contained slightly more water and less energy than estimated to be required to achieve temperature elevation and water evaporation.

Organic matter content and degradation

In Experiments B and C, the dry faeces/ash (F:FW = 1:0) composts low in organics (high ash content, 68%-77%) attained sanitising temperatures. However, 77% ash content seems close to the limit, as E and W ratios for this compost were close to the values needed according to the rules of thumb.

The degradation was higher in composts with food wastes than in those without, in addition to larger content of organics. Where sanitising temperatures were attained, the composts with food wastes degraded 1.5 to 2-fold more than those that did not contain food wastes. This meant that faeces/ash composts containing food wastes released more energy, which was shown by sanitising temperatures being maintained longer (Table 10).

pH

Composts with initial pH less than 6.5 did not self-heat. The compost with pH slightly less than 8 (pH = 7.7) experienced relatively larger changes in pH from the start, occasionally falling to about 7, but after three weeks, the pH stayed in the region of 8.5 to 9.7. Composts with initial pH>9 experienced little change in pH even from the start.

Sanitation with respect to indicator microorganisms

In Experiments A, B and C, *E. coli* and total coliforms were reduced to below detection in composts that maintained sanitising temperatures for at least six days. The times corresponding to no detection of *E. coli* and total coliforms ranged between 3 and 12 days in all composts in Experiments A, B and C. When the time >50°C was maintained was shorter than 6 days, total coliforms were detected after more than one month of composting. *Enterococcus* spp. was detectable on Day 43 and on Day 40 in composts in Experiments A and C even though these compost maintained sanitising temperatures for 4 days and 12 days respectively. This indicated that the composts were not properly sanitised. In composts in

Experiments A and B, where sanitising temperatures were maintained for >18 days and 25 days respectively, no *Enterococcus* spp. was detected in 18 days and 40 days respectively.

Discussion

Incineration of faeces (Paper I)

According to Shaaban (2007), the advantages of incineration are that it: a) Potentially destroys any material containing organic carbon including pathogens; b) typically reduces the volume and mass of material that must be disposed of in landfills by 80-95%; and c) allows heat of combustion to be recovered and used to generate steam or hot water. An added advantage with incineration in an ecosan system is that the ash can be recycled as cover material in toilets.

The disadvantages of incineration include the handling of initially unsanitised faeces/ash mixtures; the need for preparation to dry them to low moisture content (about 10% and preferably less), which was shown in Paper I; and bad smells when the moisture is higher than 10%. There is also a large risk of air pollution by furans and dioxins. Inhalation of smoke that comes out of the incinerator, when the chimney is not long enough or when the material is not dried to MC≤10%, might present health problems. Furthermore, incineration of faeces with large amounts of loose ash proved problematic. For successful incineration of faeces/ash without sieving, a modified incinerator would be needed. In addition, when incineration is performed the N, S and plant-available P are largely lost, and thus incineration is not of interest when reuse in crop cultivation is desired. However, incineration can be of interest in special situations with dense populations where space for agricultural reuse of treated faeces is limiting.

There is a challenge in drying faeces to attain a moisture content of 10% or less, which should be aimed at to reduce the strong smells that may be encountered during incineration at higher moisture content. If there are no cultural beliefs against such handling of faeces, it should be possible to dry them, especially in the tropics where the days are usually warm throughout the year. However, as there are periods of rains, which are sometimes prolonged, there might be a need to provide a store/shelter where faeces/ash mixture can be bagged and stored during periods of rains and/or of no sunlight. If drying of faeces/ash and incineration of them is acceptable to the community, it should be a feasible option.

Low cost incinerators, like the one that was used in Paper I, can be easily fabricated in local workshops and the materials required, *i.e.* steel sheets, can easily obtained. The incinerator costs about UGX. 450,000/= (USD 230). An incinerator costing this amount can serve a community estimated to comprise about 500 people, with the requirement for burning performed occasionally when the faecal mixture has been dried. As such an incinerator does not have to be used daily, it can also be utilised to incinerate community solid wastes that have to be handled by incineration. Therefore, it can be multipurpose, and the cost of the

incinerator can be shared amongst the community using it. It should be affordable, given that for a community of 500 persons, approximately UGX 900 (about half a dollar) is needed per person. Community acceptance must however be explored.

Insulation during composting (Papers II & III)

Composting experiments at the 78-L scale and at the 216-L scale showed that insulation is relevant for reaching thermophilic temperatures and maintaining them for sustained periods, even in the tropics (Papers II & III). The insulation decreases loss of internally generated heat by conduction and radiation. When composting was performed without insulation, temperatures hardly increased by 15°C above ambient temperature. The results with insufficient increase in temperatures in non-insulated composts agree with the findings by Karlsson & Larsson (2000), Björklund (2002) and Vinnerås *et al*., (2003). Heat loss from the non-insulated composts is the probable reason for the low increase in temperature in their experiments. Composting in large reactors (216-L) and much insulation (75 mm) produced higher temperatures (Paper III) compared with composting in smaller reactors (78-L) and less insulation of 25 mm (Paper II). Both the scale and the insulation probably contributed to this result.

The compost reactors used in the experiments were insulated with styrofoam provided all around the compost. Amongst the low income earners in Uganda, insulation could be provided using styrofoam. Styrofoam packaging material is considered waste material after goods have been unpacked and it is common to find pieces of styrofoam of varying thickness and shape in the normal streams of waste. Therefore, where a number of pieces can be found, they can be put together and tied onto compost reactors, using sisal strings, or even banana fibre. Styrofoam can also be used for filling the gap in a double wall structure that can be built around the compost reactor to provide insulation.

Composting heaps can be insulated using materials like tarpaulin or heavy duty polythene, applied as a cover to the heap. As tarpaulins or heavy duty polythenes are flexible, *i.e* they adopt the outer shape of the compost heap, they provide good cover for the compost, reducing both the heat and water loss. Another way could be to apply a layer of soil or old compost to act as an insulator to reduce heat and water losses. However, the effectiveness of these suggestions to provide insulation need to be investigated before being implemented on a regular scale.

Influence of moisture content (Papers II & III)

In Paper II, the MC was mainly 40-60%, even though MC of 64% was measured in one of the experiments at the start, and on Day 9 in one of the experiments. However, no rate limitation seems to have occurred as a result of this MC. In Paper III, composts with initial MC<60% in Experiments A, B and C composted well, with rapidly rising temperatures. Composts with MC>60% were inhibited and no composting occurred, apart from one experimental reactor in Experiment B (Paper III), where the initial MC was 63% and sanitising temperatures were attained. However, in this compost (F:FW = 1:1 compost in Experiment B), there

was a long delay in reaching sanitising temperatures, suggesting that the initial MC of 63% probably negatively affected the start of the compost process. Optimum MC for thermal composting is between 40-60% (Golueke, 1977; Haug, 1993; Chiumenti *et al*., 2005) while Suler & Finstein (1997) and Liang *et al*. (2003) report optimum MC in the range 50-60%. According to Golueke (1977), MC>60% in composts affects particle aggregation and air-filled porosity, which limits transport of the oxygen necessary for the composting process. This is the probable reason why most of the composts containing food wastes and MC>60% in Paper III (Experiments B and C) did not reach sanitising temperatures. In Experiment C, the compost with starting MC as low as 43% had a fast rise in temperatures, while none of the composts with MC>65% in this experiment attained sanitising temperatures. This shows that it can be better to start the compost process somewhat drier and then add water when needed, than to start with a high MC that may inhibit the compost process. In Paper III, the MC of composts with initial MC>63% remained high, causing noticeable waterlogging. The composts in fact became a wet paste. Spreading the compost mixtures on a polythene sheet and drying them by air reduced MC to about 50% in Experiment B and to <60% in Experiment C. However, the compost substrates had lost their structure, they looked like a cake and did not heat up even after this. The use of the fist test or visual inspection of the starting compost to determine whether it has the right moisture to start up the compost process proved tricky, especially for the composts with food waste. In the food wastes, the water was initially kept in intact cells and was not easily visible or squeezable, but when the cells started to disintegrate, the moisture was released and the material turned into a waterlogged paste.

Energy ratio E and water ratio W (Paper III)

According to the rules of thumb derived by Haug (1993), composts with favourable energy ratio (E>600 cal/g) and water ratio (W<10) meet the thermodynamic requirements for temperature elevation and water evaporation. These rules of thumb were met by all composts in Experiment A, the F:FW = 1:1 in Experiment B and the F:FW = 1:0 in Experiment C. These composts also heated to sanitising temperatures (Paper III). The F:FW = 1:0 compost in Experiment B had E=500 cal/g, close to 600 cal/g and W was 11, *i.e.* just over 10. Furthermore, this compost (F:FW = 1:0 in Experiment B) attained sanitising temperatures. The equations for determining E and W are sensitive to small changes in ash content and additionally, just a literature value was used for H, the heat released when organic matter is degraded. This shows that E and W are valuable criteria, but that their uncertainty was fairly large, which was shown by the compost actually heating up.

Influence of organic matter and degradation (Paper III)

In Paper III, it was shown that successful composting can be achieved even up to an ash content of 77% of TS. This seems, however, based on the E and W, to be close to the limit. Composts with more ash and less organic matter will hardly fulfil the E and W criteria. The ash content of 77% of TS, corresponding to a low

content of organic matter of 23% of TS, was achieved by sieving the faeces/ash on a quarter-inch (6.35 mm) aperture sieve.

Sieving out the ashes from the faeces/ash mixture is unhygienic and exposes the workers to health risks. A better alternative can be to apply a mixture of sawdust and wood ash during toilet use. A mixture of sawdust 40-50% (ww) and 50-60% wood ash (ww) will contain at least about 25% (TS) of organics, which in these experiments has been shown to be high enough to attain sanitising temperatures. Thus, with this mixture as cover material, no sieving should be needed.

In Paper III, the degradation in composts attaining sanitising temperatures was more than 60% in composts comprising of faeces/ash and food wastes, while it was 30-40% in composts with just faeces/ash. The large degradation that was attained in composts with faeces and food wastes was, in addition to the prolonged times at >50°C, a good indication that more heat was released, increasing the chance of attaining safe sanitation. Faeces contain little easily degradable material as this has been taken up by the human intestine (Lentner *et al*., 1981). To increase the easily degradable organics in the substrate and thus to enable it to sustain sanitising temperatures for a sufficient duration for safe sanitation, food wastes can be added (Paper II and Paper III).

Even though faeces/ash mixtures without food wastes gave rise to quick temperature elevation from the start, they did not maintain sanitising temperatures for a sufficient duration to attain sanitation. This was linked to lower fraction of organics, which led to exhaustion of the easily degradable organic matter, resulting in a temperature decrease that reached below 50°C in less than two weeks. Faeces/ash that contained food wastes and that functioned well gave a fast increase in temperatures and maintained sanitising temperatures longer as a result of more available organic matter for the compost microbes to degrade.

Influence of pH (Papers II and III)

The rapid increase in temperatures in all composts in Experiment A at pH>9 is indicates that pH up to 9 does not threaten the composting process (Papers II and III). The pH decreased during the first days of the composting and later rose. This agrees with Beck-Friis *et al*. (2003), Sundberg *et al.* (2004) and Chiumenti *et al*. (2005) and is explained by initial formation of organic acids. Beck-Friis *et al*. (2003) attributed the pH increase after the lag phase to consumption of organic acids as well as ammonium production. Organic acids are suppressive to microbial activity and growth at low pH (Cherrington *et al*., 1991; Sundberg *et al*., 2004). This can be one reason why the temperature never increased beyond 42°C in composts with low initial pH (<6.5). The pH in these composts also decreased to <6 by Day 3 (Paper III), which agrees with Sundberg & Jönsson (2005).

Temperature increase

In a well functioning compost, temperature should rise to thermophilic (>45°C) in hours to a few days (Haug, 1993; Chiumenti *et al*., 2005). This occurred in the

present study in composts that thermally functioned well (Papers II and III). For composts, there is a positive feedback mechanism that depends on the substrate composition. It is this positive feedback mechanism that results in a rapid response to temperature when the initial moisture, pH and nutrients are not rate-limiting. The temperature rises in composts as a result of the activity of microorganisms and in turn causes higher microbial activity, which further increases the temperature and so on.

Temperatures and times needed for reduction of different pathogens

According to Feachem *et al*. (1983), the time-temperature combinations lethal to all pathogens excreted in faeces including the most resistant *Ascaris* (but with the possible exception of hepatitis A virus at short retention times) are: 1 hour at ≥62°C, 1 day at ≥50°C, and 1 week at ≥46°C. Cornell Waste Management (2005) analysed data from many authors and compiled data (Table 11) on the survival and/or inactivation times of pathogens in compost or manure, and on the D-values of pathogens at various temperatures in various foods (Table 12). However, Table 11 lacks information both on the temperature distribution within composts *i.e.* the size of the low temperature zones, and on the number of mixings, which both are important for the survival as, *e.g.* shown in this thesis.

Table 11. *Survival and/or inactivation times of pathogens in compost or manure (adapted from Cornell waste Management Institute, 2005)*

Pathogen	Temp (°C)	Time	Source	Comment
S. enteriditis in compost	45	2 days	Lung *et al*., 2001	Undetectable
E. coli in compost	45	3 days	Lung *et al*., 2001	Undetectable
E. coli in pig manure	50	24 hours	Turner, 2002	Inactivation
E. coli in cattle manure	50	14 days	Jiang *et al*., 2003	None detected
E. coli in pig manure	55	2 hours	Turner, 2002	Inactivation
Faecal *Enterococci* in manure	55	2.1 hours	Lund *et al*., 1996	4log reduction
Salmonella in compost	55	80 days	Shuval *et al*., 1991	None detected
Faecal coliforms in compost	55	<120 days	Shuval *et al*., 1991	5log reduction
Faecal streps in compost	55	<120 days	Shuval *et al*., 1991	4log reduction
E. coli in manure compost	60	24 hours	Hess *et al*., 2004	Undetectable
Total coliforms in compost	60	24 hours	Hess *et al*., 2004	Undetectable
S. Typhimurium in food compost	60	9 days	Droffner & Britton, 1995	Survival time
E. coli in food compost	65	9 days	Droffner & Britton, 1995	Survival time
M. tuberculosis in biosolids	70	20 min	E & A Environmental Consult, 2001	Destruction

According to Tables 11 and 12, the survival time of most pathogens at 70°C is very short. The temperatures attained during the incineration of source separated faeces were much higher than this (Paper I), implying that when the design is such that all the material reaches high temperatures, the risk of surviving pathogenic microorganisms should be extremely low. For composting, temperature-time relationships are often quoted. In Sweden, *e.g*. the voluntary rules for certification of compost from source separated household waste distinguish between open and closed windrow composting as follows: In open windrow composting, the rule

calls for 55°C during two periods of two weeks' duration or 65°C during two periods of one week duration to ensure good hygienic compost quality (Beck-Friis *et al.*, 2001). In closed systems, the rules suggest 65°C during two days and a total retention time of 10 days at 55°C or higher (Beck-Friis *et al.*, 2001). Our results, which are supported by microbiological analyses of *E. coli*, total coliforms and *Enterococcus* spp., found that about two weeks of composting at >50°C can be sufficient to attain sanitation in well operated and well performing composts (Papers II & III). This agrees well with Schönning & Stenström (2004). It took a shorter time (<12 days) to attain a state of no detection for *E. coli* and total coliforms. With respect to *Enterococcus* spp., sanitation was not shown in composts that maintained >50°C for 12 days or less *i.e.* after more than one month (Paper III). However, Vinnerås (2007) explained that *Enterococcus* spp. has a high survival in composts, and questioned it as an indicator of the die-off of *Enterobacteriaceae*.

Table 12. *D-values of pathogens in various foods (adapted from Cornell Waste Management Institute, 2005)*

Pathogen	Temp (°C)	Time (min)	Source
Escherichia coli in turkey	55	8.0	Ahmed *et al*., 1995
Escherichia coli in pork sausage	55	8.5	Ahmed *et al*., 1995
Escherichia coli in chicken	55	9.3	Ahmed *et al*., 1995
Escherichia coli in minced pork	55	33.4	Murphy *et al*., 2004
Salmonella in minced pork	55	45.9	Murphy *et al*., 2004
Listeria monocytogenes in minced pork	55	47.2	Murphy *et al*., 2004
Escherichia coli O157:H7 in minced beef	59	1.2	Doyle & Schoeni, 1984
Clostridium perfringens in minced beef	59	5.2	Roy *et al*., 1981
Escherichia coli O157:H7 in minced beef	60	0.5	Ahmed *et al*., 1995
Escherichia coli in pork sausage	60	0.5	Ahmed *et al*., 1995
Escherichia coli in chicken	60	0.5	Ahmed *et al*., 1995
Escherichia coli in turkey	60	0.6	Ahmed *et al*., 1995
Salmonella in minced beef	60	0.8	Craven & Blankenship, 1983
Streptococcus faecalis in fish cakes	60	11.3	Mitscherlich & Marth, 1984
Streptococcus faecalis in tuna pie	60	11.3	Mitscherlich & Marth, 1984
Streptococcus faecalis in minced beef	60	12.2	Mitscherlich & Marth, 1984
Streptococcus faecalis in fish fingers	60	15.7	Mitscherlich & Marth, 1984
Escherichia coli in minced pork	70	0.1	Murphy *et al*., 2004
Salmonella in minced pork	70	0.1	Murphy *et al*., 2004
Clostridium botulinum in minced turkey	70	41.7	Juneja *et al.*, 1995

In these studies, survival of e.g. *Enterococcus* spp could be a result of incomplete mixing and survival in low temperature zones as it was hard to achieve complete mixing in the large compost reactors. This shows the importance of good design (insulation) and well planned material handling (good mixing and preferably no faecal matter in low temperature zones).

Practical considerations

The investigations in this thesis were performed using low-tech systems. A locally fabricated small incinerator made out of steel sheets was used in incineration experiments (Paper I). The incinerator was fired using a local stove, also made out of steel sheets and using sawdust, a few drops of kerosene (paraffin) and a

matchbox for lighting and starting up the fire. The incinerator and stove are low-tech even though they require local technical competence to fabricate and the incinerator also requires local technical competence to operate.

Composting was performed in locally fabricated 78-L (405x405x475 mm^3) compost reactors and in 216-L (600x600x600 mm^3) compost reactors. These require local technical competence by a carpenter to fabricate. Operation and monitoring also requires local technical competence. Measuring equipment in the form of a weighing scale (for moisture measurement) and a thermometer is strongly recommended.

A carpenter conversant with basic carpentry work can fabricate the compost reactors. Cutting, sizing and application of the styrofoam on the sides of the compost reactors can also be accomplished by the same personnel. The trickiest part of the composting is at start up. Solid waste materials hold water in intact cells and it is not easy to tell visually or by the fist test whether the starting substrate containing food waste has suitable moisture content or not. However, addition of water may be delayed from the start, as it is better to start the process drier instead of risking starting too wet. The mixing of the materials does not require skilled personnel but can be done by a person capable of using a weighing scale (perhaps 10-200 kgs) or some container of perhaps 10-50 L to enable the batching by weight or by volume. There is need for mixing space, for example, a polythene sheet, and spades for mixing. However, where available or affordable, a mixer similar to the concrete mixer could be used. Gumboots and gloves are also recommended, if affordable.

Analyses of important process parameters other than temperature require good laboratories and equipment such as pH meters, dry matter ovens and organic matter furnaces. Pathogen die-off studies require good microbiology laboratories as well as trained laboratory staff for performing the analyses.

Scale effects

In 78-L reactors, it was not possible to attain sanitising temperatures (>50°C) by composting source separated faeces with ash mixture without any food waste (Paper II), but composting experiments in 216-L reactors demonstrated that this was possible (Paper III). However, what appears to be consistent in the experiments is that during composting of source separated faeces alone, sanitising temperatures were either not attained at all (Paper II) or they were sustained for only a few days (4-12 days) when faeces/ash were composted without adding food waste (Paper III). This was probably because the faeces/ash mixture did not contain enough easily degradable organic material and thus this was quickly exhausted by the compost microbes. A relatively stable and sustained high temperature enabling safe sanitation was obtained when composting source separated faeces/ash mixture with food waste in equal wet volume (Paper II) and in equal wet weight ratios (Paper III).

Future Work

This study focused mainly on treatment methods for the faecal part. Incineration was performed on sun-dried samples (Paper I). As the faeces were collected from urine diverting ecosan toilets where ash had been used as additive material during the collection phase, starting the fire was problematic due to the abundance of fine, inert ash that fell through the grate and extinguished the fire if not sieved out (Paper I). Incineration trials on faeces collected from toilets where ash mixed with some sawdust or ground leaves are used as cover material during the collection phase are needed in future studies to determine whether the incineration is improved under such conditions. Furthermore, before implementation, studies are needed on how to design the incineration in such a way as to positively ensure that no material can pass through the process, fall through the grate, without attaining high temperatures. Investigations of pathogens (different types of bacteria, viruses, protozoa and helminths) in the outgoing material may be needed to verify that no material can escape the process without reaching sufficiently high temperatures.

The faeces that had been prepared by sun drying for the incineration process were tested for microbiological parameters, but no *E. coli* or *Enterococcus* spp. were detected (Paper I). The sun drying could have contributed to a reduction of the organisms. Therefore, a future study aimed at assessing the possibility for pathogen destruction by sun drying the faeces in the sun would be interesting.

During studies on the composting of faeces (Papers II and III), it was found that faeces/ash mixtures when mixed with food wastes attain and maintain sanitizing temperatures longer than when food wastes were excluded. This was explained by the increased fraction of organics of the faeces/ash mixtures when food waste was added. One other possibility to increase the organics of source-separated faeces and also to eliminate the need for sieving is to replace the wood ash by sawdust or a mixture of wood ash and sawdust as cover material(s) during the collection phase. The extent to which the composting process improves or changes as a result of use of sawdust or a mixture of wood ash and sawdust is one possible future study that would be highly interesting.

The material handling in and around the compost need to be studied with the purpose of working out a plan on how to handle the material in such a way that the risk of spreading of pathogens is minimised.

Further study is needed to determine the social and cultural acceptability, as well as impediments regarding the use and adoption of the different treatment methods for the faeces that have been performed and those that are planned. Such studies are also needed for the re-use of the produced products, compost and ash.

A substance flow analysis to assess the resources requirements (inputs), the sanitised products (outputs) and any environmental effects associated with the different methods of treating human faeces would be an interesting study.

Conclusions

Incineration

- Maximum water content for successful incineration of faeces, without excessive and unbearable odour, was approximately 10%. At lower water content, the odour was distinct but bearable, like burning cow dung.
- A reduction in mass of faeces/ash mixture of up to 36% was achieved after incineration. It was limited by the high initial ash content of the mixture, 81-91% on dry matter basis. For just the organics in faeces and toilet paper, the calculated mass loss was in excess of 90%.
- Nitrogen loss of 90%-94% and a loss of available phosphorus of 70-94% mean that incineration is not a good method where re-use of nutrients is a high priority.
- Proper design, construction and operation of the incinerator such that all material is burnt at high temperature is necessary to ensure that there is no risk of pathogens in the ashes, especially if they are to be used as additives in the toilets. This is also necessary for achieving low emissions of hazardous gas emissions.
- It is possible, using a locally fabricated incinerator equipped with a local stove, to incinerate faeces. Further studies need to be undertaken to find appropriate means of reducing smells and hazardous emissions from local incinerators and the material handling around it.

Composting

- To successfully thermally compost dry source separated faeces/ash and attain sanitising temperatures (>50°C) to disinfect it, the compost should be well insulated.
- The initial fraction of organic matter should not be below 25% for successful composting of mixtures of faeces/ash.
- Composts with food waste sustained sanitising temperatures for more than two weeks but not more than 12 days when food waste was absent.
- The initial moisture content when composting faeces/ash with or without food waste should be in the range 40-60%.
- Estimating MC in a fresh food waste mixture is difficult as the water is mainly contained in intact cells, which later disintegrate, resulting in loss of structure and increased amounts of free water. Hence it is better to start with a somewhat dry compost and add water than to risk starting with a too wet substrate.
- In the 78 L reactors, where sanitising temperatures were maintained for at least a week, neither *E. coli* nor *Enterococcus* spp. were detected from Day 7 and 11, respectively. The reduction of >3$\log_{10}$ for *E. coli* and >4$\log_{10}$ for *Enterococcus* spp. in combination with the long period of temperatures above 50°C indicates that the compost was sanitised.

- In the larger 216 L reactors where the composts held >50°C, sanitation with respect to *E. coli* and total coliforms was attained in mixtures of faeces/ash either separately or with food waste.
- The importance of good mixing for sanitation is shown by the fact that *Enterococcus* spp. was reduced to below detection after 11 days of composting in 78 L reactors, which maintained sanitising temperatures for only 8 days, but not in the 216 L reactors, where mixing was more difficult, and sanitising temperatures were maintained for 12 days.

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Abbreviations

AMREF	African Medical and Research Foundation
BUCADEF	Buganda Cultural and Development Foundation
CIDI	Community Integrated Development Initiatives
EcoSanRes	Ecological Sanitation Research
MDGs	Millennium Development Goals
NGOs	Non Governmental Organizations
NWSC	National Water and Sewerage Corporation
Sida	Swedish international development cooperation agency
SSWARS	Sustainable Sanitation and Water Renewal Systems
SWTWS	South Western Towns Water and Sanitation
UN	United Nations
WHO	World Health Organisation
WSP	Water and Sanitation programme of the World Bank