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Ecological Sanitation in Uganda: Promotion through Demonstration Facilities and Potential for *Ascaris* Reduction by Free Ammonia Inactivation Using Stored Urine

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Ecological Sanitation in Uganda:

Promotion through Demonstration Facilities and Potential for *Ascaris* Reduction by Free Ammonia Inactivation Using Stored Urine

by

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A thesis submitted in partial fulfillment
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DEDICATION

This thesis is dedicated to my parents, Tom and Deb Trimmer, for exemplifying the dedication, perseverance, and mindful service that I try to emulate in my life, for quietly and confidently supporting all of my endeavors, and for allowing Uganda to steal me away for three years.

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ABSTRACT

As Uganda works to transform itself into an industrialized, middle-income country in the coming decades, the country is faced with a number of problematic trends that could hinder this transition. High population growth and urbanization are quickly forcing small towns to deal with issues of limited space and the aesthetic conditions within sanitation systems, while declining soil fertility in surrounding rural areas calls into question the future nutritional security of the growing population. Ecological Sanitation (Eco-San) systems, which are designed to recover nutrients from human excreta, may help to address these trends.

Improved sanitation coverage in Uganda is currently estimated to be 34%, with most people using either improved or unimproved pit latrines. Eco-San systems, especially Urine-Diverting Dry Toilets (UDDTs, also referred to as composting toilets), have been promoted in the country, but uptake has been slow. Additionally, while UDDTs generally treat human feces to a greater degree than pit latrines and composting toilets (another type of Eco-San system), concerns have been raised as to the inactivation of environmentally persistent pathogens, such as *Ascaris lumbricoides* eggs. This research focused on two potential solutions to the issues of effective promotion and *Ascaris* inactivation, evaluating them in the context of Kalisizo, a small town in southern Uganda.

Demonstration facilities have been reported to effectively convince local stakeholders of the benefits and advantages of UDDTs, thereby increasing long-term uptake of the technology in the surrounding community. However, an unresolved question concerns whether these facilities should be installed in household or institutional settings. The initial effects of demonstration facilities constructed at local primary schools in Kalisizo were evaluated by assessing local knowledge and attitudes regarding UDDTs, both before installation and after several months of operation, through focus group discussions

and key informant interviews. In general, this promotion strategy proved to be successful. After installation, students exhibited a marked increase in knowledge regarding these facilities and their benefits, and opinions were strongly positive. These changes were seen in users of the facilities as well as non-users, and students expressed clear acceptance of using the products of the toilets to fertilize crops. The introduction of an improved sanitation system at the schools also appears to have sparked other improvements related to sanitation and hygiene. In the future, it is likely that students will be compelling representatives for UDDTs within their households and communities.

Regarding the treatment of persistent pathogens, previous work has demonstrated that the elevation of free ammonia levels to levels that can inactivate *Ascaris* eggs can be achieved through the urea addition. In this research, use of stored urine as an ammonia source for treatment of fecal products from UDDTs in Uganda was investigated. Mixtures of stored urine, fecal products from UDDTs, and wood ash were prepared, and treatment conditions (pH, temperature, ammonia concentration) were compared to the results of previous *Ascaris* inactivation studies to determine whether this strategy would be a feasible and effective treatment alternative. Results indicated that a volumetric mixture containing two parts stored urine and one part fecal products could provide 4-$\log_{10}$ inactivation of *Ascaris* eggs after five months of indoor storage or after three months of outdoor storage. This strategy could improve the safety of recovered products while maintaining their agricultural value. Social acceptance of the treatment system appears to be possible with proper education efforts, and a cost comparison showed that this system may be more economically favorable than typical double-vault UDDTs.

CHAPTER 1: INTRODUCTION – A COUNTRY ON THE MOVE

One might say that Uganda is a country on the verge of a transition. Currently, Uganda is considered to be one of the world's least developed nations (UN, 2013a). As with other landlocked countries, its development and access to world markets is hindered by its distance from coastlines and its reliance neighboring countries' infrastructure, political relations, stability, and administrative practices (Faye et al., 2004). However, the country's government has established an overarching policy goal, known as "Vision 2040", that strives to transform Uganda into an industrialized, middle-income nation by 2040 (NEMA, 2010). Uganda's ability to meet this objective will depend on a number of interrelated factors, including trends that are related to population growth, environmental degradation, and climate change. The country's response to these trends could mean the difference between the success or failure of its transformative vision.

1.1. National Trends: Population, Urbanization, Agriculture, and the Environment

Uganda is a relatively small country. According to the CIA World Factbook (2014), the country encompasses an area of 241,038 square kilometers. Compared with some of its closest neighbors, such as Kenya, Tanzania, and the Democratic Republic of the Congo, Uganda seems to be dwarfed. However, as Table 1 shows, while being much smaller in size, Uganda has a population that is not so far behind those of the larger countries. It is also much more densely populated, and it is growing rapidly.

The United Nations Population Division's "medium fertility" scenario estimates that Uganda's population will increase to above 100 million by the year 2050 (UN, 2013a), which would result in a population density of at least 507 people per square kilometer. Along with greater population density, high growth also leads to a greater need food, arable land, water, and energy.

Table 1: Geography and population statistics for Uganda and its larger neighbors

Country	Total Area (km^2)	Land Area (km^2)	Total Population[1]	Pop. Density[2] (ppl/km^2)	Growth Rate[1] (%)	Median Age[1] (yrs)
Uganda	241,038	197,100	35,918,915	182.2	3.24	15.5
Kenya	580,367	569,140	45,010,056	79.1	2.11	19.1
Tanzania	947,300	885,800	49,639,138	56.0	2.80	17.4
D.R. Congo	2,344,858	2,267,048	77,433,744	34.2	2.50	17.9

Data Source: CIA World Factbook (2014)

[1]Population statistics reflect CIA World Factbook estimates for July, 2014

[2]Population density calculated by the author as total population divided by land area

At present, 84% of Ugandans reside in rural areas. However, due to urbanization trends, this percentage will decrease significantly in coming years (CIA, 2014). Between 1980 and 2011, Uganda experienced more than a six-fold increase in urban population (NEMA, 2010). The sanitation situation within these growing urban areas is likely to be a matter of particular concern. The most recent estimates, shown in Table 2, show that 34% of Ugandans have access to improved sanitation facilities, while 23% can access shared facilities that would otherwise be classified as improved (WHO/UNICEF, 2014). It should be noted, however, that the "improved" classification is somewhat misleading. A recent study has found that systems classified as improved were not associated with lower levels of *E. coli*, helminth, and insect contamination. In fact, shared systems were found to be the least contaminated facilities (Exley et al., 2015). Whether they are improved or unimproved, the overwhelming majority of the facilities in Uganda are pit latrines. Due to limited water supplies (Mutagamba, 2003) and high infrastructure costs (Niwagaba and Asiimwe, 2005), water-based sanitation systems, such as septic tanks or centralized sewers, are unlikely to be installed or expanded significantly beyond current levels in many urban centers, especially smaller ones. Furthermore, these systems can cause significant environmental damage. Among currently operating urban wastewater systems in the country, compliance with national discharge standards is estimated to be only 40% (NEMA, 2010).

Table 2: Sanitation coverage in Uganda (2012 estimates)

Sanitation Category	Urban	Rural	Total
Improved Facilities	33%	34%	34%
Shared Facilities	50%	17%	23%
Other Unimproved Facilities	15%	40%	35%
Open Defecation	2%	9%	8%

Source: WHO/UNICEF Joint Monitoring Programme (2014)

It is expected that pit latrines will continue to dominate in most towns, creating challenges related to aesthetics and available space. While pit latrines are a significant improvement over alternatives such as open defecation, pit latrines often provide a dark, malodorous, fly-infested environment that is uncomfortable, potentially unsafe, and possibly harmful to the environment. These drawbacks will only be magnified in settings where people live in close proximity to one another. Moreover, the issue of limited space presents another concern. In Uganda, when a pit is full, the common practice involves capping the old pit and digging a new one in a different location, rather than engaging in the often expensive and logistically difficult process of emptying the pit (Mutagamba, 2003). Digging new pits is unlikely to be a feasible option in densely populated areas (Tumwebaze et al., 2011), while biosolids from latrine pits that have been emptied are sometimes deposited directly into nearby bushes or bodies of water (NETWAS-U, 2011a).

Another major concern involves producing enough food to feed the growing population. The agricultural sector employs approximately two-thirds of Uganda's workforce (NEMA, 2010), and many of these people work on small-scale subsistence farms. As population levels rise, urban areas expand, and more food is needed, farmers are likely to experience greater economic difficulties, due to reductions in available land area and increased damage to the environments on which they depend. Because Uganda's high population does not allow for the periodic restoration of soil nutrients through fallow periods (Nkedi-Kizza et al., 2002), agricultural activities are resulting in a net loss of soil nutrients over time, and feeding a growing population will become increasingly difficult. Other human-induced environmental changes are also causing further nutrient loss. A major example is deforestation, which results from the use of firewood as the primary source of fuel for cooking, local brick production, and other activities. Between 1990 and 2005, Uganda's forest area decreased by 27 percent. If the current rate of deforestation persists, Uganda's forest cover will be completely gone by 2050 (NEMA, 2010).

The loss of vegetation and supportive root structures can also increase soil erosion and the frequency of landslides, while climate change is likely to further exacerbate the situation. Ugandans are already recognizing some of the early effects of climate change in more variable seasonal rainfall patterns (NEMA, 2010), creating concerns for industries, especially for agriculture. In the future, it is expected that rainfall will become more unpredictable and that the likelihood of severe weather events will increase (NEMA, 2010). Severe weather can result in extensive soil erosion.

Already, Uganda's National Environment Management Authority (NEMA) has estimated that 97% of the country's soils have undergone some type of degradation. Some areas have reported topsoil losses of five tons per hectare per year, along with nitrogen, potassium, and phosphorus losses of 85, 75, and 10 kilograms per hectare per year, respectively (NEMA, 2010). In 2002, certain soils in Uganda were shown to have low to deficient levels of macronutrients (Nkedi-Kizza et al., 2002), and rates of fertility loss suggest that these soils are now in worse condition. If these trends continue, crop yields are likely to decline significantly, drastically increasing the potential for food insecurity within the country. NEMA (2010) cites the USDA Global Food Security Assessment 2010-2020, which predicts that 14 million Ugandans will become food insecure by the end of the current decade. This prediction is supported by Food and Agriculture Organization (FAO) statistics, which showed that Uganda's total food consumption increased by an average of 2.8% per year between 2000 and 2008. Over the same period, population increased by 3.2% per year, suggesting that per capita food consumption is declining (FAO, 2012). As in other resource-limited settings, the use of commercial fertilizers is often not a feasible option to boost crop production, since these fertilizers are too expensive for many farmers (Wambui, 2011). It has been estimated that less than 5% of banana farmers in the East African highland regions use fertilizers, a fact also related to high transport costs and low availability of credit (Van Asten et al., 2004).

Considering the manifold issues resulting from these trends, it is likely that a multi-faceted approach will be needed to move Uganda toward its "Vision 2040". Within a broad and integrated strategy, Ecological Sanitation (Eco-San) could have a part to play as a potentially beneficial and sustainable approach to sanitation in the country. The Eco-San concept seeks to address many of the problems surrounding conventional sanitation systems, declining soil fertility, and environmental degradation. Systems based on Eco-San principles have already been promoted in certain areas of Uganda, most commonly in places where soil conditions hinder pit latrine construction, but widespread exposure has not occurred in many other locations, including small towns such as Kalisizo.

1.2. Kalisizo: Sanitation in a Small Town

Located in the southern district of Rakai, which borders Tanzania and Lake Victoria, Kalisizo sits on the main road that connects Uganda's capital city of Kampala to the Tanzanian border. Kalisizo's location within Uganda is shown in Figure 1. It is a growing peri-urban area that retains, and is surrounded by, its rural roots. In Uganda, small towns are defined as having populations between 5,000 and 50,000 (WaterAid/BPD, 2010), and Kalisizo Town was estimated to have a population of approximately 10,400 residents in 2002 (Kalisizo Town Council, 2011). If the surrounding rural areas are included, the total population increases to 32,200 (Uganda Bureau of Statistics, 2011). While Kalisizo is not as large as some other Ugandan towns, its residents are beginning to face problems seen by small town populations throughout the developing world. In some ways, these towns function as interfaces between urban and rural environments, and communities are often forced to handle issues found both in cities and in rural areas. These challenges include poor infrastructure, limited space, depletion of natural resources, and weak economies dependent on agriculture (Breslin, 2002). Figure 2 provides photographs of Kalisizo showing it as a town with both urban and rural characteristics.

Figure 1: Map of Uganda showing the location of Kalisizo (Uganda Bureau of Statistics, 2011)

Figure 2: Urban and rural characteristics of Kalisizo, Uganda (photographs taken by Debra Trimmer). (a) Many small, locally-owned shops line the streets of Kalisizo, showing it to be a growing per-urban area; (b) cattle and other livestock are commonly seen on roads throughout the town, showing that the area's rural roots remain intact.

As mentioned previously, the sanitation situation in these towns is of particular concern. In Kalisizo, a centralized, water-based system is currently not a feasible option. Infrastructure costs would be too high, and the available water quantity would be too low. At present, most households in and around Kalisizo use traditional pit latrines, which, while presenting some risk of groundwater contamination, do not provide an environment quite as problematic as that created by a flushing toilet without enough water. However, as population density increases and available land is reduced, the space concerns related to pit latrines must be acknowledged. Kalisizo is not yet at the point where no more room for new latrines exists. However, in the center of town, plots are becoming crowded, and it is becoming increasingly difficult to locate appropriate latrine sites. In the future, if the country's overall urbanization trend is any indication, the conditions seen in the center will expand outward. Unlike some towns, where space is already at a premium (Kamuteera et al., 2013), Kalisizo has an opportunity to address the issue before it becomes a serious problem.

1.3. Research Goals and Objectives

Eco-San systems provide a sanitation option that can utilize available space more efficiently than pit latrines, while also protecting the town's water supply and the surrounding environment. When these advantages are combined with the potential benefits for neighboring farmers, a persuasive argument can be made for the promotion of Eco-San facilities within the local context of Kalisizo. At this point, then, two questions need to be answered:

1.) What is the best way to promote Eco-San systems to stimulate acceptance and correct operation?
2.) Do Eco-San facilities in the field effectively treat feces, and, if not, can alternative treatment options increase the safety of recovered products?

The research presented here evaluated, within the context of Kalisizo, possible answers to each of the above questions. In response to the first question, the effectiveness of school-based demonstration facilities was assessed according to their ability to promote knowledge, acceptance, and correct operation of Eco-San systems within local communities. Special focus was placed on the role of primary school students as users and advocates of these facilities. Regarding the second question, an alternative treatment process in which stored urine is mixed with feces, resulting in high ammonia concentrations, was evaluated according to its ability to inactivate the most resistant pathogens commonly found in human excreta (*Ascaris lumbricoides* eggs). Specific objectives were as follows:

1.) *Promotion and education through school-based demonstration facilities*

    a. Assess the attitudes and levels of knowledge regarding Eco-San systems in Kalisizo prior to the installation of demonstration units in local primary schools, with a focus on primary school students

    b. Assess attitudes and levels of knowledge several months after installation to determine if the demonstration units increased acceptance and understanding and enabled students to become effective promoters of the facilities

    c. Assess user operation at local primary schools to determine if the demonstration facilities were used correctly

2.) *Treatment of feces using ammonia from stored urine*

    a. Measure treatment conditions in various mixtures of feces, stored urine, and wood ash and compare results with previous pathogen inactivation studies to assess treatment effectiveness

    b. Measure treatment conditions in fecal vault and stored urine samples from demonstration Eco-San facilities and assess treatment effectiveness

CHAPTER 2: GENERAL LITERATURE REVIEW – SANITATION FROM A HOLISTIC PERSPECTIVE

This chapter presents an overview of a number of approaches to sanitation and then goes on to discuss Eco-San systems in greater detail. The drivers and potential benefits of Eco-San systems are described, along with two important concerns related to the research goals and objectives stated in the previous chapter. These concerns include the low level of Eco-San adoption in Uganda despite promotion efforts and the effectiveness of treatment processes within Eco-San facilities.

Sanitation, and, more specifically, the management of human excreta, is an issue that is connected to a number of other areas, including human health, water supply and quality, conservation of resources and the environment, climate change, economics, nutritional security, soil fertility, and population growth. On the global stage, according to 2011 data, an estimated 36% of the world's population lacks access to improved sanitation facilities, and over one billion people practice open defecation (UN, 2013b). In 2012, 280,000 diarrheal deaths were estimated to be caused by inadequate sanitation, and, overall, 58% of all diarrheal diseases were estimated to be caused by the water, sanitation, and hygiene cluster of risk factors (Pruss-Ustun et al., 2014). Major priorities, therefore, are the provision of adequate sanitation facilities and eliminating open defecation (UN, 2013b). However, while the number of people having access to sanitation systems is certainly of great importance, other significant questions concern the way in which those systems interact with and impact resource supplies, economics, food security, human health, and other issues.

2.1. Conventional Approaches to Sanitation and the Need for Change

Throughout the world, two broad categories of sanitation systems predominate. In developed countries, the most common systems are sometimes referred to as "flush and discharge" approaches (Esrey et al., 1998), which include centralized sewage systems and decentralized septic systems. Both of these options are water-based. In septic systems, which are more common in rural settings, water is used to transport human excreta and other waste streams to a septic tank, where primary treatment occurs and solids are removed. The effluent is then discharged into a soil absorption field, where additional biological and physical treatment occurs in the soil media (EPA, 2000). In more densely populated areas, water-based sewers collect the various waste streams and transport them to a central treatment facility, where a combination of physical, chemical, and biological treatment takes place. The effluent is then discharged into local surface water or groundwater, or it is reused. In terms of separating dangerous pathogens from human contact and reducing pathogen levels to an acceptable standard, wastewater treatment systems function well if they are adequately designed and maintained.

To operate effectively, water-based sewage systems require a large supply of water. On average, one person excretes approximately 35 kilograms of feces and 500 liters of urine each year, and, over that period of time, a wastewater system requires approximately 15,000 liters of water per person for conveyance (Esrey et al., 2001). As population continues to grow and water resources become increasingly scarce, many countries will not have a large enough supply of water to meet the needs of centralized, water-based sanitation systems (Werner et al., 2003). Even if the required water is available, this type of system results in the contamination of water that could have been used to meet other needs, and in the production of a much larger amount of potentially dangerous material than if excreta were kept separate from water (Langergraber and Muellegger, 2005). In addition to these water supply and quality concerns, sewage systems are connected to high infrastructure costs and require a large workforce educated in the design, construction, operation, and maintenance of these systems. Additionally, effective treatment often involves significant energy and chemical inputs. Many developing countries are unable to meet these requirements (Esrey et al., 2001).

In Uganda, while some “flush and discharge” systems are seen in urban areas, “drop and store” systems are much more widespread, with the pit latrine being the most commonly used technology

(Uganda Bureau of Statistics and ICF International Inc., 2012). These systems are designed to contain and store excreta in an underground pit. If they are well-maintained, pit latrines can serve as an effective barrier between humans and the pathogens present in excreta, and their simplicity and decentralized nature make pit latrines an inexpensive option for much of the world's population (Gajurel and Wendland, 2004).

While they do not intentionally contaminate water used in conveyance systems, pit latrines do have the potential to affect groundwater supplies. In many situations, pit walls allow liquids to percolate into the surrounding soil (Bhagwan et al., 2008), where nutrients, pathogens and other dissolved or suspended material may eventually reach the water table (Gajurel and Wendland, 2004), especially if pit latrines are not properly sited. For many low-income populations in rural or peri-urban areas, shallow groundwater often constitutes a primary source of drinking water (Werner et al., 2003), meaning that any contamination of groundwater supplies could have significant impacts on local community health. Moreover, pit latrines have a number of limitations related to location. In areas with high water tables, rocky soil, or unstable soil, these facilities become difficult to install (Niwagaba and Asiimwe, 2005). In more densely populated peri-urban or urban areas, available space becomes an issue. When full, pit latrines can be emptied, but the process may require expensive tanker trucks to remove and transport the sludge (Gajurel and Wendland, 2004). If they are not emptied, as is usually the case in Uganda, they must be capped and a new pit dug in another location. With limited space, few suitable locations for excavation are likely to be found (Langergraber and Muellegger, 2005). Additionally, especially when latrines are poorly constructed, the presence of offensive odors and flies, which function as disease vectors, can result in significant nuisance and risk for users (Esrey et al., 2001).

It is important to remember that pit latrines can provide a number of benefits and are a significant improvement over the practice of open defecation. Throughout the world, the installation and use of pit latrines has saved many lives (Breslin, 2002). However, in addition to the drawbacks already mentioned, the rationale behind these systems views urine and feces primarily as waste products, when, in fact, these materials could be used as valuable resources. In most cases, "drop and store" and "flush and discharge" technologies can be considered "linear flow" systems (Esrey et al., 2001), in which the valuable nutrients and organic matter contained within excreta move in one direction. In most cases, flows end with these resources being discharged to water bodies or stored underground, where they are not useful and can cause significant environmental damage.

The loss of these materials and the damage being done to the natural environment, combined with such issues as population growth, climate change, and the depletion of natural resources, point to the need for a change in thinking about sanitation. Global population continues to grow (UN, 2013a), requiring ever greater amounts of food, water, energy, living space, and other resources. However, soil fertility, a prerequisite for food security, is generally on the decline (Esrey et al., 2001). Three-quarters of Africa's farmland has experienced severe soil degradation due to erosion, which partly explains why agricultural productivity on the continent has been stagnant over the past forty years (Mihelcic et al., 2011). This trend of degradation is especially prevalent in developing countries, such as Uganda, where subsistence agriculture predominates. This type of agriculture often depends on the use of naturally-occurring nutrients found in the soil, which are taken up by crops. At low population densities, these nutrients can sometimes be replenished during fallow periods (Nkedi-Kizza et al., 2002), but, considering current population levels and projected future growth, fallow periods are not likely to be feasible in many places. Complete replenishment of nutrients using fertilizer inputs often does not occur, due to the fact that many farmers in developing countries are unable to afford commercial fertilizers (Werner et al., 2003), resulting in soil fertility decreases over time.

Even in countries where fertilizer use is common, projections of natural resource availability suggest that fertilizer production may become much more difficult and expensive within this century. It is well-established that phosphate rock, an essential component of agricultural fertilizers, is not a renewable resource. Estimates suggest that global phosphate rock reserves, which include known deposits that can be exploited without a significant increase in cost, may be exhausted within 60 to 100 years (Werner et al., 2003; Langergraber and Muellegger, 2005; Vaccari, 2011). Currently, it is conservatively estimated that at least 71% of the phosphorus present in a person's body originates from phosphate mining (Vaccari, 2011), suggesting that decreased availability of phosphate rock could have a dramatic effect on food security and nutritional status. The production of commercial fertilizers also requires significant energy and sulfur inputs, supplies of which are also increasingly limited (Langergraber and Muellegger, 2005). The Haber Process, for example, which is used to synthesize ammonia from gaseous nitrogen and hydrogen, requires extremely high temperatures and pressures to force the reactants to dissociate and form ammonia (Modak, 2002). Large amounts of energy are necessary to create the desired conditions.

Other factors further exacerbate declining soil nutrient levels. For example, to feed growing populations, a need for additional agricultural land often causes deforestation. Deforestation is most detrimental to low-income, rural communities (UN, 2013b) and contributes to greater topsoil erosion during rain events, with nutrients contained in the soil being lost in the process. Climate change is also expected to increase the variability of rainfall, and the frequency and intensity of severe weather events could increase (NEMA, 2010), potentially increasing the magnitude of soil erosion even further.

Certainly, environmental policies that curb deforestation, decrease erosion, and mitigate the effects of climate change are critical. Even with these measures in place, however, nutrients taken up by crops are still extracted from the soil when those crops are harvested, and nutrient levels must be replenished. Since commercial fertilizers are not a feasible option for many farmers in developing countries, other sources of nutrients must be found. It is possible that a more holistic approach to sanitation, one in which urine and feces are viewed as potential sources of valuable resources rather than as objectionable waste products, may offer at least part of the solution.

2.2. The Case for Ecological Sanitation

Conventional sanitation systems are designed to protect populations from hygiene risks and to protect the environment from pollution (Langergraber and Muellegger, 2005). When viewed from a certain perspective, these systems can achieve the stated goals if they are well-maintained and operated effectively. However, from another viewpoint, conventional systems “misplace” the resources in human excreta by directing them into water and deep pits, locations where they do not belong (Esrey et al., 1998). In effect, the potential for pollution occurs as soon as human excreta are mixed with water or deposited in deep pits. The example of the natural world, along with a cyclical understanding of the processes occurring within it, shows that, ideally, the nutrients and organic matter contained in human excreta should be returned to soil, the place from which they were taken when harvesting crops (Esrey et al., 1998). Even when conventional sanitation systems are adapted to recover beneficial materials, the cost and energy requirements are significant, partially because these systems were not initially conceived with resource recovery in mind (Gajurel and Wendland, 2004).

Ecological Sanitation (Eco-San) provides an alternative, “closed-loop” approach (Esrey et al., 1998), one which combines the two main goals of conventional systems with the additional objectives of safely recovering valuable materials from excreta and conserving water resources. A summary of the cyclical nature of these systems is shown in Figure 3. This concept of reuse can trace its origins back many centuries. Historically, a number of societies have recognized the benefits of using human excreta to fertilize agricultural land. For example, China has a 4,000-year history of using human excreta, or “night soil”, to fertilize fields (George, 2008), while, over 1,000 years ago in Syria, feces were dried, collected, and sold (Peasey, 2000). In Japan, the town of Edo, which eventually grew into Tokyo, took measures to collect human excreta and return it to farmland, protecting the quality of neighboring streams in the process. Narain (2003) contrasted the practices of Edo with those of ancient Rome, where the Tiber River became polluted and aqueducts were needed to bring clean water from afar.

Modern Eco-San systems build off of these longstanding ideas and acknowledge the importance of cyclical nutrient flows, especially when one considers the global problems of decreasing soil fertility (Esrey et al., 2001) and declining reserves of phosphate rock and fossil fuels used to produce commercial fertilizers (Vaccari, 2011). In both developed and developing countries, Eco-San systems can help to address many of the issues surrounding population growth, climate change, and limited resources. Eco-San facilities can be built as permanent structures, addressing concerns of limited space in urban environments where pit latrines are common (Langergraber and Muellegger, 2005). By keeping excreta separate from water, either in the form of groundwater supplies close to pit latrines or conveyance water in sewage systems, this resource can be conserved and protected from contamination. Finally, the decentralized nature of Eco-San systems, combined with their relatively low energy requirements, can contribute to greater resiliency in the face of climate change. Based on an analysis of embodied energy and carbon footprint, Eco-San systems can become net energy producers over their service life, and resource recovery in these systems can also significantly lower their global warming potential to levels below those of Ventilated Improved Pit (VIP) latrines and pour-flush latrines (Galvin, 2013).

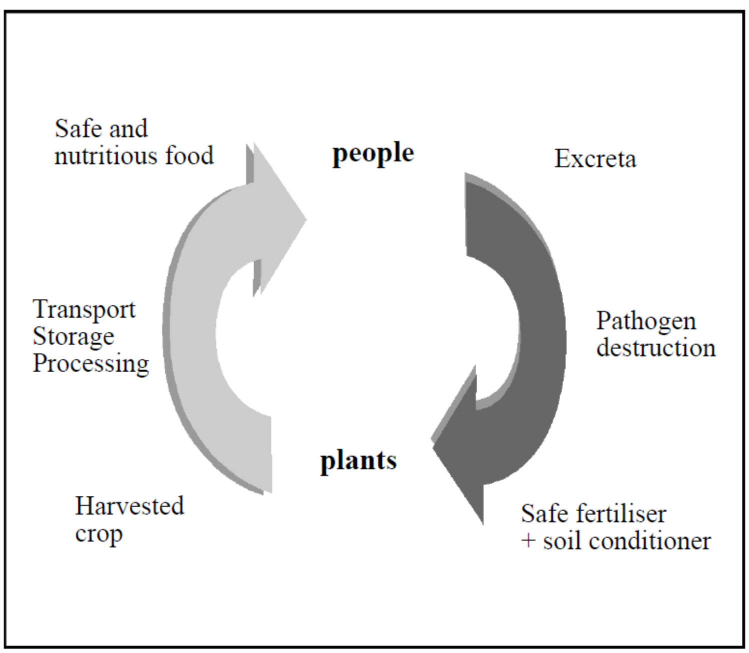

Figure 3: The cyclical nature of nutrient flows in Eco-San systems (Esrey et al., 2001)

The Eco-San concept includes a number of toilet designs and systems that are appropriate for various contexts. In some of these designs, urine is diverted so that it does not come into contact with feces. This practice reflects an additional principle of Eco-San systems known as source separation. As previously discussed, separating excreta from water greatly reduces the volume of material that must be treated while preventing water resources from being contaminated. Separating urine from feces allows each of these substances, which have significantly different properties from one another, to be treated in a specific and appropriate manner. A large portion of excreted nutrients, including 70% to 90% of excreted nitrogen and 25% to 67% of phosphorus, are present within urine (Jonsson et al., 2004; Shaw, 2010), and they are present in water-soluble forms that are easily accessible to plants (Jonsson et al., 2004). Compared to the fecal fraction, urine contains few pathogenic organisms (Esrey et al., 1998), and, if kept separate from feces, urine can be treated simply by storing it, undiluted, in a closed container for a certain period of time. At temperatures of 20°C or higher, a storage time of at least six months is recommended for systems that encompass more than a single household (WHO, 2006). Because of its high nutrient content, urine can be used as a fast-acting fertilizer for many crops, especially those with a high nitrogen demand (Jonsson et al., 2004). A number of studies have shown that the effects of urine fertilization are comparable to those of commercial fertilizer application, and, in some cases, urine application has been found to be more effective (Richert et al., 2010; Shaw, 2010).

In general, smaller amounts of nutrients are excreted in feces, although this fraction does contain significant amounts of phosphorus and potassium (Gajurel and Wendland, 2004). Feces are also high in organic matter, which can improve the structure, buffering capacity, and water retention of soils (Jonsson et al., 2004). However, the pathogen load in feces is quite high. Considerable treatment is necessary to sanitize the material before it can be safely used in agriculture (Langergraber and Muellegger, 2005). The World Health Organization (WHO, 2006) recommends that at least one year of dry storage at ambient temperatures between 20°C and 35°C is needed to inactivate most pathogens, while other sources suggest that this period of time may be insufficient to eliminate more persistent pathogens (Hawksworth et al., 2010; Peasey, 2000).

The numerous Eco-San systems in existence are designed to treat urine and feces, while also presenting users with a facility that is acceptable and easy to operate effectively. Despite the potential advantages and benefits that could result from wider implementation of Eco-San principles, in practice, these systems face a number of operational issues. One of the most prevalent concerns involves promoting these systems to stimulate acceptance and correct operation (Mutagamba, 2003), while another question focuses on whether Eco-San facilities in the field effectively treat feces, especially when considering the most persistent pathogenic organisms (Peasey, 2000). This research focuses on detailed aspects of these issues, as well as potential solutions, within the context of Kalisizo, Uganda.

2.3. Ecological Sanitation in Uganda: a Brief History

In Uganda, promotion of Eco-San systems began in 1997 in the southwest, with pilot projects located in Kisoro and Kabale Districts. These areas were chosen because of conditions, including rocky soils, loose soils, and a high water table, that make construction of pit latrines difficult and problematic (Niwagaba and Asiimwe, 2005). These initial pilots were implemented by the South Western Towns Water and Sanitation Project, with funding from the Ugandan and Austrian governments (Tumwebaze et al., 2011). Simple composting toilet designs that mix urine and feces, such as the Arbor-Loo and the Fossa Alterna (Esrey et al., 2001), were the first types of Eco-San systems to be introduced. However, partly because they resembled normal pit latrines, and partly because the local community considered the reuse of human excreta to be a foreign concept, users did not add the carbonaceous materials necessary to provide adequate conditions for the composting process, and the units failed (Niwagaba and Asiimwe, 2005). Subsequent projects focused on the installation and use of urine-diverting dry toilets (UDDTs), which separate urine from feces and treat the fecal fraction by establishing dry, high pH conditions. These facilities have structural characteristics, such as elevated floor slabs and urine diversion devices, that distinguish them from pit latrines, and they were operated with greater success (Niwagaba and Asiimwe, 2005). Several photographs of UDDT facilities are shown in Figure 4.

Figure 4: Demonstration UDDTs installed in primary schools in Kalisizo, Uganda (all photographs taken by Debra Trimmer). (a) External front view; (b) external side view; (c) external rear view, showing two fecal collection vaults; (d) internal view, showing the urine diversion device

Following these early efforts, in 1998, the Ministry of Water and Environment's Directorate of Water Development integrated Eco-San promotion into its national water and sanitation programs (Tumwebaze et al., 2011). From 2002 to 2004, the Ministry of Water and Environment collaborated with the Ministry of Health to develop a national strategy promoting Eco-San principles, which focused on nutrient reuse and the protection of natural water resources (Niwagaba and Asiimwe, 2005). In most cases, Eco-San systems were promoted in areas with problematic geological conditions similar to those in Kisoro and Kabale, and, while some composting designs were constructed, the majority of Eco-San systems incorporated UDDTs (NETWAS-U, 2011b). More recently, in 2008, the Ministries of Health, Water and Environment, and Education and Sports, with support from the World Bank's Water and

Sanitation Program and the National Sanitation Working Group, established a Ten-Year National Strategy on Ecological Sanitation (2008 – 2018), with the goal of having Eco-San systems account for at least 15% of the country's overall sanitation coverage by the year 2018 (Tumwebaze et al., 2011).

Progress toward this goal is difficult to monitor, with district-level officials often lacking the resources to collect accurate household data (Ofumbi, 2010), and the estimates of Eco-San coverage from different sources are extremely variable. In 2011, for example, while one article reported that the current number of Eco-San facilities in Uganda was 8,000 (Tumwebaze et al., 2011), another source estimated that 30,000 Eco-San units existed in the country (NETWAS-U, 2011b). In either case, though, Eco-San coverage is far below the target set for 2018. Uganda's Demographic and Health Survey is likely to be one of the more reliable data sources, since it is used, in conjunction with other national surveys, by the WHO/UNICEF Joint Monitoring Programme to estimate the country's progress toward the United Nations Millennium Development Goals for water and sanitation. The most recent Demographic and Health Survey, conducted in 2011, estimates that, although several initiatives have been undertaken to increase the demand for and uptake of Eco-San systems, only 0.4% of the population use these types of facilities (Uganda Bureau of Statistics and ICF International Inc., 2012).

Perhaps part of the reason for this lack of uptake involves the way in which Eco-San facilities are promoted. They are most commonly encouraged in areas where geological conditions hinder pit latrine construction. While a number of locations in Uganda face these challenges, many do not, and the presence of Eco-San systems is often uncommon in these other areas. However, Eco-San facilities may still be appropriate in these places, helping to address a range of issues extending beyond the current focus on pit latrine feasibility. The small town of Kalisizo offers an example of one of these locations.

2.4. Treatment Processes in Eco-San Systems

Besides these considerations regarding Eco-San promotion, another important question concerns whether or not the products of Eco-San systems are being effectively treated before use or disposal. In general terms, a wide variety of pathogenic organisms, including numerous types of bacteria, viruses, protozoa, and helminthes, can be found in human excreta, and especially in feces. The inactivation rates of these pathogens depend on a number of environmental factors, including pH, moisture content, temperature, storage time, ammonia and salt levels, and competition with or predation by other organisms (Gajurel and Wendland, 2004; Hill et al., 2013). In an effort to ensure the safety of Eco-San products, a variety of primary and secondary treatment processes have been recommended, each aiming to manipulate one or more factors so that inactivation rates increase. In the context of most Eco-San systems, primary treatment steps refer to processes that take place onsite, within the toilet structure, while secondary treatment includes additional steps that may occur after products are removed from the facility (Esrey et al., 2001). Under a given set of conditions related to issues such as local climate, energy availability, and user preference, certain types of treatment processes may be more appropriate, and more effective, than others.

2.4.1. Primary Treatment: Composting

In Eco-San systems, primary treatment steps fall into two general categories, composting and dehydration. Composting toilets can range from simple, temporary structures, such as the Arbor-Loo, to more permanent facilities, such as the Modified Blair Toilet (Esrey et al., 2001). These systems usually do not separate urine and feces streams, although exceptions have been identified in some locations. For example, Hurtado reported that composting toilets in Panama were separating urine from fecal matter (Hurtado, 2005). They require the addition of dry, carbonaceous bulking materials, such as sawdust, dry leaves, or dry grass (Mihelcic et al., 2009) to provide adequate conditions for the composting process. The goal of composting toilets is to achieve thermophilic conditions, which can stabilize organic matter and inactivate pathogens present in human excreta through elevated temperature. The World Health Organization recommends that temperatures should be maintained at or above 50°C for at least one week and that a curing period of two to four months should follow (WHO, 2006). Slightly lower temperatures, if maintained above 42°C, are also reported to remove all pathogens after six months (Mihelcic et al., 2009).

In practice, however, these temperature levels are rarely achieved in Eco-San composting vaults. In a study in Mozambique, for example, the maximum temperature recorded in samples from Eco-San systems was 30.5°C (Van der Meulen et al., 2003), far below the temperatures needed to sanitize compost. In the case of solar heated composting systems in Mexico, most temperatures corresponded to local ambient temperatures, although, in one toilet, the compost temperature of 40°C was significantly higher than the ambient temperature of 28°C (Redlinger et al., 2001). However, this compost temperature was still lower than the recommended level. In Vietnam, where an average outdoor air temperature of 32.4°C was recorded, the average air temperature inside collection vaults was 34.7°C, while the average material temperature was 33.9°C. Again, the highest recorded temperature of 40.1°C was below the levels recommended for treatment through increased temperature (Chien et al., 2001). A study conducted in Panama presented similar results. The average temperature in composting vaults was found to be 29.5°C, almost the same as the average daytime temperature of 29°C. Only 32 percent of vault temperatures were above ambient levels, while only two percent were above 40°C (Mehl et al., 2011). Similarly, in El Salvador (Moe and Izurieta, 2003) and in the United States (Hill et al., 2013), vault temperatures were found to be only slightly higher than ambient temperatures. In general, the various studies concluded that, if any decomposition is occurring in these systems, the process occurs at ambient temperatures, progresses slowly, and is unlikely to result in a treated end product (Hill et al., 2013).

Thermophilic composting is difficult to achieve, especially when considering decentralized settings in the field. A number of operating conditions, including pH level, moisture content, carbon-to-nitrogen ratio, and aeration, must be maintained at certain levels simultaneously. According to Mehl et al. (2011), for aerobic decomposition, the pH should fall between 7.5 and 8.5 to promote the optimal biological activity, while Bhagwan et al. (2008) reported that 6.5 to 8.0 is the ideal pH range. Additionally, the moisture content should fall between 40% and 60% to ensure that enough water is present, while also maintaining sufficient air space to allow for aerobic conditions (Mehl et al., 2011). The optimal carbon-to-nitrogen ratio is approximately 30:1, and periodic mixing is often necessary to maintain fully aerobic conditions (Hill et al., 2013). The addition of fibrous bulking materials, such as straw, also helps to create space for oxygen (Van der Meulen et al., 2003). Meeting all of these requirements simultaneously is a significant operational challenge. In Panama, for instance, laboratory analyses of samples from five composting toilets were conducted to determine whether these toilets were attaining the desired conditions. In terms of pH, two of the five samples fell within, or were very close to, either of the acceptable ranges stated by Mehl et al. (2011) and Bhagwan et al. (2008), while the pH levels of the other three samples were above 9.0, where decomposition is likely to be inhibited. Two of the five reported moisture levels fell within the acceptable range of 40% to 60%, while two were too dry and one was too wet. Finally, carbon-to-nitrogen ratios of all samples fell between 5:1 and 10:1, far below the requirement and similar to the ratios reported for raw human feces (Mihelcic et al., 2009). Combined with the absence of increased temperature, these results suggest that thermophilic composting is not occurring. Samples also contained a number of pathogens, further supporting the conclusion that the composting processes taking place in Eco-San facilities do not produce fully treated products (Mehl et al., 2011).

Even in settings where thermophilic composting does occur, insulation is required to maintain sanitizing temperatures (Niwagaba, 2009). Vinneras et al. (2004), for example, studied composting in a 90-liter insulated reactor. After ten days, temperatures rose to above 60°C, but a well-insulated reactor was needed. Additionally, to compensate for the inert materials commonly added to composting toilets, such as ash and soil, energy-rich substances, such as food waste (Schonning, 2003), should also be added so that sufficient heat is produced. Furthermore, the contents of the reactor may not be completely mixed and could contain pockets of lower temperature material, especially if the incoming air is not preheated. Pathogen destruction in these areas may not occur, and, once the thermophilic composting stage has passed and overall temperature has decreased, regrowth of pathogens is a possibility (Vinneras et al., 2004). Given the difficulty and the variety of issues associated with small-scale composting of human excreta, the World Health Organization recommends that composting should be conducted offsite, at a centralized facility, where the process can be controlled and monitored by experienced technicians (WHO, 2006).

2.4.2. Primary Treatment: Dehydration

In contrast to composting toilets, dehydration facilities attempt to create an environment in the collection chamber that is characterized by high pH levels (at or above 9.0) and low moisture content (at or below 25%) through the addition of materials, such as wood ash, sawdust, or lime, that have desiccating and/or alkaline properties (Mihelcic et al., 2009). Some toilet designs also attempt to promote an increase in temperature through solar heating, which, in addition, can improve the rate of drying. Urine-diverting dry toilets (UDDTs), the facilities promoted in Uganda after the initial composting models proved to be unsuccessful, fall into the dehydration category. As implied by the name of the facility, UDDTs divert urine into a separate storage container to ensure dry conditions in the fecal collection vaults. As stated previously, compared to the fecal fraction, urine is generally low in pathogens, and, for large-scale systems involving multiple households, closed storage for a period of six months is established as being sufficient to treat the material. In the case of small, single-household systems, urine can be used for agricultural purposes after a short storage period and dilution (WHO, 2006). Treatment of the collected feces, on the other hand, is an area of much greater concern.

Raw human feces have a neutral pH between 6.6 and 7.0 (Dinoto et al., 2006) and a relatively high moisture content of 80% to 83% (Nordin, 2007). As a result, substantial additions of other materials are necessary to achieve the desired high pH and low moisture conditions. Studies in Panama have found the most commonly available additives in that area to be sawdust and wood ash. While sawdust is an effective desiccant, its pH can range from 4.5 to 7.8. Wood ash also has desiccating properties, and it has an alkaline pH ranging from 9.4 to 11.3 (Mihelcic et al., 2009), suggesting that, if locally available, wood ash is the additive more likely to result in the desired pH conditions. In Panama, it was found that facilities using wood ash, rather than those using sawdust or a combination of the two, were more likely to exhibit a pH greater than 9.0 (Mehl et al., 2011). In Uganda, wood ash is the most common additive that is recommended and used (NETWAS-U, 2011b), and some users do not even realize that other options are possible (Kamuteera et al., 2013). This prevalence is likely due to the fact that relatively large amounts of ash are produced in many homes and institutions, since most people use firewood as cooking fuel (NEMA, 2010).

In general, the dehydration process is easier to achieve than onsite composting. To meet the required conditions for dehydration, only two parameters, pH and moisture content, must be manipulated, and, through the addition of one or two desiccants after use, it is possible to attain the required levels. In decentralized settings, such as those commonly associated with Eco-San systems in developing countries, dehydration is recommended over composting as the more reliable option for primary treatment in the collection vault (Gajurel and Wendland, 2004). Given sufficient time, the pH and moisture conditions recommended in dehydration systems have been shown to inactivate a number of pathogens of interest (Esrey et al., 2001). It is reported that six months of storage with a pH at or above 9.0 can result in a 4 to 6 $\log_{10}$ reduction in bacteria and viruses (Stenstrom, 2002), while the World Health Organization (WHO, 2006) recommends that at least one year of dry storage at ambient temperatures between 20°C and 35°C is needed to inactivate most pathogens.

However, despite their relative ease of operation as compared to composting toilets, onsite dehydration systems still experience operational issues, since their use remains more complex than simple pit latrines. These issues may result in a failure to achieve the required treatment conditions. In

Panama, for example, some of the samples taken from Eco-San systems were shown to have pH levels that were less than 9.0, and moisture contents of all samples were above the recommended maximum. Even among the toilets where wood ash was used as the desiccant, average pH was only 8.3 (Mehl et al., 2011). Some common problems included adding insufficient amounts of desiccating materials, urine entering the fecal vault, and storage times that are shorter than those recommended. To achieve the required pH and moisture conditions, it is normally recommended that one or two cups (200 – 500 ml) of desiccant should be added to the fecal vault after each use (Austin, 2006; Mehl et al., 2011). A supply of wood ash, or other suitable material, that is adequate to meet this regular demand may not be immediately available to toilet users (Kaggwa et al., 2003; Kamuteera et al., 2013), or users may simply forget to add desiccant occasionally. If urine enters the fecal chamber, significant moisture will be added to the mixture, and it becomes much more difficult to achieve a moisture content below 25%. More humid conditions, during rainy seasons, for example, may also increase the moisture content. Even if the required levels are attained, emptying the vault before the storage period has been completed, either because the vault is not large enough or because users simply decide to empty the vault early, could expose users to active pathogens.

2.4.3. The Problem of Persistent Pathogens

Other sources suggest that, even if a pH of 9.0 and a moisture content of 25% are sustained for an entire year, this period of time may be insufficient to eliminate more persistent pathogens (Hawksworth et al., 2010; Peasey, 2000). Helminthes are of special concern, especially the eggs of *Ascaris lumbricoides*, which are extremely persistent (Mehl et al., 2011). Worldwide, it is estimated that 1.3 billion people are infected with *A. lumbricoides*, with most infections occurring in developing countries. Ascariasis is endemic in areas of Latin America, the Far East, and Africa, with children under fifteen being greatly affected. Although the condition has a low mortality rate, it can lead to undernourishment, diarrhea, vomiting, intestinal obstruction, and other symptoms that are associated with poor growth and development (Hawksworth et al., 2010). In a study among schoolchildren in Uganda, it was found that 28.8% of those tested in Rakai District, where Kalisizo is located, were infected with *A. lumbricoides*, with an average of 2,289 eggs per gram of infected feces (Kabatereine et al., 2001). In view of these results, any Eco-San system implemented in this area should be designed and operated with the goal of inactivating these persistent pathogens.

The eggs of the genus *Ascaris* are excreted in feces, where they can cause infection through three main transmission pathways. These pathways include transmission from surfaces or materials contaminated by feces, transmission to workers in fields fertilized with fecal materials, and transmission by the consumption of vegetables fertilized with fecal materials (Vinneras et al, 2004). The inactivation of these microscopic, single-celled eggs is extremely difficult. It is hypothesized that the presence of a four-layer shell, 3 to 4 µm thick, plays a major role in imparting resistance to a variety of environmental stressors (Brownell and Nelson, 2006). Studies report that a moisture content below 5% (WHO, 2006) is required for inactivation, while Moe and Izurieta (2003) report that eggs can survive for at least 700 days when exposed to pH levels ranging from 9 to 11 and for more than 400 days at a pH above 11. Brownell and Nelson (2006) state that, among water-related pathogens, *Ascaris* eggs are the most resistant to ultraviolet radiation, and Pecson et al. (2007) maintain that these eggs have the highest resistance to numerous other treatment methods. High temperatures, however, are reported to effectively inactivate eggs. In meosphilic anaerobic digesters operated at 35°C, nearly all *Ascaris suum* eggs were inactivated after 24 days, and it was reported that faster inactivation could occur if the eggs' development cycle is aerobically triggered before entering anaerobic digestion (Manser et al., 2015). In El Salvador, Moe and Izurieta (2003) found that, when peak temperatures in solar toilets exceeded 36°C, *Ascaris* eggs were inactivated in a matter of weeks. In contrast, Brownell and Nelson (2006) stated that eggs can survive for more than a year at 40°C but are destroyed in minutes at temperatures above 60°C. In most instances, temperatures that ensure inactivation are not found in onsite Eco-San systems.

Ascaris eggs have also been shown to be removed from wastewater through sedimentation in waste stabilization ponds (Verbyla et al., 2013). However, since the goal is to reuse solid material from Eco-San systems, sedimentation would not be an effective treatment mechanism.

In locations where *Ascaris* infection is endemic, reuse of the products from Eco-San systems, even if those products maintained a pH above 9.0 and a moisture content below 25% for one year, may actually place users at greater risk of infection. For example, in a rural community in El Salvador, where eight percent of the study population were infected with *A. lumbricoides*, a higher prevalence of *Ascaris* infection was found among users of urine-diverting toilets, compared to people with solar toilets, pit latrines, or no sanitation facility. It was concluded that this higher prevalence occurred because urine-diverting toilets did not inactivate *Ascaris* eggs and additional opportunities for exposure were provided when the fecal material was taken out of the vaults. This conclusion is supported by the observation that a higher prevalence of infection was seen among agricultural workers who were exposed to biosolids from the urine-diverting toilets, compared to those who had not been exposed (Corrales et al., 2006). Similarly, in northern Vietnam, where fertilizers from Eco-San systems are widely used, the prevalence of *Ascaris* infection is reported to be approximately 90 percent. In southern Vietnam, where the population often defecates over fish ponds, prevalence is lower, between 45 and 60 percent (Peasey, 2000).

In communities where these persistent pathogens are found, Eco-San systems should be operated with the goal of inactivating these organisms. Because of the resistance of *Ascaris* eggs to various treatment options common in Eco-San systems, their inactivation can be seen as an indicator of overall safety and effective treatment (Gajurel and Wendland, 2004). However, conditions in most toilet vaults are not adequate to destroy these pathogens, even after a year of storage. As a result, secondary treatment is often recommended, especially if the fecal products will be used for agricultural purposes (Hawksworth et al., 2010; Mehl et al., 2011; Peasey, 2000).

2.4.4. Secondary Treatment Options

A number of low-cost possibilities for secondary treatment exist, including composting, anaerobic digestion, incineration, solar drying, additional storage, and chemical treatment. Composting as a secondary treatment is more likely to achieve the necessary conditions for a substantial increase in temperature than if it is attempted as a primary treatment within the latrine vault, because the fecal matter can function as one component of a larger compost pile that includes significant amounts of dry, carbon-rich bulking material. With these additional ingredients, the required operating conditions are more likely to be attained, and sanitizing temperatures between 50°C and 65°C may be reached during the thermophilic phase of the composting process. However, it is often necessary to provide insulation around the compost pile, to help ensure that significant heat is not lost and all parts of the pile reach the desired temperatures. Niwagaba (2009) found that compost reactor bins without insulation did not exceed temperatures of 50°C, while reactors with Styrofoam insulation were able to achieve higher temperatures. In view of these issues, composting to achieve treatment through increased temperature remains a complex process, even as a secondary treatment step, when the process can be better controlled. It is recommended, therefore, that composting be conducted in a centralized setting (WHO, 2006), where experienced operators can regularly monitor conditions and ensure effective treatment.

Whereas composting is an aerobic process that requires a sufficient supply of oxygen, anaerobic digestion takes place in the absence of oxygen. Organic matter is broken down to produce a mixture of methane and carbon dioxide (commonly called biogas), water, and remaining slurry. The biogas produced can be used for cooking and, in some cases, for a small amount of lighting, while the slurry can function as a soil conditioner or fertilizer. In rural, small-scale systems, animal manure from household livestock is often the primary substrate, while human excreta and other organic wastes may be used as supplementary inputs. Although anaerobic digestion can generate multiple beneficial products, the mesophilic process that occurs in small-scale systems is relatively ineffective in terms of pathogen reduction. On average, the process results in approximately 50% inactivation of helminth eggs, meaning that additional treatment steps are required if the remaining slurry is to be used for agricultural purposes (WHO, 2006). However, anaerobic digesters at higher mesophilic temperatures of 35°C have been shown to inactivate all *Ascaris* eggs after 24 days (Manser et al., 2015).

Incineration is an effective and rapid method for sanitizing feces after primary storage, and the process can be performed relatively inexpensively using locally-manufactured incinerators. However, some of the agricultural value of the product is lost, since most of the carbon, nitrogen, and sulfur within the material is burned off. While fractions of the potassium and phosphorus are also lost, significant amounts of these two nutrients remain, suggesting that the incinerated products do still have agricultural value. Alternatively, the ash that is produced could also function as a possible additive in dehydration toilets, lowering the demand for wood ash or other desiccants. Potential issues include fuel requirements and air pollution. At temperatures below 850°C, dioxins can form (Niwagaba, 2009). Dioxins are persistent organic pollutants that are able to travel long distances from the emission source and accumulate in food chains. Human exposure generally occurs through the intake of contaminated food, and dioxins can negatively affect development, reproductive functions, and certain hormones. Certain types of dioxins are also classified as being carcinogenic to humans (WHO, 2010).

Solar drying was recommended in Panama by Mehl et al. (2011), although it is not known whether this step will reliably inactivate all remaining pathogens, including *Ascaris* eggs. The suggested procedure involves spreading a thin layer of stored feces onto a metal sheet and exposing it to full sunlight for one week. Other passive solar drying configurations have also been recommended (Andreev et al., 2009). These measures expose the fecal material to further dehydration, increased temperatures, and solar radiation, each of which could result in additional pathogen reduction after primary storage. However, it is important to note that this process is seasonally dependent. The dry season would constitute the time of year most conducive to this treatment method (Mehl et al., 2011), while exposing the open feces to rainfall might encourage regrowth of pathogens or the transport of organisms into other areas.

Perhaps one of the simplest secondary treatment options involves extending the storage time of fecal products. However, since fecal collection chambers are often designed to accommodate storage periods of six months to one year, and since the large vault sizes needed for longer storage times might prove to be impractical and expensive, additional storage generally requires that the feces be relocated. The second phase of storage could take place in a separate compartment or in a designated building for larger systems with multiple toilet units incorporating replaceable fecal chambers. Another option would involve burying the stored feces in the soil (Mehl et al., 2011). The material could be left in the soil indefinitely, or it could be excavated later for agricultural use. However, after at least 18 days in the soil, fertile *Ascaris* eggs embryonate and become infective (CDC, 2013), and, between 20°C and 30°C, eggs can remain viable in soil for several months and up to two years (WHO, 2006).

Chemical treatment could involve the addition of acidic materials, such as phosphoric acid, alkaline materials, such as lime, or oxidizing agents, such as chlorine (Niwagaba, 2009). The addition of wood ash, or other materials with similar properties, to the vaults of dehydration toilets is a form of chemical treatment. Acidic and basic substances are usually added to cause a pH change, since many pathogens cannot survive at low or high pH levels. However, increased concentrations of ammonia have also been shown to adversely affect pathogens, independent of pH. Pecson et al. (2007) compared the results of several studies and noted significant variability in pathogen reduction, even at similar pH levels. For example, at similar temperatures and moisture levels, Mendez et al. (2002) found 90% inactivation of *Ascaris* eggs after two hours at a pH of 12.5, while Plachy et al. (1996) reported only a 3.6% inactivation after seven days at a pH of 12. Pecson et al. (2007) maintain that the variability in inactivation rates can be explained, at least partially, by different concentrations of ammonia. The destructive effect of ammonia is thought to be related to the molecule's small size and its high solubility in water and in lipids, enabling it to pass through organisms' cellular barriers and disrupt internal chemistry (Nordin, 2010). The uncharged form of ammonia (NH_3), which is present in significant amounts at high pH levels, has been shown to impact pathogens much more severely than the ammonium ion (NH_4^+), its conjugate acid, which is generally the dominant form at pH levels of 9.0 or lower. The uncharged ammonia fraction is also increased when temperature increases. High total ammonia concentrations at high pH levels and high temperatures, then, could provide the most effective scenario for pathogen reduction.

CHAPTER 3: ECO-SAN PROMOTION THROUGH SCHOOL-BASED DEMONSTRATION FACILITIES

This chapter presents research related to the first set of objectives outlined in Chapter 1. It concentrates on the use of school-based demonstration facilities as a potential strategy for promoting Ecological Sanitation (Eco-San) systems within the local community. To evaluate whether this strategy improved acceptance and understanding of Eco-San systems, knowledge and attitudes were assessed in each school community before and after demonstration facilities were installed, with a special focus on students, who could become critical advocates for these systems in the future. Additionally, regular monitoring occurred to determine whether the facilities were being operated correctly.

The chapter begins with a literature review that explores a variety of strategies for promoting sanitation technologies, with emphasis on techniques that have successfully encouraged adoption of Eco-San systems. It continues with a description of the methods used to evaluate the effects of school-based demonstration facilities and goes on to present and discuss the results that were obtained.

3.1. Literature Review: Sanitation Promotion Strategies

Eco-San systems provide an approach to sanitation that, in addition to conventional goals such as protecting populations from hygiene risks and reducing environmental pollution, seeks to recover resources from human excreta (Esrey et al., 2001). Nutrients contained in excreta can be used to restore soil productivity and improve agricultural yields (Jonsson et al., 2004), which is of special importance for resource-limited areas, such as Uganda, where soil fertility is declining (Nkedi-Kizza et al., 2002; NEMA, 2010), populations are growing (UN, 2013a), and future nutritional security is uncertain (FAO, 2012). Urine-Diverting Dry Toilets (UDDTs), one type of Eco-San system, have most commonly been promoted in areas where geological conditions hinder the construction of pit latrines, which are the most prevalent sanitation technology used in Uganda (Niwagaba and Asiimwe, 2005). UDDTs are generally uncommon or nonexistent in other parts of the country. However, UDDTs may still be an appropriate option, addressing a range of issues that extend beyond a focus on pit latrine feasibility. Full pit latrines are often capped, after which a new pit is dug in a different location (Mutagamba, 2003), while UDDTs are permanent structures, addressing concerns of limited space in urban or peri-urban environments (Langergraber and Muellegger, 2005). Additionally, by keeping excreta separate from water, this resource can be conserved and protected, and the decentralized nature of Eco-San systems combined with their low energy requirements can contribute to greater resiliency to climate change.

In 2008, several government ministries in Uganda established a goal of having Eco-San systems account for at least 15% of the country's sanitation coverage by the year 2018 (Tumwebaze et al., 2011). However, recent estimates of sanitation coverage reveal that Eco-San adoption is far below this target. The country's most recent Demographic and Health Survey, conducted in 2011, estimates that only 0.4% of the population use these types of systems (Uganda Bureau of Statistics and ICF International Inc., 2012). An important question, then, is how best to promote Eco-San facilities in the Ugandan context.

3.1.1. Sanitation Marketing: Supply and Demand

Lessons learned from efforts to encourage the use of other sanitation options provide valuable information for the specific case of Eco-San promotion. Over the past several decades, strategies to encourage good sanitation and latrine use have undergone significant change. It has become apparent that the previous "supply-led" model, which involved subsidized construction of sanitation facilities at the household level, was not sustainable, economically feasible, or particularly effective (Jenkins and Sugden, 2006). Although it was hoped that behavior change would follow the hardware subsidies, a willingness to maintain the new facilities or to purchase similar facilities often did not result (Jenkins and Sugden, 2006). Even if this strategy were effective, public funding is generally insufficient to replicate the model on a large scale. Improving sanitation and hygiene has since been recognized as a complex form of behavior change, one that may take decades to fully accomplish (Jenkins and Sugden, 2006).

Promotion efforts have now shifted toward “demand-driven” models, which focus on marketing and creating demand for sanitation products that are made available through the private sector or that can be installed by community members. Jenkins and Sugden (2006) reported that most new household sanitation systems in Africa, as well as in other parts of the world, has been privately acquired through the market, and that this model has accounted for all of the increases in sanitation coverage seen in Kampala, Uganda during the 1990s. However, certain types of subsidies, which generally focus on promotion and training, rather than physical infrastructure, are still necessary and useful. Given the fact that sanitation improvements can most greatly benefit public health if all, or nearly all, members of a community engage in those improvements, it is important to work toward universal coverage. Invariably, some individuals will be more reluctant to adopt improved practices, while others may be financially unable, suggesting that targeted subsidies for promotion, marketing, and education may be needed (Jenkins and Sugden, 2006).

Community-led total sanitation (CLTS) provides one example of this type of promotional campaign. This approach attempts to empower local communities to stop open defecation and to build and use latrines without the support of external hardware subsidies (Harvey, 2011; Meeks, 2012). Rather than focusing on health impacts or standards, CLTS works from a starting point of self-respect. In other words, instead of promoting the health benefits of latrines, facilitators focus on the unpleasant aesthetic conditions created by open defecation, such as the fact that excreta are seen out in the open and the possibility that people are eating food that has come into contact with excreta. The eventual goal is for those who practice open defecation to want to change their behavior and avoid the feelings of shame that those conditions might cause, so that they feel as if they are valued and respected members of the community (Harvey, 2011). As community members identify the negative aspects of open defecation, they see that the community must do something to improve its situation, and that it is important for everyone to be involved. Harvey (2011) reported that this approach has been very successful in Zambia, where CLTS implementation in twelve villages increased sanitation coverage rates from 23 percent to 88 percent. In Mali, Meeks (2012) also reported that sanitation improvements and behavior changes resulting from CLTS were sustained after villages had achieved open defecation free (ODF) status, with a majority of study participants reporting that they had made improvements to their latrines or were maintaining them. While this model seeks to avoid hardware subsidies, so that communities implement their own sanitation solutions, "software" subsidies are still needed to fund the initial educational sessions and the program facilitators. In this way, funding that is specifically targeted and based on lessons learned from previous experiences can have a positive and sustainable impact on sanitation practices. However, it is important to note that research in Kalisizo, Uganda presents a significantly different context than those in Mali and Zambia. Although people in some areas of Uganda practice open defecation (Uganda Bureau of Statistics and ICF International, 2012), it rarely occurs in Kalisizo, because most households already have pit latrines (Uganda Bureau of Statistics, 2011).

3.1.2. Additional Dimensions of Eco-San Systems: Seeing is Believing

Along with these general issues concerning behavior change, promotion of Eco-San systems must address additional complexities, including local disbelief, cultural taboos, and increased responsibilities of users. For communities, such as those in Uganda, that do not have a tradition of human excreta reuse, Eco-San facilities can be especially difficult to promote. Initial reactions often involve skepticism (Guzha and Musara, 2003) and, in some cases, fears related to the adverse effects of wood ash, commonly used to raise pH in the feces vaults, and the possible use of feces and ash in witchcraft (Tumwebaze et al., 2011). However, Tumwebaze et al. (2011) also found that these ideas could be addressed with increased sensitization. Although beliefs in witchcraft remain fairly prevalent in Kalisizo, Drangert (2004) reported that its association with feces was diminished when people moved from rural areas to towns and other urban centers.

As community members come to better understand Eco-San systems, other concerns begin to surface. Except in circumstances where adverse soil conditions make pit latrine construction prohibitively expensive (Kaggwa et al., 2003), Eco-San facilities are often more expensive than pit latrines and other sanitation options (Rajbhandari, 2008; Uddin et al., 2011). Cost comparisons between UDDTs and pit latrines vary considerably in the literature. Rajbhandari (2008) provided data showing that the average cost of pit latrine construction was 56% of the average UDDT construction cost in Nepal, while Uddin et al. (2011) reported a pit latrine construction cost that was only 20% of the cost of UDDT construction in Kenya. One approach to addressing this concern involves a distinction in classification. A pit latrine is only a toilet, while an Eco-San facility can be seen as a combination of a toilet and a treatment or recycling system (Rajbhandari, 2008). While this categorization provides justification for the increased cost of Eco-San systems, it does not necessarily provide an economic incentive to adopt the technology. Long-term economic benefits of installing an Eco-San system can be realized, however, due to the permanence of the structures and the potential value of urine and feces as fertilizers and soil conditioners. These practical, financial advantages of Eco-San facilities are likely to be a driving factor for adoption (Rajbhandari, 2008), but these advantages will only be attained if the systems are well-maintained, and if the products are actually used, or sold for use, in agriculture.

To ensure a long lifetime for the facility and the production of acceptable agricultural inputs, correct operation of the facility is essential. For UDDTs, proper operation involves complete separation of urine from feces, usually accomplished through the installation of a urine diversion device in the squat hole. An alkaline desiccating material, such as wood ash, is also added to the fecal collection chamber after each use. These measures promote a dry environment in the fecal chamber, which is necessary for the treatment of the fecal products (Tushabe et al., 2003). Additionally, they help to reduce the prevalence of flies and odors, providing users with a more comfortable and aesthetically pleasing environment (Breslin, 2002). The diverted urine is piped away from the fecal chamber, either to a nearby soak pit or into a container that can be stored for later use. These steps require further behavior changes and can represent a significant barrier to implementation. In general, intensive sensitization is needed prior to implementation (Niwagaba and Asiimwe, 2005), while post-construction monitoring is often required to promote acceptance and proper operation (Kaggwa et al., 2003). As a negative example, a project in Mexico that did not incorporate this level of training and follow-up resulted in the construction of units that were never used or only used for a short time (Peasey, 2000).

Even with a rigorous education and training plan that is sensitive to local practices, communities may be resistant to the idea of using human excreta to fertilize agricultural crops. A study in Zimbabwe found negative perceptions towards its use on leaf, stem, and root crops (Manyanhaire et al., 2009). Similarly, surveys conducted in Panama revealed that a majority of respondents perceived the handling of human excreta to be a great health risk (Wilbur, 2014). In a Ugandan fishing village on Lake Victoria, where Eco-San units were installed due to soil conditions that hindered pit latrine construction, local residents had no desire to use or consider the benefits of the collected excreta (Kaggwa et al., 2003). In a broader market study conducted among farmers and other stakeholders in Uganda, low willingness to use fecal sludge from Eco-San facilities was found to be due to negative attitudes toward feces among both farmers and consumers. While some farmers reported that they did use urine to boost crop production, they also mentioned that consumers avoided their produce upon learning that urine fertilizer was being used (NETWAS-U, 2011a). The fertilizer value of collected urine and feces is one of the main incentives for the uptake and correct operation of Eco-San facilities. If these products are viewed in a negative light, operation may suffer and the system may fail.

Regardless of the quantity and quality of education and sensitization efforts, early responses to Eco-San concepts commonly involve a substantial amount of skepticism (Guzha and Musara, 2003), which might focus on the safety and agricultural value of urine and feces, the ability of the facility to minimize flies and odors, or the system's appropriateness in a given community. As a result, many promoters of Eco-San systems have come to believe that demonstration facilities are needed to convince community members that Eco-San principles can work in the local context. A number of studies have discussed the value of these demonstration units. In Tanzania, for example, a pilot project introduced a small number of Eco-San facilities before wider implementation, and it was noted that uncertainties about the technology diminished when people observed units that were functioning well (Shayo, 2003). A study in Mozambique reported that individuals found Eco-San concepts to be simple and easy to understand when demonstration units were put in place (Breslin, 2002). In Zimbabwe, after initial responses of skepticism, attitudes toward Eco-San systems improved, with communities indicating that demonstration units created awareness and improved understanding of these systems (Guzha and Musara, 2003). Bregnhoj et al. (2003) noted that it was much easier for promoters to ensure good operating practices when monitoring a limited number of facilities, and, once local members of the community saw the process at work in these units, Eco-San systems were often perceived as beneficial and plausible options. In general, these examples show how the idea that "seeing is believing" can be applied to Eco-San promotion, and how demonstration facilities, coupled with education and training programs, can function as targeted subsidies that increase demand for Eco-San systems.

3.1.3. Demonstration Facility Location: Households or Institutions

A major question regarding demonstration facilities concerns where the units should be located. In general, two conflicting schools of thought can be found. Some studies maintain that the Eco-San concept should first be introduced in individual households of community leaders, and then the systems can later be implemented in schools and institutions. Institutional projects can present greater challenges than those on the household level, because issues of ownership, management, and monitoring are not always well-defined in institutional settings. In South Africa, for example, Austin (2003) reported that, despite careful planning and intensive training at a rural school where an Eco-San system was installed, teachers were not committed to ensuring proper use of the facility by the students, and, as a result, the system failed. Because of the absence of a feeling of ownership, toilets in institutional and public settings have often been misused and found to be in poor condition (Langergraber and Muellegger, 2005). In a household setting, family members feel a sense of ownership of the facility, which has the potential to lead to better operation and increased acceptance of the concept (Austin, 2003). As interest grows within a community, other individuals see well-operated demonstration models at houses of community leaders (Breslin, 2002), and, once the concept is familiar, then implementation at schools and other institutions can take place. Students will already be familiar with the principles and operation of the technology through their experiences at home (Austin, 2003).

However, if other aspects of institutional settings are considered, they may appear to be ideal locations for the installation of demonstration facilities. Institutions, such as schools, are often natural meeting places for the community and can accommodate a large number of people for training sessions. A number of studies discuss the benefits of institutional settings. For example, in Zimbabwe, demonstration facilities at churches, schools, and community halls were described as increasing overall confidence in Eco-San systems among members of the community (Manyahaire et al., 2009), while another study conducted in the same country reported that school demonstration facilities, supported by informational booklets, resulted in positive attitude changes among local residents (Guzha and Musara, 2003). Schools in particular have the potential to establish awareness and acceptance of Eco-San concepts at a relatively young age (NETWAS-U, 2011b; Niwagaba and Asiimwe, 2005). A study in Nepal remarked that school students can be excellent representatives for Eco-San systems and can encourage potential users within the community to adopt the technology (Rajbhandari, 2008). In general, upon seeing a successful demonstration project in an institution, interest in and eventual acceptance of the system within the surrounding community is often improved, since initial fears and uncertainties regarding the final products can be laid to rest (Shayo, 2003; Werner et al., 2003).

The relative merits of implementing demonstration units in household or institutional settings are likely to be dependent upon the local context of the project. This research investigated the initial effects of demonstration facilities located in primary schools within Kalisizo, a small town in southern Uganda, in an effort to determine whether this promotion strategy would be successful in encouraging acceptance and uptake of Eco-San systems in the area. Due to the short-term nature of this work, rather than basing the level of success on the number of new facilities being installed, the effect of the demonstration units was assessed through qualitative evaluations of attitudes and knowledge among students and local community members. When a new concept is first being introduced, it is reported that reliable indicators of success include estimations of how consumer awareness has changed (Jenkins and Sugden, 2006). Appraisals of local attitudes and knowledge before and after installation of the demonstration facilities provided pertinent information related to this issue. Special focus was placed on students, who could function, initially at a local level but perhaps eventually at a national level, as compelling advocates for Eco-San systems.

3.2. Research Methods

This research employed a qualitative approach incorporating focus group discussions (FGDs) and key informant interviews (KIIs) to gather information on knowledge and attitudes regarding UDDTs at two primary schools in Kalisizo. Additionally, a quantitative approach involving physical and chemical testing was used to assess the schools' operation of the facilities. The research was connected to a project undertaken by a Non-Governmental Organization called Brick by Brick Uganda. Founded in 2003, this organization partners with primary schools in Rakai District, where Kalisizo is located. It focuses on sustainable economic development, health education, and infrastructure improvement. Its close ties to school communities, administrators, community leaders, and local government officials provided Brick by Brick with an ideal opportunity to test the effectiveness of demonstration UDDTs in an institutional setting.

3.2.1. Brick by Brick Uganda's Eco-San Pilot Project in Kalisizo

In 2013 and 2014, Brick by Brick worked with two primary schools located in Kalisizo Town to implement an Eco-San Pilot Project, which involved the installation and operation of one demonstration UDDT at each school. The goal of the project was to determine whether this type of facility is a feasible sanitation option in the context of Kalisizo, and in the context of primary schools within small towns. If this initial, small-scale project proved to be successful, Brick by Brick Uganda planned to expand the pilot, addressing all of a school's sanitation needs with a larger Eco-San system.

3.2.2. The School Communities

The two schools involved in the initial pilot were Saint Andrews Matale Hill Primary School and Kalisizo Muslim Primary School, both of which are government-aided (public) Universal Primary Education (UPE) schools located in Kalisizo Town, within Rakai District. As of 2010, the district's population was estimated to be 466,900 (MWE, 2010). The number of students enrolled at each school varied by year. Each institution's total enrollment generally fell between 300 and 500 students, although actual daily attendance is often far less. As with many schools in Uganda, these two are associated with religious institutions. As a result, most students attending Saint Andrews are Catholic, while Muslim individuals form a significant portion of the student body at Kalisizo Muslim. However, Muslim students do not form a majority at Kalisizo Muslim. The population of Rakai District is 60% Catholic and only 9% Muslim (Uganda Bureau of Statistics, 2002). The primary school's connection with the Uganda Muslim Education Association (UMEA) causes its student body to contain a larger percentage of Muslim students than other schools, but those students still make up less than half of the total school population. Both schools involved in the pilot project were chosen as a matter of convenience, since they were located in Kalisizo, close to Brick by Brick's field office, and enabled Brick by Brick staff to easily monitor the facilities. They were not selected with the goal of conducting a cultural comparison between a Catholic school and a school with a relatively high Muslim population.

Generally speaking, when compared with students attending private institutions, students enrolled in UPE schools come from less privileged backgrounds, especially in rural areas of the country (Grogan, 2006). This discrepancy is to be expected, since school fees to attend public institutions were eliminated in 1997, while private schools charge significant sums that are often impossible for low-income families to afford. Public primary education is still not completely free, since parents or guardians are expected to provide school supplies, uniforms, and, in some cases, money or food for lunch, but the major financial barrier has been removed (ODI, 2005). With the elimination of school fees, public institutions lost a significant source of revenue, with the expectation that government funding would correspondingly increase. However, corruption and other institutional constraints have historically hindered the movement of funds from the central government through local governments and administrators to the intended beneficiary schools. A study conducted in 1997 by the Economic Policy Research Centre in Kampala found that only 35% of funds released from the central government to schools were reaching their intended beneficiaries (ODI, 2005). Funding problems, along with drastically increased student enrollment after the elimination of school fees (Grogan, 2006), seriously limited administrations' abilities to improve their schools.

Brick by Brick has worked with Saint Andrews and Kalisizo Muslim for several years. Prior to infrastructure improvements that have since been completed, school buildings were often characterized by unfinished classrooms, dirt floors, leaking roofs, and missing doors or windows. Students were commonly asked to walk long distances to collect water, and the condition of school latrines was generally worse than that of the other school structures. Each school did have an agricultural garden, which was used for educational purposes and to produce some food for student lunches.

With the exception of a few specific communities, examples of which will be discussed in later sections, Eco-San systems were extremely uncommon in Rakai District. The coverage of Eco-San facilities in the district has not been well-documented in publically accessible literature, but it was estimated to be less than 1% (Rakai District Health Office – personal communication). In comparison, pit latrine coverage in Rakai District was reported to be 84% in 2010 (Uganda Bureau of Statistics, 2011).

3.2.3. Implementation of the Pilot Project

As with all of Brick by Brick's infrastructure projects, the school communities were involved in the Eco-San Pilot's planning and construction activities, providing input on the location and design of the facilities and supplying certain materials, unskilled labor, and food for skilled workers. An important example of the schools' design input relates to the fact that a substantial fraction of students were Muslim. It was important to consider Islamic cultural norms related to defecation and toilet use, which were described by Kalisizo Muslim's head teacher. The practice of using anal cleansing water, instead of toilet paper, is often employed by Muslims, and at least one source (Ofumbi, 2010) has mentioned that this practice is incompatible with Eco-San systems, because water cannot enter the fecal vault. If the design of the UDDT facilities is modified slightly, though, it is possible to create a system that Muslims can use effectively (Warner, 1998). In collaboration with the Kalisizo Muslim administration, Brick by Brick modified the design to include a separate wash hole that would direct water away from the facility and into a soak pit. This design was incorporated at both schools, to accommodate any Muslim students in attendance at either institution.

Additionally, each school selected a specific group of students who would use and operate the toilet. In both cases, female students in their sixth year (known as Primary Six) were chosen. Over the past several years, government agencies and Non-Governmental Organizations in Uganda have been placing emphasis on female education, in an effort to ensure that girls stay in school. Many girls face especially difficult circumstances as they enter puberty, due, for example, to shame or embarrassment that is felt as a result of menstruation (Sommer, 2010; McMahon et al., 2011). As a result, these two Kalisizo schools wanted to provide their older female students with an improved, more private sanitation facility, in the hope that it would provide an added incentive for girls to stay in school.

Along with the installation of the facilities, Brick by Brick incorporated a strategy designed to educate and sensitize each school community, with special emphasis on the users of the facilities. The strategy included several educational sessions, the first of which took place before construction began and provided school leadership with a general overview of Eco-San systems, covering basic concepts and principles related to separation of urine and feces, nutrient and water cycles, protection of natural resources, and the value of human excreta. During and after facility construction, students and faculty at each schools received information that focused on the following topics:

- facility operation (desiccant addition, urine collection and storage, alternating use of vaults)
- treatment processes (urine storage, dehydration of feces, secondary treatment of feces)
- emptying of the vaults (handling of feces, secondary treatment, options for disposal or reuse)
- nutrient reuse (agricultural benefits of urine and feces, application techniques)

These sessions included the students using the facility. Photographs taken during these sessions are shown in Figure 5. After operation commenced, Brick by Brick staff conducted regular monitoring visits, approximately once a month, to observe the conditions of the toilets, measure temperature, pH, and moisture levels within the vaults as described below (more detailed procedures for these measurements are included in Appendix A), and address any issues identified by the users. A UDDT evaluation guide, included in Appendix B, was used to assess the condition of the facilities during each monitoring visit. During the visits, key concepts were reinforced, especially if operational problems were noted.

3.2.4. Assessing Eco-San Promotion through Demonstration Facilities in Schools

To evaluate the effectiveness of a strategy focusing on school-based demonstration facilities, two phases of qualitative data collection and analysis were completed. In each of the two school communities, attitudes and level of knowledge regarding Eco-San systems were assessed twice. The first phase occurred prior to educational sessions and installation of the facilities, while the second phase took place after installation and several months of operation. The assessments were conducted through focus group discussions and key informant interviews. By comparing the results of both phases, changes in attitudes and knowledge were identified. One round of focus group discussions was also conducted in Kasensero, a fishing village on Lake Victoria that is also in Rakai District. UDDTs had previously been constructed in this village because local soil and groundwater conditions hindered the installation of pit latrines. Kasensero functioned as a control community, allowing the results from the two school communities in Kalisizo to be compared to those from a village where Eco-San systems are already well-known and commonly used. Interview subjects for the first phase of data collection included experienced Eco-San operators and caretakers from multiple communities in the district, including Kasensero, with the goal of identifying experiences and issues common to Eco-San systems in the area. The second phase of interviews included the students and teachers at Saint Andrews and Kalisizo Muslim who had been most involved in the operation and maintenance of the installed facilities.

Figure 5: UDDT educational sessions at Kalisizo primary schools (all photographs taken by the author). (a) Brick by Brick Uganda's program coordinator explaining Eco-San concepts in a classroom setting; (b) Brick by Brick Uganda's program coordinator showing the demonstration UDDT to students.

3.2.5. Qualitative Data Collection

A breakdown of the various qualitative data collection activities that occurred during both phases is provided in Table 3. Prior to the first phase of data collection, semi-structured guides for focus group discussions and key informant interviews were developed. The content of these tools was guided by surveys conducted in Panama by Kaiser (2006) and Mehl (2008), and in Uganda by Kamuteera et al. (2013). After development, the guides were translated into Luganda, the predominant language in Rakai District. The English versions of the Stage 1 data collection tools can be found in Appendix B.

The first phase of data collection took place between August, 2013 and December, 2013 and examined different topics regarding the acceptability of UDDTs in Kalisizo Town. Focus group discussions and key informant interviews were not conducted by the author. Rather, they were conducted, in the locally-spoken language of Luganda, by Ugandans who worked as research staff for Rakai Health Sciences Program, a local HIV/AIDS research institution, and were used to evaluate attitudes, particularly barriers and motivators, and levels of knowledge in Kalisizo school communities, as well as among residents of Kasensero, with respect to subjects' experiences using UDDTs. Participants were recruited through discussions with teachers in the school communities, or from community leaders in Kasensero. They provided lists of several students and parents (in the case of schools) or community residents (in the case of Kasensero) who would be articulate and comfortable enough to actively participate in discussions. Brick by Brick staff then randomly selected a subset from these lists, students were asked if they would like to participate, and informed consent was obtained from the subjects and from their legal guardians (in the case of minors) prior to participation, as described in further detail below. As the first phase progressed, an iterative approach to data collection was followed, which involved allowing guiding questions and probes to emerge from data that had been collected in earlier focus groups and interviews, particularly to explore knowledge and attitudes towards UDDTs in these settings. This approach allowed guide questions to be refined and, if necessary, redefined.

Focus group discussions contained between seven and ten participants and were conducted at central, private venues. In the case of student groups, the venue was located at the school in question, while, for parents, the location was either at the school or a nearby central venue within the community. In Kasensero, focus groups took place in a central venue within the village. Several photographs taken during focus group discussions are shown in Figure 6. Key informant interviews were conducted at private locations convenient to each subject. On average, key informant interviews and focus group discussions lasted for 45 and 90 minutes, respectively. Each interview and discussion group was conducted in Luganda and was tape-recorded to ensure that all important points were captured. The tapes were used to support complete and accurate transcription, and were later stored in locked files at the Brick by Brick office.

Table 3: Breakdown of qualitative data collection activities

Data Collection Phase	Data Collection Method	Participants	Location	Number
Phase 1	Focus Group	Female students	Kalisizo Muslim	1
	Focus Group	Male students	Kalisizo Muslim	1
	Focus Group	Female students	Saint Andrews	1
	Focus Group	Male students	Saint Andrews	1
	Focus Group	Female parents	Kalisizo Town	1
	Focus Group	Male parents	Kalisizo Town	1
	Focus Group	Female Eco-San users	Kasensero Village	1
	Focus Group	Male Eco-San users	Kasensero Village	1
	Key Informant Interviews	Eco-San operators in outside communities	Rakai District	6
Phase 2	Focus Group	Female student users	Kalisizo Muslim	1
	Focus Group	Female student non-users	Kalisizo Muslim	1
	Focus Group	Male student non-users	Kalisizo Muslim	1
	Focus Group	Female student users	Saint Andrews	1
	Focus Group	Female student non-users	Saint Andrews	1
	Focus Group	Male student non-users	Saint Andrews	1
	Key Informant Interviews	Eco-San operators at intervention schools	Kalisizo Muslim, Saint Andrews	6

In the second phase, focus group discussions and key informant interviews explored topics similar to those discussed during the first phase, allowing the results from the two phases to be compared. However, a specific set of study objectives and questions was developed for this second phase to guide facilitators and interviewers, focusing on changes in knowledge and attitudes, acceptance of the facilities, and user experiences. These Phase 2 Objectives and Questions can be found in Appendix B. The second phase took place between July, 2014 and August, 2014.

Figure 6: Phase 1 focus groups conducted before installation of demonstration UDDTs (all photographs taken by Max Ssenyonga). (a) Focus group including male adults from Kasensero, the control community; (b) focus group including female adults from Kalisizo Muslim Primary School; (c) focus group including male students from Saint Andrews Matale Hill Primary School; (d) focus group including female students from Saint Andrews Matale Hill Primary School, reading consent forms prior to the discussion.

In both phases, interviews were transcribed by the primary interviewer within a median time of 26 hours after data collection. Each focus group was facilitated by a moderator, a note taker, and an assistant note taker. All discussions were transcribed by the note taker within a median time of 29 hours after the end of the session. Each focus group discussion was reviewed by the moderator before being passed on to the member of the team responsible for quality control, who read the handwritten transcripts and cross-checked them against the recording. This procedure was designed to ensure accurate transcription and translation that considered contextual meaningfulness, completeness, and preservation of appropriate local terms in the transcript. Interview data were transcribed verbatim. After editing, all transcripts were typed. Typed transcripts were returned to the note taker (focus group discussions) or the interviewer (key informant interviews) for review to correct typographical errors and make appropriate edits.

3.2.6. Qualitative Data Analysis

Data analysis was conducted iteratively to identify emerging and diverging themes. As a result, data collection and analysis often took place simultaneously, so that the analysis could inform and shape new waves of data collection. Completed transcripts were read to identify broad themes, and the team of researchers held weekly progress review meetings to discuss emerging qualitative themes. The analytical process was based on immersion in the data and repeated reading, sorting, and coding, as recommended by Corbin and Strauss (2007). The research team used Creswell's "lean coding" approach, in which a shortlist of five to seven tentative codes was developed, then categories were expanded through rereading and open coding until saturation was reached (Bowen, 2008; Creswell, 2007). These categories became the final codes, which were then linked to the major research questions. Transcribed data were imported into Atlas.ti (Muhr, 2004), the Knowledge Work Bench, Version 5.5.9, to facilitate the application of codes and development of data summaries. The language of participants was used to guide development of code labels, which were identified short descriptors, known as *in vivo* codes, representing barriers, motivators, advantages, challenges, training experiences, and recommendations.

3.2.7. Ethical Considerations

The research activities were approved by the Uganda Virus Research Institute's Science and Ethics Committee (UVRI-SEC), and the Uganda National Council for Science and Technology (UNCST), as required by the regulatory research processes in Uganda. Appendix C contains letters from the UVRI-SEC and UNCST approving the research activities. The Rakai District Education Office supported this research, and the University of South Florida Institutional Review Board (IRB) staff reviewed the research proposal and concluded that USF IRB approval was not necessary (see Appendix C for the relevant email message from USF IRB staff). All participants were given information relating to the research and provided written informed consent before participation. Parental consent was obtained for all children under 18 years of age, as required by Uganda research regulatory procedures. Appendix C also contains the approved, English-language version of the consent form that was used to obtain consent from all participants. After each focus group discussion and key informant interview, the note-taker, facilitator, and/or interviewer provided additional information on Eco-San and general sanitation, whenever it was deemed appropriate.

3.2.8. Physical and Chemical Testing

During a monitoring period that extended for approximately ten months after UDDTs were installed, pH, moisture content, and temperature conditions were measured every one to two months in fecal vaults and stored urine at both schools. Detailed procedures for all physical and chemical tests are included in Appendix A. Measurements of pH were performed using the method described by Mehl et al. (2011). Samples of fecal products were collected in a container, an approximately equal volume of water was added, the mixture was shaken, and the pH of the supernatant was measured using pH indicator strips. Temperature measurements were performed according to Standard Method 2550 B (Rice et al., 2012). A single thermometer (Taylor 9842 Digital Waterproof Thermometer) was used for all measurements, but the instrument was cleaned between each use with alcohol swabs (Kendall, 70% isopropyl alcohol). Moisture content was measured according to the procedure described in Standard Method 2540 G (Rice et al., 2012); however, samples were heated and dried using a solar oven constructed in-house. An adjustable cardboard panel, covered with aluminum foil, directed sunlight through a clear plastic opening in the top of the oven compartment to heat samples, which were placed on a black platform inside the compartment. The interior walls were also covered with aluminum foil to redirect any stray sunlight toward the platform. Because solar drying was used, moisture content measurements could only be performed during appropriate weather conditions, and extended drying times (5 to 8 hours per day for 5 to 10 days) were required.

3.3. Results

In Phase 1, a total of 77 people participated in focus group discussions, and nineteen of these participants were residents of Kasensero fishing village, where UDDTs had previously been installed. An additional six people were interviewed as Key Informants due to their roles as operators or caretakers of Eco-San systems. These individuals resided in a few different communities throughout Rakai District where Eco-San facilities were in use. The data collection activities of Phase 2 included a total of 65 participants, all of whom were students or teachers at the two primary schools where Brick by Brick installed demonstration UDDT facilities. Of these participants, two teachers and four students who were identified as being highly involved in the operation of the facilities were interviewed as Key Informants.

3.3.1. Participant Demographics

Table 4 provides demographic information for all Phase 1 and Phase 2 participants. Among Phase 1 participants, 69% of adults were married, agreeing with data from a recent national survey in which 61% of respondents (age 15 to 49) were married (Uganda Bureau of Statistics and ICF International Inc., 2012). Of participants in both phases, 61% identified themselves as Catholic, while 25% were Muslim. This distribution is not representative of the country as a whole. Overall, 42% of the population is Catholic, 42% is Protestant, and 12% is Muslim (CIA, 2014). Because one school being studied was associated with the Catholic Church and the other was part of the Uganda Muslim Education Association, this research contained higher percentages from these two religious groups.

The six Phase 1 interview participants were found in communities throughout Rakai District where Eco-San systems were being used, and each was involved in the daily management of the local facilities. The interview subjects ranged in age from 17 to 40, and two of the six participants were female. These individuals came from both school and general community settings. Two subjects worked at primary schools, two worked or studied at secondary schools, and the remaining two operated and maintained public, community-based Eco-San systems that served up to 100 people daily.

Table 4: Demographic information of all focus group and interview participants

Phase	Characteristics		Number	Percentage
1 (n = 83)	Data Collection Method	Focus Group Discussions	77	93%
		Key Informant Interviews	6	7%
	Sex	Female	41	49%
		Male	42	51%
	Age	10 to 13	28	34%
		14 to 17	12	14%
		18 and above	43	52%
	Marital Status	Married	29	35%
		Single	51	61%
		Widowed	3	4%
	Religion	Catholic	46	55%
		Muslim	24	29%
		Protestant	13	16%
	Facility Use	Eco-San Users	25	30%
		Eco-San Non-Users	58	70%
2 (n = 65)	Data Collection Method	Focus Group Discussions	59	91%
		Key Informant Interviews	6	9%
	Sex	Female	44	68%
		Male	21	32%
	Age	10 to 13	38	58%
		14 to 17	25	38%
		18 and above	2	3%
	Marital Status	Married	1	2%
		Single	64	98%
		Widowed	0	0%
	Religion	Catholic	44	68%
		Muslim	13	20%
		Protestant	8	12%
	Facility Use	Eco-San Users	24	37%
		Eco-San Non-Users	41	63%

In Phase 2, all 59 focus group participants were students in the two Kalisizo primary schools where Brick by Brick had installed demonstration facilities, while the six interview subjects included two teachers and four students who had been given leadership roles in the operation and management of the facilities. In this phase, females comprised approximately two-thirds of all participants, since, at both schools, female students in Primary 6 had been chosen to operate the facilities. To obtain perspectives from both female users and non-users, in addition to male non-users, more female students were included in the Phase 2 focus groups.

3.3.2. The Views of the Control Community and Outside Operators

During Phase 1, focus group discussions were conducted among students and parents at the two Kalisizo primary schools, as well as among residents of Kasensero fishing village. Kasensero functioned as the control community in this research, since Eco-San systems had previously been installed due to soil conditions that were unsuitable for pit latrine construction. Table 5 provides a summary of the questions that were asked of participants during the focus groups in both communities. Follow-up questions regarding Eco-San knowledge were often more detailed during Kasensero focus groups, due to the participants' higher levels of knowledge. In Kalisizo focus groups, if no participants exhibited knowledge regarding Eco-San systems, basic principles were described to provide a basis for answering subsequent attitude questions. Interviews were conducted among experienced operators of Eco-San systems throughout Rakai District, and Table 6 shows a summary of the questions asked during these interviews.

Among residents of Kasensero fishing village, knowledge regarding these systems was fairly high, especially in the cases of the facility operators who were interviewed. Of the six interview participants, five had received some level of training on the principles and operation of Eco-San systems. In the case of the sixth, she had worked to train herself to ensure that she would operate the facilities correctly: "I did not receive any training…I live here most of the time, and it's imperative for me to take care of the toilet facility and live at least in a healthy environment" (interview, female operator). All of these operators were aware of key issues involving the separation of urine and feces, the addition of wood ash to promote dry conditions within the fecal collection vaults, the importance of allowing for a storage period before emptying a full fecal vault, and the necessity of regular monitoring to ensure that users are following the correct procedures. For example, regarding the addition of ash: "After using the

Eco-San toilet one has to pour ash in the feces hole. One uses one handful of ash after using the toilet. This ash helps to dry the feces" (interview, male operator). With regard to urine diversion, another operator made the following statement: "How to use the different holes, we were taught their uses. The small hole drains urine while the bigger one collects human feces. When it gets full you close it for six months, during which time you use the other" (interview, female operator). Similarly, concerning the problems that can arise with urine diversion: "Feces should never mix with urine. If the urine hole is blocked, we have to unblock it to prevent mixing of these components (urine and feces)" (interview, male operator).

Table 5: Phase 1 focus group discussion questions

Category	Question
Introduction	What is the importance of using pit latrines/toilets in our environments?
	What different types of pit latrines/toilets exist in our community? Which ones have you heard exist in other places?
Knowledge	Have you ever heard of/seen/used Eco-San systems? If yes:
	Where have you heard of/seen/used these toilets?
	When did you first hear of/see/use these toilets?
	What are the major differences between UDDTs and pit latrines?
	What do you think are the major benefits in using UDDTs over pit latrines?
	What do you think are the major disadvantages in using UDDTs over pit latrines?
	What are the different steps taken in operation of UDDTs?
Attitudes	Tell me about your experiences or what you have seen/heard are people's experiences in using UDDTs?
	What do you think are the major advantages in using UDDTs over other types of latrines?
	What are the major challenges in using UDDTs compared to other types of latrines?
	What are your thoughts and feelings about the whole process of handling urine and feces in Eco-San systems?
	Do you think community members would be receptive to installing UDDTs in their homes instead of pit latrines?
	What are the anticipated challenges in installation and operation of UDDTs in ordinary homes?
	Do you think people in homes will be willing to learn about the principles of the system?
	Will they be willing to follow operational procedures?
	Will they be willing to reuse urine and feces after treatment?
	What about among school communities and other public places? Do you think they will be receptive to install UDDTs?
	What are the anticipated challenges in installation and operation of UDDTs in schools and other public places?
	Do you think schools and public communities will be willing to learn about the principles of the system?
	Will they be willing to follow operational procedures?
	Will they be willing to reuse urine and feces after treatment?
	What do you think will be people's thoughts about crops that have been fertilized with treated urine and feces?
	Will they take as important the nutrient value of the treated feces and urine?
	Will they consider the consumption of the fertilized crops to be risky?
	Will they be willing to consume these crops fertilized with urine and feces?
Recommendations	What are your thoughts about what can be done to overcome the discussed challenges?

However, some discrepancies among participants' responses were noted with regard to certain key operational guidelines. For example, most operators and users mentioned that they needed to store the collected feces for a period of at least six months, which agreed with the minimum recommendation of the World Health Organization (WHO, 2006). However, when one Key Informant was discussing the alternating use of a UDDT's two vaults, he stated, "Once one chamber is full, you close it and use another chamber. After three months you open the full chamber and remove the feces debris" (interview, male operator). The storage time reported by this individual is significantly shorter than the recommended time mentioned by other participants and by Eco-San promotional materials found in Uganda.

Table 6: Phase 1 key informant interview questions

Category	Question
Facility installation	In what year was your Eco-San system installed?
	Why was an Eco-San system chosen instead of a pit latrine or other sanitation system?
	Who or what organization installed this Eco-San system?
	Did you receive training when the facility was installed?
	If so, what topics were included in this training?
Facility use and operation	Is the Eco-San system used only by members of one household/institution, or do others also use the facility?
	Do children use the facility? If so, what challenges do they experience?
	Are desiccating materials added to the vault?
	If so, what materials are added, when are they added, and what is the amount added?
	What challenges are experienced in adding desiccants?
	How long are feces stored in the vault before emptying?
	How long is urine stored before use or disposal?
	Would it be acceptable to use treated feces and urine for agriculture in your community?
	Are treated urine and feces ever used? If so, in what way are they used?
User satisfaction	Do the users prefer this Eco-San system over other types of latrines/sanitation systems?
	Why?
	What are the advantages of this facility over other types of latrines?
	What are the disadvantages when compared to other types of latrines?
	What challenges have been experienced in using this facility?
	What has been done to address these problems?
	What suggestions do you have for addressing these problems?
Recommendations	Another group is planning to set up Eco-San systems to serve schools. What advice would you give them?

During both focus groups and interviews, a wide array of issues and challenges related to the operation and perception of Eco-San systems were discussed. A number of these issues have also been observed in other countries and in other areas of Uganda (Austin, 2003; Kaggwa et al., 2003; Kamuteera et al., 2013). One of the most prevalent issues concerned the availability of wood ash. Some type of desiccant is a crucial component of UDDT operation, since the reduction of flies and odors and the treatment of feces are dependent upon its regular addition (Esrey et al., 2001). Due to the widespread use of firewood as cooking fuel in Uganda (Uganda Bureau of Statistics and ICF International Inc., 2012), wood ash is the most common desiccant recommended in the country. However, a substantial amount, between one and two cups, is needed after each use (Mehl et al., 2011), and households and institutions often do not produce an adequate supply. In the words of one participant: "The school kitchen produces very little ash and most students do not want to carry it from their homes. They complain their homes are far and ash is heavy to carry" (interview, male operator). This issue has also been seen in UDDTs located in other areas of Uganda (Kaggwa et al., 2003; Kamuteera et al., 2013). Interviews also revealed that this problem can be seasonal. One operator explained, "Wood ash is scarce during rainy season" (interview, male operator). During this time, many households switch to other types of cooking fuel due to lower availability of firewood, perhaps because local loggers are less likely to work in the rain. In other words, ash may be least available when it is most needed to maintain dry conditions within the vaults. Due to these shortages, operators sometimes switch to a different desiccant material:

> "No, there is always not enough ash, and this mostly happens during rainy season…That is why sometimes I end up buying lime to substitute the ash. However, this lime is expensive, yet the money I collect from people who use this toilet is very little. So, I end up sacrificing my own money to use on maintaining this toilet" (interview, male operator).

Another commonly reported challenge involved clogging and blockage of the urine piping. Attempts to remove these blockages could have adverse effects on the integrity of the pipe. As one primary school operator described, "Some school children at times pour ash in the urine hole, and this causes blockage. During unblocking, one may use much force, and this may affect the pipe joint" (interview, male operator). Accidentally depositing ash in the urine hole appears to be fairly common, and the ash often contains small stones, sticks, and other debris, which contribute to the clog. Sometimes, other materials were also found in urine pipes: "Someone puts the feces at the place where urine should instead be going…The children can push stones in the pipe" (interview, male operator). If the pipes do happen to be blocked, some users may simply continue to use the facility, regardless of the consequences: “When it (the urine pipe) gets blocked, the children do not mind. Instead, they continue to use it, so that the urine overflows and pours into the chamber, causing mixing” (interview, male operator).

Both of the preceding issues, along with other types of misuse, contribute to a major obstacle in the acceptance of Eco-San systems. When the system is operated incorrectly, users may be forced to endure unpleasant and unhygienic conditions. As one participant stated:

> “If you are not a clean person, you are likely to cause problems. The toilet can stink. For example…the Eco-San toilet in our zone…we totally failed to use that toilet…Even when you try to squat, you have to squat halfway because you always find the urine floating where it is supposed to go. When you squat on the hole for feces, you can see the feces and maggots. The rear metallic doors are worn away and rusted” (focus group, female user).

One of the Key Informants also reported that a number of users do not follow the appropriate procedures, allowing urine and water to enter the fecal vaults. “At least every day, there has to be a person who mixes his/her urine and feces” (interview, male operator).

Another issue observed by experienced Eco-San users and operators involved a general lack of clean water available nearby for hand-washing. Beyond concerns of basic hygiene, this situation also deterred users from depositing ash into the fecal vaults, especially when a cup was not present within the toilet for this purpose: “We do not have water at the toilet. After using the toilets, one walks for about 200 meters to get water for washing hands. Most children fail to pour ash because they do not want to become dirty with ash” (interview, male operator). This issue could also be particularly problematic for Muslim users, who, in Uganda as well as in other countries, traditionally use water, rather than toilet paper, to clean themselves (Warner, 1998).

Finally, emptying of fecal vaults was seen as a significant issue by a number of users. In school settings, students were expected to be involved in this process and move the feces to another storage location: “Emptying…is a big challenge. Students do not want to carry a sack with feces. They do not like it at all” (interview, male operator). Other users outside of a school setting were extremely resistant to the idea of handling feces: “Some people detest scooping dried feces from the chambers. They look at it as being indecent…Most people perceive that…it is unbecoming to handle feces. Even if you explain that it has been treated with ash and it is not dangerous, still they cannot accept it” (interview, male operator). These problems were complicated further if the material was not as dry as it should have been: “We noted that the feces remain wet by the time we come to empty…it smells bad and cannot dry, instead maggots multiply. During rainy seasons…it can flood. Many insects and houseflies keep around that place and make the place so filthy” (interview, male operator). Even beyond these issues, additional problems were created when users needed to empty fecal materials that that were wet and odorous: “We use students to empty them, yet we remove wet feces…The work is hard…Removing wet, smelly feces is a challenge. When feces are removed towards lunch, the students fail to eat. They lose appetite because of that smell” (interview, male operator).

Despite the broad range of issues experienced and observed by Eco-San operators and members of the control community, participants displayed a number of positive attitudes toward Eco-San systems, due to their advantages when compared with pit latrines. Almost all Key Informants mentioned the durability or the permanence of Eco-San systems. According to one operator, “It lasts long because it has to be emptied regularly. It does not fill up like ordinary pit latrines. Once one chamber is full, you empty it and use another chamber. It lasts longer” (interview, male operator). Some participants saw Eco-San systems as facilities that will last for several decades, referring to them as “toilets of the children and grandchildren” (focus group, female user). This recurring process of vault reuse makes Eco-San systems ideal for areas with growing populations and limited land area, such as fishing communities and small towns: “Places with big populations, like Kasensero, need Eco-San types of toilets, because they last long once they are well managed” (interview, female operator).

Although participants acknowledged the problems that can arise when an Eco-San system is mismanaged, they also noted that, when operated correctly, the facility provides a more pleasant and hygienic atmosphere than a pit latrine does:

> “The Eco-San toilet does not spread infections…It is not like any other toilets. It does not smell, the ash dries the feces, and the urine goes to other places. When the two are put together it attracts houseflies and this produces maggots as well. When these are separated…they do not mix, and there is no problem” (interview, female operator).

In addition to being more hygienic, Eco-San facilities were also thought to be structurally safer. One participant noted that, during rainstorms, these systems maintain their structural integrity. In contrast, “When it rains heavily, most pit latrines here [in Kasensero] get flooded with water and they collapse” (interview, male operator). Due to the comparatively small size of the Eco-San fecal vaults, which contributes to the facility’s structural stability, they are also relatively easy to empty when the feces are ready to be removed. This view was expressed in economic terms by one of the Key Informants: “One of the advantages of using an Eco-San toilet is that you don’t need a lot of money to empty it” (interview, male operator). In this case, the participant was comparing Eco-San facilities with pit latrines and septic systems, which can be quite expensive to empty in small towns without wastewater treatment facilities, due to substantial pumping and transportation costs (NETWAS-U, 2011a).

A final benefit commonly reported among focus group and interview participants involved the agricultural value of the products of Eco-San systems. Users discussed their own application of these materials, or the application of others within their communities: “Dried feces are used as manure in our school garden” (interview, male operator). Some participants emphasized positive effects on crop production, but they also acknowledged that some people in their communities were not willing to buy items that had been fertilized with Eco-San products: "We got good yields and tried to sell some crops, but people who knew we had used fecal manure from the Eco-San toilet refused to buy maize" (interview, male operator). The prevalence of these negative attitudes toward Eco-San fertilizers has also been observed in other areas of Uganda (NETWAS-U, 2011a) and in other African countries, such as Zimbabwe (Manyanhaire et al., 2009). In the United States, negative perceptions regarding land application of biosolids are also a significant issue (Robinson et al., 2012). Faced with this reluctance, some farmers were reported to apply Eco-San fertilizers secretly and sell the produce to unknowing customers. According to one interview subject in Kasensero, customers "consume them [vegetables] without knowing they were grown with that fertilizer. The person who uses that fertilizer cannot use it when other people are seeing him/her. People buy these crops from markets without knowing how they were grown" (interview, female operator).

3.3.3. The School Communities before Installation of Demonstration Facilities

In contrast to the control community and the interviewed Eco-San operators, the level of knowledge regarding Eco-San systems in the two Kalisizo school communities was very low, especially among students, prior to the introduction of the demonstration facilities. Many focus group participants had never seen or heard of UDDTs, while some students who thought they had encountered them revealed, through their descriptions, that they had actually mistaken other types of toilets for these facilities: "I used it. There is water where you defecate, and, after the process [defecation], you pull a metal lever, the water flows over, and the waste is carried away" (focus group, male student). From this account, it is clear that the student was referring to a water-based, flushing toilet. A few households, hotels, and other institutions in Kalisizo have these types of facilities available, and some students are likely to have observed them and acknowledged them to be different from the nearly ubiquitous pit latrine. A related misconception among students and parents involved the cost of emptying an Eco-San facility. Many participants expressed the belief that these systems are expensive to empty, because “you have to hire a truck to empty it” (focus group, male student). It is probable that this participant was again misidentifying a water-based system, in which a septic tank needs to be emptied by a truck with pumping equipment, as an Eco-San system.

Perceptions of Eco-San systems within Kalisizo schools were generally more negative than those from the Kasensero control community. On balance, negative attitudes outweighed positive ones. Positive views echoed some of the benefits described by the control community, including permanence and fertilizer value, although opinions regarding fertilizers were mixed. Regarding permanence: “Once you have built an Eco-San toilet, you get relieved from digging toilets all the time, because for the local toilets (pit latrines) after three years it gets full and you dig another one, but with Eco-San you get relieved from this problem” (focus group, female parent). This idea of permanence was seen as especially valuable in a small town setting, because it could save valuable space: “For some of us who live in the town council, we stay on small plots that have limited space and thus this toilet helps us not to dig pit latrines anywhere…You dig once and for all” (focus group, female parent). Some participants were excited by the idea that a toilet could produce something of value: “I have liked this kind of toilet because it does not serve only one purpose…We use our very wastes on our crops and get nutritious food. I think we even need to clap for this” (focus group, female parent). However, others expressed an aversion to the use of human excreta, even though it is common in the area to use bovine waste as a soil amendment. According to one participant, “By handling a person’s feces…naturally you feel disgusted…and thus you don’t feel good using feces or urine as fertilizers on vegetables” (focus group, female parent).

It is likely that some negative attitudes were caused by misconceptions, but, even after Eco-San systems were explained, negative views remained predominant. Although participants reported no socio-cultural barriers, which had been found previously in some areas of the country (Kaggwa et al., 2003) but not others (Niwagaba and Asiimwe, 2005), a number of practical concerns were expressed.

Beyond being perceived as expensive to empty, Eco-San systems were also thought to be expensive to construct, especially relative to pit latrines. As one participant explained, “For the local latrines, you just dig a deep hole and that is all, but, with the Eco-San toilet, you require a lot of things to build this toilet” (focus group, female student). This individual went on to provide examples of the additional expenses involved, such as the cement needed for the concrete floors of the collection vaults and the metal panels that act as access doors to the vaults.

Certain structural characteristics of UDDTs also stimulated a negative reaction. Due to the presence of fecal collection vaults, the toilet room is raised a few feet above the ground, and stairs are usually constructed leading to the entry. Focus group participants noted that this component could create difficulties for disabled or elderly users: “We have old people who have problems with their legs and cannot climb these stairs. We also have disabled people at home who cannot manage to climb this toilet” (focus group, female parent). Some UDDTs in Uganda incorporate a ramp, making these facilities more accessible, but a perception that the facilities require stairs could hinder initial acceptance.

Participants also recognized the possibility that people might use the facility incorrectly: “They may defecate where you are supposed to urinate and vice versa, or he/she may mix both urine and feces” (focus group, male student). The student further explained that misuse could result in odors and an objectionable atmosphere within the facility. Additionally, the size of school systems was seen as a potential issue: “What I see is that in a school, these toilets may not work well, since the pupils are many at school, the bucket of urine will be filled so fast, and the urine will be pouring down” (focus group, female parent). These concerns led participants to express skepticism regarding the idea of locating Eco-San facilities in public places, since it would be difficult to monitor users and maintain acceptable standards of hygiene. One parent commented, “In public places…these toilets cannot work…but will instead spread diseases. These toilets can only work well if they are installed in people’s homes” (focus group, female parent).

3.3.4. The School Communities after Installation of Demonstration Facilities

The second phase of focus group discussions and key informant interviews took place after UDDTs had been installed in the two school communities in Kalisizo and a group of students had been using the facilities for more than six months. Focus group and interview questions were similar to those used during Phase 1 to facilitate comparison. Table 7 provides a summary of additional questions that were incorporated in Phase 2. These questions focused specifically on how knowledge and attitudes had changed and on the experiences of facility users.

Table 7: Additional questions for Phase 2 focus groups and interviews

Category	Question
Changes in knowledge and attitudes	Do school community members have a better understanding of the principles of Eco-San systems?
	Do school community members feel that UDDTs are an appropriate and beneficial sanitation option?
Acceptance and user experiences	What benefits have members of the school community seen as a result of the UDDTs?
	What disadvantages have community members seen?
	Have any problems been identified?
	How does the use of UDDTs generally compare with use of pit latrines and flushing toilets?
	What changes could be made to address any issues with UDDTs?
	Would members of the school community recommend that more UDDTs be constructed at local schools?

After facility installation and several months of operation, attitudes and levels of knowledge within these schools had changed considerably. These changes can be seen in Table 8, which summarizes the occurrence of different themes that were expressed during both phases of the research. Students, including those who were not using the toilets, exhibited extensive knowledge concerning UDDT principles and operation, articulating proper procedures and the basic rationale behind those procedures. Participants discussed topics that included the importance of applying wood ash to the fecal collection vaults, separating urine from feces, and emptying the collection vaults. For example, one student user described the importance of desiccant addition as follows: "When you go to defecate, after you are done, you put the ash on the human excreta so that the human excreta do not produce germs which will cause infections" (focus group, female user). Similarly, another user mentioned that ash addition can help to control odors: "If you do not put the ash, the human excreta will stay wet [makes disgusted face]; there is going to be a lot of smell in the process, like these [pit] latrines, which smell as they tend towards filling up" (focus group, female user). In a separate focus group, a non-user echoed this statement, saying, "If you do not pour…ash, they smell badly, and no one would be willing to use them" (focus group, male non-user). Similarly, urine diversion and collection was described by one user as follows: "There is…a pipe through which the urine passes and collects into the jerry cans. Such things are not found in the ordinary toilets (pit latrines)" (interview, female user). Another non-user, who had not received initial training from Brick by Brick, provided an astute description of the alternation between the two collection vaults and the emptying procedure:

> "The reason the ash is poured there is to have the human excreta dry; thereafter, that chamber is closed after getting filled up. Now the new chamber is opened for use, while you leave the previous chamber for some time. By the time you are about to have the other chamber filled, the first one that was closed should have already dried and turned into manure. So, you can now remove it and use it for agriculture" (focus group, male non-user).

Beyond participants' increased knowledge of these documented principles and practices, they also reported that local knowledge was being used to innovate and improve the system. For example, instead of simply storing urine for an extended period, operators added other materials that were believed to aid in treatment: "Before we put the fertilizers in the gardens we mix the collected urine with an herb called 'kawunyira' that controls or stops the bad odor. Later, we put it to the banana trees without a stench" (focus group, male non-user). Other materials, including wood ash, tobacco leaves, and red pepper, were also mentioned (interview, female operator), and it was noted that this supplemented urine can function as an effective pesticide.

With regard to participants' attitudes and opinions toward UDDTs, a substantial improvement over views that were expressed in Phase 1 was seen. However, a few disadvantages were still noted, mostly related to occasional problems with operation. For example, wood ash was not always added after use. According to one student, sometimes users "do not want to use ash. If you do not pour…ash, they (toilets) smell badly, and no one would be willing to use them" (focus group, female non-user). In other instances, ash was being added incorrectly, with some entering the urine diversion system: "When you pour the ash and it mistakenly goes in the hole for urine, it is very difficult to get it out. It gets stuck there" (focus group, female user). If this mistake resulted in serious clogging, participants reported that teachers and operators would close the facility for a few days, until the blockage had been removed.

Table 8: Incidence of themes expressed by participants from different groups. Symbols represent how often each theme was mentioned by all participants in a given group. For focus groups: x = 1 to 4 occurrences; xx = 5 to 14 occurrences; xxx = 15 or more occurrences. For interviews: x = 1 to 2 occurrences; xx = 3 to 4 occurrences; xxx = 5 or more occurrences.

Thematic Categories	Specific Themes	Phase 1			Phase 2	
		Control Community Focus Groups	Operator Interviews	Kalisizo School Focus Groups	Kalisizo School Focus Groups	Kalisizo School Interviews
Level of knowledge	UDDTs incorrectly identified		x	xxx		
	Desiccant use	xxx	xxx		xxx	xxx
	Urine diversion	xxx	xxx		xxx	xxx
	Periodic emptying	xx	xx		xx	xxx
	Knowledge of structural characteristics				xx	x
	Importance of monitoring	xx	xx			
	Incorporation of local knowledge				xx	x
Attitudes - disadvantages, challenges, and barriers	Expensive to maintain/empty		x	xxx		
	Lack of a feeling of ownership		x	xx		
	Not ideal for public places			xx		
	Not sufficiently large for school setting			x	x	
	Expensive to construct		x	xx		
	Not convenient for disabled/elderly			xx		
	Significant risk of infection	x	x	x		
	Mismanagement leads to problems	xxx	xxx	xx	xx	x
	Resistance to agricultural reuse	xx	xx	xx		
	Large amounts of wood ash required	xxx	xxx			
	Difficult to empty		xx	x		
	Urine piping becomes clogged	xx	xx		xx	
	Lack of water for hygiene	xx	xx			
	Fecal pile requires manual leveling				xxx	
	Heavy and odorous urine containers				xx	
Attitudes - advantages, benefits, and motivators	Durability/permanence	xx	xxx	xx	xxx	
	Value of agricultural reuse	xx	xxx	xx	xxx	x
	Absence of flies and odors	xx	xx		xxx	xx
	Easy to empty	x	x		xxx	
	Safer/less accidents				x	
	Long-term economic value				xxx	
	Urine diversion enhances hygiene				xxx	xxx
	Other hygiene facilities put in place				xx	

Other operational issues focused on the size of urine collection containers and the disagreeable task of moving them. The urine diversion systems were designed to direct urine into 20-liter containers positioned beside the fecal vaults. Urine production rates were such that these containers often filled in less than one week, and a large number were needed to allow for the necessary treatment period. Near the end of the storage period, the schools began to run out of containers:

> "We have not been using the toilet for the past few days because all the jerry cans (used as collection and storage containers) still contained urine, and the teacher had mixed that urine with ash and leaves…Yesterday, we took that urine to the garden. We washed the jerry cans, and we resumed using the toilet again" (focus group, female user).

Once these containers had been filled at the toilet, they were moved to another location for storage. Carrying these containers was also an issue for operators, since they were heavy and were occasionally characterized by an unpleasant smell: "Primary Six girls complain about having to carry filled up jerry cans…They smell a lot" (focus group, female non-user). During a monitoring visit, it was observed that one of the urine collection containers was overflowing, even though it was still connected to the urine diversion pipe. This scenario could have contributed to the odor identified by the users.

Despite the presence of these operational challenges, overall perspectives regarding these facilities were positive, and a number of benefits were reported. As in the first phase, the permanence of the facilities was emphasized, but, in Phase 2, the advantages of this quality were much more developed, especially with regard to economics: "When the toilet is full, you can remove the human excreta and use it again. But, with these other ordinary [pit] latrines, when it gets full, you just abandon it and dig another one" (focus group, female user). Participants recognized that this repeating cycle of emptying could be economically beneficial over the long term, since periodic emptying is relatively inexpensive and precludes the need for construction of additional facilities. Another student stated, "It lasts longer than ordinary pit latrines, as you have to empty human excreta regularly…We do not spend a lot of money because Eco-San is permanent" (focus group, female non-user).

This value was further enhanced by the fertilizers that UDDTs produce. Again, long-term economic benefits were emphasized: "You get manure, which you may use on your crops, and in the end you get money. You can use this money to build structures here at school" (focus group, female non-user). By applying UDDT products to school crops, higher yields can be obtained, and the school saves the money normally used to purchase food. The schools also provided urine fertilizer to students' families, potentially improving the economic and nutritional status of those households. Alternatively, the schools are hoping to sell fertilizer to local community members: "The teacher told us that whoever wants fertilizers can get some to take home. If your parents permit you, you can bring a small jerry can and put…urine…If you still need more, you come back and get more. The teacher told us that, if we get people who want to buy the fertilizer, we should bring them to her" (interview, female operator).

Although, during Phase 1, some negative views were expressed regarding the use of UDDT products in agriculture, most Phase 2 participants did not report reluctance in this area and also displayed an understanding of the additional barriers to pathogens that exist between crop fertilization and consumption. As one student stated, "We cannot detest these crops because we know it very well: the manure is applied to the soil, and the crops sprout out of the soil. The manure remains under the ground, and maize has to be cooked before it is eaten" (focus group, female non-user). The participants also discussed an improvement in quality regarding the crops fertilized with urine and expressed their willingness to consume these crops: "Students in the boarding section were very happy because the maize was so big and good" (interview, male non-user). Similarly: "Such bananas always produce big bunches and…soft fruit. Food from such plants is always tasteful" (focus group, female non-user). However, it should be noted that, at the time of Phase 2 focus groups and interviews, fecal products had not yet been put to use. This acceptance of UDDT fertilizers was likely influenced by initial observations of the benefits of urine application and perhaps by the content of educational sessions.

Opinions regarding the hygienic conditions of the facilities were also favorable. Participants noted that a major advantage of the UDDT was the absence of flies and odors, which, in addition to the use of wood ash, was partially attributed to the design of the urine diversion system:

> "A pupil may go to the pit latrine and urinate all over the toilet, and you also go in to use in the same pit latrine. You may pick up some germs or infections. But with the Eco-San toilet, you cannot urinate over the toilet. The hole for urine was well-designed and it is big enough. When you pass urine, it goes to the hole and then through the pipe. You cannot pick up infections from the Eco-San toilet" (focus group, female user).

Participants also expressed an understanding of the potential for insects to carry diseases as a result of fecal contamination, and they saw Eco-San facilities as providing an effective barrier against infection: "Eco-San toilets do not spread diseases because they do not produce insects or maggots like those you find on top of the ordinary latrines. You can get diseases from the maggots" (focus group, female user). Although other research (Austin, 2003) and the control community mentioned considerable issues regarding urine diversion systems, Phase 2 participants in the school communities actually viewed them as improvements over the simple holes of pit latrines, creating a more hygienic environment. The smaller feces hole and the absence of a deep pit were also thought to make the facility safer. It has been reported in Uganda that some pregnant women will avoid using latrines, due to fears of losing the child in the pit (Kaggwa et al., 2003). Participants considered UDDTs to be less dangerous in this regard, since, if someone or something fell into the hole, recovery would be a relatively simple matter of opening the vault's rear access door: "If an item fell in the Eco-San toilet, it can be easily recovered. An item like a 'geometry set' can be easily picked from an Eco-San toilet" (focus group, male non-user).

One of the most interesting benefits reported by participants transcends the specific characteristics of UDDTs and involves a broader conversation about general sanitation and hygiene concerns. In addition to the demonstration toilets, students reported other facilities and features that had been put in place after installation of the UDDTs: "Eco-San toilets help to prevent infections like cholera and dysentery because there is a hand-washing facility….Eco-San toilets help to enforce hand washing after toilet use" (focus group, female non-user). A hand-washing station to complement the

UDDT had not been installed initially. The school later added this feature. Of course, hand-washing facilities and pit latrines are not exclusive of one another, but it seems that the installation of an improved system that placed value on proper sanitation and hygiene prompted the schools to consider other ways in which hygiene could be promoted.

Similarly, when users discussed the advantages of the wash hole, included in the UDDT design to facilitate cleaning with water rather than toilet paper, other positive effects were revealed:

> "It helps girls to keep themselves clean. When a girl is in her menstruation period, when the pad is used up, you can go to the Eco-San toilet and remove it, because they put for us a bucket where we dump the used-up pads. After removing the used-up pad, you put a new one. I don't see a provision of a bucket in these other ordinary latrines" (focus group, female user).

These girls now had a private place where they could wash and dispose of pads during menstruation. Again, menstrual hygiene facilities could be incorporated into ordinary pit latrines, but it appears that the presence of a sanitation system seen as more hygienic has catalyzed the provision of other health-related elements.

3.3.5. Assessment of Schools' Operation of UDDT Facilities

Visits conducted by Brick by Brick staff to monitor operation largely confirmed what was reported in the Phase 2 focus groups and interviews. With the exception of observed issues related to occasional deficiencies in the addition of wood ash, inadequate mixing within fecal vaults, and minor overflowing of urine containers, toilets were kept in good condition for the duration of the monitoring period. Compared with the schools' pit latrines, substantial reductions in flies and odors were observed, likely due to a generally effective urine diversion system and sufficient desiccant use. During the visits, pH and temperature conditions within fecal collection vaults and stored urine were measured, and samples were taken from fecal vaults to test the moisture content of the material. Results of all measurements are included in Appendix D, and a summary is presented in Table 9.

Table 9: Summary of treatment conditions in stored urine and fecal products in school UDDTs

Material	Measurement	Range	Average ± Standard Deviation	Recommended Range
Fecal Products	Temperature (°C)	22.3 - 34.3	25.6 ± 4.4	> 42.0[a]
	pH	9.0 - 10.5	10.2 ± 0.6	> 9.0[b]
	Moisture Content (%)	8 - 19	15 ± 4	< 25[b]
Stored Urine	Temperature (°C)	20.0 - 23.6	21.8 ± 1.1	> 20.0[b]
	pH	8.5 - 9.0	8.9 ± 0.2	> 8.8[b]
Ambient Storage Temperature (°C)		19.7 - 23.9	21.8 ± 1.3	-

[a] Mehl et al. (2011), refers to required temperature for pathogen removal during composting
[b] WHO (2006)

Moisture content and pH conditions within fecal products met the recommended storage conditions of pH levels above 9.0 and moisture contents below 25%, suggesting that most pathogens (with the exception of extremely persistent organisms such as *Ascaris lumbricoides*) would be removed after a storage period of twelve months (WHO, 2006). The pH and moisture content values did vary considerably depending on the sampling day and on the location of the sample within the pile. This variation was likely a result of inadequate mixing. However, the values still reached or surpassed the storage recommendations, and they were also better than vault measurements from previous studies. In China, for example, moisture contents from 15% to 66% were observed in dry toilets that had been in use for three months (Peasey, 2000). In Panama, composting toilets in which wood ash was used as the desiccant were found to have moisture contents ranging from 29% to 47%, while pH levels in these toilets averaged 8.3 (Mehl et al., 2011). These findings suggest that more ash was being added to the UDDTs in Kalisizo than to the toilets studied in Panama and in China.

The temperature within fecal products reached a maximum of 34.3°C, almost 15°C higher than the corresponding ambient temperature. These temperatures are comparable to the average temperature of 33.9°C observed in fecal piles in Vietnam (Chien et al., 2001), although the ambient vault temperature there (34.7°C) was much higher than in Uganda. These results indicate that some level of biodegradation was occurring within the vaults. However, the process was extremely inconsistent, as shown by the wide range of observed temperatures and an average temperature that is far below the maximum. In these UDDTs, it is possible that the biodegradation process was enhanced by incomplete mixing in certain areas of the pile that did not exhibit prohibitory pH and moisture levels. Even in the absence of adequately mixed conditions, however, no temperatures were observed above 42°C, the level at which all pathogens are destroyed after six months of storage (Mehl et al., 2011).

3.4. Discussion

Based on the information from qualitative data collection and from facility monitoring, a number of significant trends were noted. A discussion of these trends is included in this section, and a number of recommendations for expansion are presented.

3.4.1. Improved Knowledge as a Result of Demonstration Facilities

In general, Eco-San operators and residents of Kasensero fishing village, used as a control community in this research, exhibited a relatively high level of knowledge, due to the fact that UDDT facilities had been installed previously in this community. Similar to other shoreline settlements in Uganda (Kaggwa, 2003), Kasensero was provided with public Eco-San facilities, to be used by all members of the community, and with school-based facilities for students. These systems were installed by a variety of NGOs over a number of years. For example, one participant reported that the facility he was using had been in place since 2007. As a result, participants had several years of experience, and at least some had received training from the organizations putting the facilities in place. This experience led to a fairly high level of knowledge related to topics including desiccant use, separation of urine and feces, emptying of vaults, and the agricultural value of collected urine and feces. However, it was noted that operators and residents occasionally expressed incorrect information regarding topics such as the required length of closed storage time prior to emptying the vault. This discrepancy may suggest that some Eco-San training sessions in Uganda have not been providing correct information or that the information has not been interpreted correctly by users in the field. In either case, the health of users and operators may be placed at risk as a result.

In the Kalisizo schools prior to installation of the demonstration facilities, students and parents knew very little about UDDTs, with most participants incorrectly identifying Eco-San facilities. At this point, due to their lack of knowledge and familiarity with these systems, students would have been unlikely to actively promote UDDTs among their families and communities. Even if they were to advocate for these systems, their lack of knowledge and the prevalence of key misconceptions would have limited and weakened the effectiveness of their promotion efforts. With inadequate training among students and no demonstration units to act as examples, Phase 1 findings suggested that uptake of Eco-San systems would be unlikely in these communities.

After installation of the demonstrations, though, dramatic improvements in levels of knowledge were seen within the school communities. These changes were apparent in both users and non-users of the facilities, which is significant. Most of the educational sessions that Brick by Brick conducted focused on training the users of the facilities. The fact that non-users also exhibited knowledge of these system's principles and procedures showed that students were discussing the facilities amongst themselves and informally teaching their peers, and that observation of the facilities themselves may have been improving knowledge among students. In other words, the facilities were functioning as effective demonstrations, and students may have already been acting as advocates for Eco-San systems within the schools.

3.4.2. Improved Attitudes as a Result of Demonstration Facilities

Similar to the level of knowledge, attitudes regarding UDDTs in the school communities improved significantly after installation of demonstration facilities. During Phase 1, a number of negative attitudes were expressed. For example, as it was in Kasensero, the possibility of misuse of the facilities was emphasized. When users do not follow the correct procedures, Eco-San promotion efforts are in serious jeopardy. In South Africa, for instance, teachers were not committed to ensuring that students used Eco-San facilities properly, and the project failed (Austin, 2003). In another fishing community in Uganda, less than two months after an Eco-San system had been installed, it was found to be in poor condition, due to a lack of ownership within the community and deficient operation and maintenance (Kaggwa et al., 2003). Additionally, the high construction cost of UDDTs was discussed by participants. These opinions agreed with the previous findings of Rajbhandari (2008) and Uddin et al. (2011), who reported that pit latrines are significantly less expensive than UDDTs and that the issue of high construction cost is a common criticism of Eco-San facilities. The facilities were also seen as being expensive to empty during Phase 1, but these opinions may have been a result of misconceptions.

After demonstration facilities were installed, some negative opinions did remain, including the possibility of misuse. However, overall attitudes were positive. Regarding other topics, a significant shift toward advantages that can be realized over time was seen. For example, it is encouraging to note that, during Phase 1, UDDTs were seen as being relatively expensive, both in terms of construction and emptying. In contrast, responses from Phase 2 displayed a significant shift toward long-term benefits, in which students identified the economic value that a UDDT could provide over time, both due to its permanence and the agricultural value of its products. Regarding this important issue of agricultural reuse, as with the emptying issue, positive shifts in attitudes toward the use of UDDT products were seen after the demonstration facilities had been installed, and students could articulate these benefits effectively.

The introduction of these facilities also brought about other benefits that were not directly related to the specific characteristics of UDDTs. After installation, the schools had put other features in place, including hand-washing facilities and buckets for the private disposal of menstrual pads, that provided significant hygienic benefits for students. This issue of handling menstruation in a discreet and sensitive manner is especially important. Menstruation has been linked with feelings of shame and embarrassment among female students due to teasing and stigmatization, and female students face especially difficult circumstances when they do not have access to adequate sanitation facilities at school (Sommer, 2010; McMahon et al., 2011). As a result, girls may be regularly absent during their menstrual periods and may eventually drop out of school completely. The establishment of private UDDT facilities, in conjunction with the school-provided wash water and disposal bucket, has helped empowered female students to manage these times without feelings of humiliation or shame. Furthermore, it is possible that the schools' provision of these additional hygiene-related items has enabled these girls to feel more valued and respected within the community, perhaps making it more likely that the girls will continue their education.

Overall, after demonstration UDDTs were installed in the schools, both attitudes and levels of knowledge improved dramatically. Students were able to articulate the principles and advantages of Eco-San systems effectively, with knowledge being transferred between student users and non-users at the schools. The strategy of installing demonstration facilities in school communities has shown itself to be successful in this context. It has resulted in a marked improvement in both knowledge and attitudes among students at the schools, and those students have shown, through their ability to educate their peers, that they can act as valuable promoters and advocates for Eco-San systems in their communities. Acknowledging that behavior change is a complex process and that several years may elapse before substantial increases in local uptake of Eco-San systems materialize, that possibility seems significantly more likely after the installation of demonstration units. As a result of these units, students have been empowered to act as ambassadors for Eco-San facilities.

Results from monitoring of the facilities showed that the schools operated the demonstration UDDTs correctly and effectively for the duration of the monitoring. Periodic monitoring of the facilities established that a supply of ash was typically available for use inside the toilet, revealing that users who occasionally did not add ash were either forgetting or choosing not to do so. However, the overall contents of the vaults suggested that sufficient ash was being added on a regular basis and that the problem of not adding ash was occurring relatively infrequently. Generally, fecal vault conditions were better than those observed in a number of previous studies (Mehl et al., 2011; Peasey, 2000). These findings provide further support for the conclusions that the demonstration facilities had a positive impact on students' knowledge and opinions, and that students could act as important advocates in support of these systems. As a result of this initial success, Brick by Brick decided to expand its pilot project by constructing a larger system of UDDTs designed to meet the sanitation needs of all students and teachers at one of the two primary schools where the demonstration facilities were installed.

3.4.3. Agricultural Reuse and Handling of Fecal Products

An important caveat regarding these improved attitudes involves the question of agricultural reuse of fecal products in the schools. When Phase 2 occurred, the schools had not yet emptied any fecal material from the UDDT vaults. The positive attitudes participants expressed regarding agricultural reuse and the improvements seen in crop yields resulted from the schools' use of urine as a liquid fertilizer. The nutrient value of urine and its benefits with regard to crop yields are well-established (Richert et al., 2009; Shaw, 2010), showing that reuse of could help to address concerns in Uganda related to declining soil fertility and food security (NEMA, 2010). Its reuse is also often considered to be simpler and more widely accepted than reuse of feces (Shaw, 2010).

Although some members of the control community expressed acceptance of fecal reuse, the significant difficulties expressed by others provide some insight into potential challenges that the schools could face regarding future reuse of fecal products. The views of people who were actually emptying facilities and handling fecal products were predominantly negative, expressing disgust regarding the process, especially if facilities were not operated optimally and fecal products were not dry. One operator interviewed during Phase 1 reported having to "force" students to perform the emptying task, and some community members expressed resistance toward handling fecal products even if they were provided with gloves and other protective equipment. In light of these viewpoints, handling and reuse of fecal products is an issue that could prove to be significantly problematic in the

Kalisizo schools. However, it is noted that, if the schools continue to operate the facilities well, adding sufficient desiccant and ensuring effective urine diversion, the fecal products should be dry and relatively innocuous when the time comes to empty the vault. This issue is one that deserves further study as operation at the schools continues.

3.4.4. Advantages of Demonstration Facilities in Institutional School Settings

With regard to the question of whether demonstration facilities should be installed in households or in institutions, this research provides evidence in support of institutional installation in primary schools. The question of ownership is often mentioned as an issue in institutional settings, and was also expressed during Phase 1 of this research. The possibility of mismanagement was related to the potential lack of ownership felt by users of a public facility, also described by Austin (2003). The opinions expressed by Phase 1 participants supported the view that Eco-San systems should first be installed in households, rather than in public places, such as schools, since a greater sense of responsibility is likely to result in a household setting.

However, after facilities were installed, the Kalisizo schools showed a strong sense of ownership of the demonstration facilities through their willingness to adapt and make changes to the systems as needed. For example, the problem of odorous urine containers was a negative operational aspect observed by Phase 2 participants. When urine is excreted, it contains a high concentration of urea. During storage, ammonia is produced and pH increases to between 8 and 9 through the hydrolysis of urea, catalyzed by urease-positive bacteria, which are ubiquitous in collection systems (Mihelcic and Zimmerman, 2014). Ammonia volatilization at high pH causes much of the odor that is frequently noticed in stored urine. School users added local herbs, such as "kanyuwira", and other materials to urine containers to address the odor issue. To the author's knowledge, the treatment effects of these additional ingredients have not been studied or quantified. The statement that the herb "kawunyira" prevented unpleasant odors suggests that the material may decrease urine's pH, reducing ammonia volatilization, or may impart another scent that masks the odor of ammonia gas. Regardless, this willingness to innovate suggests that the schools felt a sense of ownership for the demonstration facilities and did not simply wait for the implementing organization (Brick by Brick) to address issues or make changes. The question of ownership is an important one, especially in institutions and other public settings, but it seems that these schools did feel responsible for the facilities, which increases the possibility that they will continue to operate the UDDTs effectively in the future.

An additional factor that may provide further support for the installation of demonstrations in institutions rather than in households involves the perceptions of members of the larger community. Throughout Uganda, a number of NGOs have worked on both the institutional and household levels, sometimes providing certain infrastructure, such as water supply systems, sanitation facilities, or other structures. Local community members have become accustomed to seeing these services, but, if one household receives some type of benefit from an organization, surrounding neighbors often have an understandable expectation that they will receive the same service in the future. In the case of household demonstration facilities, this progression will not occur. The lack of service to other households may be seen as favoritism and can result in feelings of resentment that might actually limit future uptake of sanitation facilities. In contrast, demonstration facilities located at a school are more likely to be seen as providing a service to the general community, since the children from many different households benefit.

Additionally, information regarding facilities introduced at schools seems more likely to disseminate throughout the community at a faster rate. It is likely that students have already been teaching their peers about Eco-San systems informally, and those students hail from a number of different households in and around Kalisizo, where they can spread their knowledge to members of their families. Other, more formalized knowledge dissemination strategies that take advantage of the characteristics of a school setting are discussed below.

On the whole, this question of whether demonstrations should be installed in households or in institutional settings is likely to remain context-specific in many situations, but this research suggests several advantages provided by institutional school settings. In light of these advantages, Brick by Brick's planned expansion of the school-based system seems to be appropriate.

3.4.5. Recommendations for Expansion

Given Brick by Brick's planned expansion, this section presents recommendations that may prove useful, both for Brick by Brick and for others installing UDDTs. The recommendations are informed by the ideas and opinions of participants from both phases of this research. With regard to facility design, the urine diversion system has been reported to be the component most susceptible to operational issues, such as clogging and discomfort associated with carrying urine collection containers. Similar clogging issues were observed in Ethiopia, and it was noted that, especially in small pipes with shallow slopes, additional clogging can be caused by solid crystals that precipitate out of the urine (Drangert, 2004). Although not an ideal solution, the schools' strategy of temporarily closing the facility does seem to be a better management strategy than the situation that had been described in Kasensero, in which continued use caused urine to back up and overflow onto the floor and into the fecal vault. A better solution might involve a redesign of the urine piping that allows for easy cleanout of pipe bends, where particles are likely to collect. Austin (2006) recommended the installation of inspection caps at all bends, facilitating easy cleaning, as well as the use of non-metal piping with a minimum diameter of 38 mm and a slope of 2% to minimize blockages. As an additional measure to reduce pipe blockages, one Key Informant from Phase 1 stated that sieving wood ash before it was used in his facility helped to decrease clogging issues. Since beginning to use a simple net to remove pieces of debris from the ash, this operator reported that no blockage issues had occurred at this facility.

Regarding the concern of carrying heavy, odorous collection containers, the system should be built so that larger (100 to 200 liter) plastic tanks, rather than 20-liter jerry cans, can be accommodated for urine collection. Cylindrical plastic tanks between 100 and 200 liters are sold in small towns and other urban centers throughout Uganda. The tank should be fitted with a tap that allows smaller containers to be filled at convenient times and moved to a storage location, as well as an overflow pipe leading to a nearby soak pit. Jerry cans of the standard size (20 liters) could still be used for transport and storage of the urine. However, they could be filled only partially, so that they are not as heavy and not as likely to overflow. The dilution that is required prior to use could then occur directly in the jerry can immediately before agricultural application. For example, if a 1:3 urine dilution is used, a quarter of the jerry can could be filled with urine, and then the remaining three-quarters would be filled with water just before applying to crops (Shaw, 2010). These provisions would help to reduce the discomfort that students have associated with carrying full urine containers.

While the availability of sufficient supplies of wood ash did not appear to be a serious issue for the schools, it was perhaps the area of greatest concern among the control community and experienced operators interviewed during Phase 1. It is likely that, with the introduction of a larger system designed to accommodate all members of a school community, ash availability will become a potential problem. For the demonstration facilities, schools obtained supplies of ash from their own kitchens, but the amount required for a full-scale system will likely exceed the quantity produced by a school kitchen. Some Phase 1 operators reported that other materials, such as lime or dry soil, were used or mixed with wood ash to reduce the total amount of ash needed. However, lime is quite expensive and is unlikely to be affordable for these schools, while a mixture of dry soil and ash may not raise the pH of the fecal products to the levels measured in this research. Another option discussed by Key Informants in Phase 1 involved asking students to collect wood ash produced at their homes and bring it to the school on a regular basis. Theoretically, if all students and teachers brought enough ash for themselves, this system would be effective. If some individuals did not participate, however, this solution may not provide the required amount. This solution also might not be feasible if household uptake of UDDTs increased, since students' families would then need the ash for use at home. An additional alternative, which may be especially applicable in small towns and other more densely-populated areas, involves the possibility of buying supplies of wood ash from local bakeries or restaurants, which use large quantities of firewood on a daily basis. Kamuteera et al. (2013) investigated UDDT operation in Rukungiri, another small town in southwestern Uganda. The authors noted anecdotal evidence suggesting that bakeries would be willing to sell ash to local institutions. This potential solution may also be applicable in the context of Kalisizo and has the added benefit of not placing the burden of ash collection on the student population.

Perhaps most importantly, based on the comments of operators and members of the control community from Phase 1, continuous training is an important part of any Eco-San project. Especially when facilities are installed in a community or institutional setting, some individuals will invariably enter or leave the user population over time, and new users must receive training. Ideally, this training would be conducted by current members of the population and be integrated into overall system management. However, at least for the first several months of operation of a new system, regular monitoring and re-training is essential to identify issues and correct them. These considerations are likely to hold true in the case of Brick by Brick's expansion as well, even though the school has already had experience with the demonstration facility. Given the significant increase in the scale of the system, a plan of regular monitoring should be put in place to recognize any potential issues before they become inhibitory and jeopardize the long-term success of the project. However, the positive attitudes reported during Phase 2 suggest that, even when faced with operational concerns, future Eco-San projects will possess a great deal of momentum and an increased likelihood of success.

A formalized plan for the dissemination of information regarding Eco-San systems to the surrounding community could also be included in an ongoing training plan. In collaboration with school administration and teachers, Eco-San principles and other environmentally-conscious topics could be incorporated into the school curriculum, providing students with a greater depth of understanding regarding these systems and how they can interact with broader issues facing the country. For example, the permanence of UDDTs helps to address population and urbanization trends, since space limitations are beginning to become important concerns for small towns such as Kalisizo. The practice of building new pit latrines in different locations (Mutagamba, 2003) on a regular basis may soon become infeasible. The benefits of Eco-San systems with regard to soil fertility and food security are also significant areas that should be emphasized. Urine can function as an effective alternative to nitrogen-rich chemical fertilizers, while fecal products provide other important nutrients, such as phosphorus and potassium, and organic matter that improve soil conditions for crop growth (Jonsson et al., 2004). Phase 2 participants have already reported seeing improved maize and banana yields as a result of urine application. Finally, the health benefits of UDDTs should be discussed, especially related to the possible transmission of pathogens through insects, which land of fecal matter in latrines and then can come into contact with people, food, or drinking water. If operated correctly, UDDTs minimize the presence of insects, thereby reducing the possibility of infection. These topics could be incorporated into social studies and science curricula, providing students with practical demonstrations of social and biological concepts. In conjunction with these educational approaches, schools could host events for members of the local community. Students could present songs, skits, or speeches to express their knowledge and opinions regarding Eco-San systems and the issues that can be addressed through their use. Perhaps an event that occurs once a year would provide students and community members with an institutionalized program for better understanding the concepts and advantages of Eco-San systems. As people in the surrounding community learn more about Eco-San facilities, they may become more willing to install these systems in their homes.

Finally, it is important to remember that different school communities are not identical or equivalent to one another. As previous studies have shown (Austin, 2003), Eco-san systems will not automatically be successful when installed in schools. Any school-based project, including those focused on sanitation improvements, must take into account local, contextual factors and the unique characteristics of the school in question. For the case of ventilated improved pit (VIP) latrines, Ness (2015) has developed a framework focused on the relationship between user preferences and design factors that influence acceptance of communal school VIP latrines, suggesting that effective school sanitation programs require the careful consideration of these preferences and factors. As in the implementation of this research, school administrators and parents should be involved early in the planning process, intensive education and monitoring programs should be put in place, and opportunities for the school to make choices (including the fundamental question of whether or not the project should occur) should be provided. Perhaps most critically, any implementing organization must develop a strong relationship with the school community that engenders an atmosphere of mutual respect and before any facilities are installed.

3.5. Conclusions

Overall, the results of this research have indicated that the promotion strategy of installing demonstration UDDT facilities in schools is an effective technique for improving knowledge and attitudes within local communities and in enabling students to become compelling advocates for Eco-San systems and general sanitation practices, at least in the context of Kalisizo, Uganda. Students exhibited a marked increase in knowledge regarding these facilities and their benefits, and, after several months of operation, their opinions were strongly positive, perhaps to a greater degree than those expressed by the control community. These changes were seen in users of the facilities as well as non-users, showing that student users were transferring knowledge and promoting Eco-San systems to their peers. Perceived benefits of UDDTs covered a wide range of topics, and students expressed clear acceptance of using the toilet products to fertilize agricultural crops. Monitoring of the facilities revealed that, with the exception of minor issues, UDDTs were being operated correctly and were achieving the recommended pH and moisture levels in fecal vaults. Additionally, the introduction of an improved sanitation system at the schools appears to have inspired other improvements related to sanitation and hygiene issues, with new hand-washing stations being installed and provision being made for female students who are menstruating. These advances could have important long-term effects, fostering a school environment that is safer and more hygienic, empowering girls to effectively manage menstruation without feelings of humiliation or shame, and demonstrating to students that they are valued and respected. It is possible that these effects will make it more likely that female students will continue their education. In the future, it is likely that students will be compelling representatives for Eco-San systems and other sanitation and hygiene issues within their households and communities.

The results of this research also suggest several avenues for future work, which could include the following topics:

- The long-term success of demonstration UDDTs and full-scale systems within Kalisizo schools
- Future uptake of UDDTs within Kalisizo and the surrounding areas
- Developing attitudes toward agricultural reuse of UDDT products as these materials are used
- The effects of UDDTs on the long-term economic, nutritional, and health status of users
- Alternative urine treatment using local materials, such as wood ash, tobacco leaves, and herbs

The strategy of installing demonstration facilities in school communities has shown itself to be initially successful in this context. It has resulted in a marked improvement in both knowledge and attitudes among students at the schools, and those students have shown that they can act as valuable promoters and advocates for Eco-San systems in their communities. Behavior change is a complex process, especially with regard to the additional responsibilities that Eco-San facilities place on users, such as desiccant addition and emptying of vaults, which can act as barriers to continued and correct use (Wilbur, 2014). Substantial increases in local uptake of Eco-San systems may not materialize for several years, but the possibility of increased uptake seems significantly more likely after the installation of demonstration units in Kalisizo schools. Users of the facilities expressed attitudes that were more favorable toward these systems and toward agricultural reuse than non-users had before the facilities were installed. Similar results were found among users and non-users of composting latrines in Panama, with users expressing greater acceptance of agricultural reuse (Wilbur, 2014). Through these units, students have been empowered to act as ambassadors for Eco-San systems. School-based demonstration facilities are recommended as effective tools for Eco-San promotion, with the understanding that additional considerations, including local community involvement, intensive education and monitoring programs, and a general atmosphere of respect and trust, are also critical components of any Eco-San system installation. This approach would help to incorporate traditional sanitation behaviors and practices, to respect user preferences, and to minimize the need for significant changes in behavior, all of which can function to improve local acceptance and adoption (Wilbur, 2014).

CHAPTER 4: AMMONIA TREATMENT OF COLLECTED FECES USING STORED URINE

This chapter presents research related to the second set of objectives outlined in Chapter 1. It begins with a focused literature review exploring the need for more effective treatment in Eco-San systems due to persistent pathogens such as *Ascaris lumbricoides*, as well as previous work regarding *Ascaris* inactivation through ammonia treatment. The chapter continues by describing the methods used to evaluate the viability and potential effectiveness of ammonia treatment using stored urine in the Ugandan context. It then presents and discusses the results that were obtained.

4.1. Literature Review: Ammonia Treatment for *Ascaris* Egg Inactivation

Ecological Sanitation (Eco-San) systems provide an approach to sanitation that, in addition to conventional goals, such as protecting populations from hygiene risks and reducing pollution in the environment, seeks to recover valuable resources from human excreta (Esrey et al., 2001). Nutrients contained in excreta can be used to restore soil productivity and improve agricultural yields (Jonsson et al., 2004), which is of special importance for resource-limited areas, such as Uganda, where soil fertility is declining (Nkedi-Kizza et al., 2002; NEMA, 2010), populations are rapidly growing (UN, 2013a), and future nutritional security is uncertain (FAO, 2012). However, when the products of Eco-San systems will be used in agriculture, the hygienic quality of those products must be ensured. Evidence suggests that, at least in some cases, safe conditions for nutrient recovery from excreta are not being achieved (Hawksworth et al., 2010; Peasey, 2000).

A variety of primary and secondary treatment processes are recommended to ensure the safety of Eco-San products. In the context of most Eco-San systems, primary treatment refers to processes that take place onsite, within the toilet structure, while secondary treatment includes additional processes that may occur after products are removed from the facility (Esrey et al., 2001). Primary treatment strategies can be divided into two general groups, composting and dehydration. The facilities most commonly promoted in Uganda, Urine-Diverting Dry Toilets (UDDTs), fall into the dehydration category. These toilets divert urine into a separate storage container, and wood ash is added to the vaults where fecal matter is collected to ensure dry, alkaline conditions. Compared to the fecal fraction, urine is low in pathogens, and, for large-scale systems involving multiple households, closed storage for six months has been established as being sufficient to treat the material (WHO, 2006). In the case of small, single-household systems, stored urine can be used immediately for agricultural purposes after dilution (WHO, 2006). Treatment of feces, on the other hand, is an area of much greater concern.

In decentralized settings, such as those commonly associated with Eco-San systems in developing countries, dehydration is recommended over composting as a more reliable option for primary treatment in the collection vault (Gajurel and Wendland, 2004). Given sufficient time, the pH and moisture conditions achieved in dehydration systems have been shown to inactivate a number of pathogens of interest (Esrey et al., 2001). Stenstrom (2002) reported that six months of storage at a pH at or above 9.0 resulted in a 4 to 6 $\log_{10}$ reduction in bacteria and viruses. The World Health Organization (WHO, 2006) recommends that, at an ambient temperature between 20°C and 35°C, at least one year of dry storage (at or below a moisture content of 25%) is needed to inactivate most pathogens. However, even if these pH and moisture content conditions are achieved, this period of time may be insufficient to eliminate more persistent pathogens (Hawksworth et al., 2010; Peasey, 2000). Helminthes are of special concern, especially the eggs of *Ascaris lumbricoides*, which are considered to be one of the most environmentally persistent pathogens (WHO, 2006).

Worldwide, it is estimated that 1.3 billion people are infected with *A. lumbricoides*, with most infections occurring in developing countries. Ascariasis is endemic in areas of Latin America, the Far East, and Africa, with children under fifteen being greatly affected (Hawksworth et al., 2010). In Latin America and the Caribbean, it has been reported that impoverished people living in rural areas, in shanty towns, or in city slums are at a greater risk of Helminth infection (Gibson, 2014). Although the condition has a low mortality rate, it can lead to severe morbidity and is associated with poor growth and development. When larvae migrate to the lungs, symptoms can include difficulty breathing, wheezing, dyspnea, nonproductive cough, high fever, and angioedema. Infection can also result in abdominal distension and pain, nausea, loss of appetite, vomiting, diarrhea, and obstruction of the small intestine (Gibson, 2014). In a study among schoolchildren in Uganda, it was found that 28.8% of those tested in Rakai District, where the current research took place, were infected with *A. lumbricoides*, with an average of 2,289 eggs per gram of infected feces (Kabatereine et al., 2001). The highest mean egg count in the country was 7,146 eggs per gram of feces, while the World Health Organization recommends that feces used for agriculture should contain less than one egg per gram (WHO, 2006). In view of these results, any Eco-San system implemented in this area should be designed and operated with the goal of inactivating these persistent pathogens. Based on the WHO recommendation, a 4-$\log_{10}$ reduction would be needed to achieve the recommended concentration. Additional decreases due to die-off in the soil (90% reduction of *Ascaris* eggs in 15 to 100 days) and hygiene considerations (e.g., washing vegetables provides 1 – 2 $\log_{10}$ pathogen reduction) would further reduce risks (WHO, 2006). For the purposes of this research, it was assumed that an overall 4-$\log_{10}$ reduction of *Ascaris lumbricoides* eggs prior to soil application would allow for the safe reuse of treated feces in agriculture.

Because of the resistance of *Ascaris* eggs to various treatment options common in Eco-San systems, their inactivation can be seen as an indicator of safety (Gajurel and Wendland, 2004). However, conditions in most toilet vaults are not adequate to destroy these pathogens, even after a year of storage. A moisture content below 5% (WHO, 2006) is required for inactivation, while Moe and Izurieta (2003) report that eggs can survive for at least 700 days when exposed to pH levels ranging from 9 to 11 and for more than 400 days at a pH above 11. High temperatures, however, are reported to effectively inactivate eggs. In El Salvador, Moe and Izurieta (2003) found that, when peak temperatures in solar toilets exceeded 36°C, Ascaris eggs were inactivated in a matter of weeks. In contrast, Brownell and Nelson (2006) stated that eggs survived for more than one year at 40°C but were destroyed in minutes at temperatures above 60°C. In most instances, the temperatures required to ensure inactivation are not found in onsite Eco-San systems. As a result, secondary treatment is often recommended (Hawksworth et al., 2010; Mehl et al., 2011; Peasey, 2000).

A number of low-cost options for secondary treatment exist, including composting, anaerobic digestion, incineration, solar drying, additional storage, and chemical treatment. Chemical treatment could involve the addition of acidic materials, such as phosphoric acid, basic materials, such as lime or wood ash, or oxidizing agents, such as chlorine (Niwagaba, 2009). Increased concentrations of ammonia have also been shown to adversely affect pathogens, independent of pH. Pecson et al. (2007) compared the results of several studies and noted significant variability in pathogen reduction, even at similar pH levels. For example, at similar temperatures and moisture levels, Mendez et al. (2002) found 90% inactivation of *Ascaris* eggs after two hours at a pH of 12.5, while Plachy et al. (1996) reported only a 3.6% inactivation after seven days at a pH of 12. The variability in inactivation rates can be explained, at least partially, by different concentrations of ammonia (Pecson et al., 2007).

The destructive effect of ammonia is thought to be related to the molecule's small size and high solubility in water and lipids, enabling it to pass through an organism's cellular barriers and disrupt internal chemistry (Nordin, 2010). Free ammonia, NH_3, which is present in significant amounts at high pH levels, has been shown to impact pathogens much more severely than the ammonium ion (NH_4^+), its conjugate acid. As described below, free ammonia concentrations can be increased through increases in temperature, pH, and/or total ammonia concentration.

4.1.1. Ammonia Equilibrium Chemistry

Elevated free ammonia concentrations can be achieved by addition of urea to a closed system (Vinneras et al., 2004; Nordin et al., 2009a; Sharad et al., 2012; Cruz-Espinoza et al., 2012). In the presence of the urease enzyme, which is ubiquitous in the environment, urea is degraded, forming ammonium ions and raising pH (Nordin, 2010):

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4{}^+ + HCO_3{}^- + OH^- \qquad (4.1)$$

The ammonium ions resulting from this reaction are in equilibrium with free ammonia molecules in solution according to the following acid-base reaction (Bell et al., 2007):

$$NH_4{}^+{}_{(aq)} \leftrightarrow NH_{3(aq)} + H^+{}_{(aq)} \qquad (4.2)$$

The relationship between the activities of ammonium ions and free ammonia in solution is defined by the acid-base equilibrium constant for ammonia. Equation 4.3 shows this relationship, which also reveals the influence of pH, through the presence of the hydrogen ion (Bell et al., 2007):

$$K_a = \frac{\{NH_3\}\{H^+\}}{\{NH_4{}^+\}} \qquad (4.3)$$

Ammonia's equilibrium constant, K_a, is affected by the temperature and ionic strength of the solution. In a dilute solution at 25°C, the negative logarithm of the equilibrium constant (pK_a) is 9.25 (ATSDR, 2004), meaning that, at a pH above 9.25, free ammonia dominates, while ammonium ions are predominant at lower pH. Higher temperature decreases pK_a, while a higher ionic strength increases pK_a (Bell et al., 2007).

Free ammonia in the aqueous phase is also in equilibrium with gaseous ammonia in the surrounding air. The relationship between the activity of aqueous ammonia and the partial pressure of ammonia gas is described by Henry's Law:

$$H = \frac{P_{NH_{3(g)}}}{\{NH_{3(aq)}\}} \qquad (4.4)$$

where H is reported to be 1.6×10^{-5} atm-m^3/mol at 25°C (ATSDR, 2004). In an open system, where air is constantly being exchanged, substantial amounts of ammonia will be lost over time. However, in closed systems, including those in which ammonia treatment was evaluated in this study, the fraction of ammonia lost to volatilization should be negligible (Pecson et al., 2007) because the Henry's law constant is quite small. Since the gas fraction can be neglected, pH, temperature, and total ammonia concentration were measured, and the acid-base relationships described above were used to estimate free ammonia levels in solution.

4.1.2. Effectiveness of Ammonia Treatment through Urea Addition

A number of studies have shown that adding urea to elevate ammonia concentrations can be an effective option for *Ascaris* egg inactivation. Eggs of *Ascaris suum*, which infect swine, have been used in place of *Ascaris lumbricoides* in these studies, due to their relative availability and safety. It has been shown that the inactivation rates of both species are similar when subjected to alkaline ammonia treatment (Nordin et al., 2009a). Vinneras et al. (2004) tested source-separated fecal matter that had been watered down to a moisture content of 90%. Urea was mixed into the sludge at a concentration of 30,000 mg/L NH_3-N, causing pH to increase from 8.0 to 9.2. After 50 days, no viable *Ascaris* eggs were found in the sludge, supporting the idea that high concentrations of ammonia can result in significant inactivation. Pecson and Nelson (2005) assessed the influence of temperature, pH, and ammonia levels on Ascaris reduction. Inactivation over short periods (24 hours and 72 hours) was evaluated at a variety of pH (7 – 11), temperature (32°C - 52°C), and ammonia (0 – 4,000 mg/L NH_3-N) levels. Inactivation rates were found to increase with increasing temperature and ammonia concentration, regardless of pH. Pecson et al. (2007) added dissolved ammonia rather than urea to municipal sludge to achieve supplementary concentrations of 1,000 and 5,000 mg/L NH_3-N. Samples were incubated at varying temperatures and pH levels. All three factors (temperature, pH, ammonia) were shown to increase die-off rates of *Ascaris* eggs. An increase in either temperature or ammonia always resulted in higher die-off rates, while an increase in pH caused faster die-off when the temperature was above 30°C.

Several studies focused specifically on material that had been collected from dehydration toilets similar to the UDDTs found in Uganda. Nordin et al. (2009a) adjusted the moisture content of fecal matter collected from a single household's toilet to 83% by weight. Urea was added to samples that were stored at various temperatures. At 24°C, an average free ammonia concentration of approximately 800 mg/L NH_3-N was estimated to achieve 99% inactivation of Ascaris eggs after 35 days. At 34°C, similar concentrations were shown to achieve the same level of inactivation in less than one week. Sharad et al. (2012) directly measured Ascaris inactivation in UDDT vaults due to urea addition. Conditions within vaults were adjusted to ensure pH levels between 8.0 and 10.0 and moisture contents between 23% and 50%. In a third of the samples, treatment for at least 72 hours and a free ammonia concentration of at least 90 mg/L NH_3-N had a statistically significant association with at least 50% inactivation of *Ascaris* eggs. A separate study simulated conditions in dry toilet vaults with added urea in El Salvador. Samples with free ammonia concentrations of 1110 mg/L NH_3-N and temperatures of 28°C achieved inactivation of all Ascaris eggs after 14 days. The lower moisture contents used in this study may have contributed to faster inactivation by facilitating the movement of free ammonia molecules into fecal material and allowing greater contact with Ascaris eggs (Cruz-Espinoza et al., 2012).

Conditions within dry toilets were also simulated in a study conducted in Brazil (Magri et al., 2013). Emphasis was placed on the incomplete mixing that is likely in these systems. Samples were prepared so that layers of feces were sandwiched between layers of additives (wood ash, oyster shells, and/or urea). After 120 to 192 days at an average temperature of 22°C, 90% inactivation of *Ascaris* eggs was achieved. In this case, slow inactivation times are likely attributable to the lack of mixing, which was demonstrated by the wide range of moisture contents (19% to 67%) observed in the samples.

4.1.3. Effectiveness of Ammonia Treatment through the Addition of Urine

The strategy of adding urea has resulted in significant pathogen reduction under a variety of conditions, except when samples were not well-mixed. In Uganda, however, while urea can be obtained as a fertilizer, acquiring sufficient amounts may be difficult for a typical UDDT user, due to cost. It is reported that fertilizers are too expensive for many farmers in Uganda (Wambui, 2011). An alternative, low-cost option involves the use of human urine. Urine contains high amounts of nitrogen, most of which is present as ammonia or urea. It may be possible to use the ammonia in urine to sanitize both the urine itself and the products from toilet vaults, since ammonia is not consumed as pathogens are destroyed. Additionally, the fact that urine is a liquid could help to improve mixing and ammonia distribution during treatment. Two recent studies have begun to investigate this possibility.

McKinley et al. (2012) mixed dry material (feces and sawdust) from composting toilets with stored urine, fresh urine, and/or wood ash. In all mixtures, urine was added until the dry materials were saturated, and mixtures were stored in sealed containers at ambient temperatures averaging 19.5°C for 16 weeks. The most effective mixture included compost, stored urine, and ash. This mixture, which contained free ammonia concentrations that varied between 2,200 and 2,800 mg/L NH_3-N and pH values between 10.4 and 11.6, achieved 99% *Ascaris* inactivation after 8 weeks. An additional study (Fidjeland et al., 2013) mixed feces with urine and water to simulate storage conditions in pit latrines, vacuum toilets, and pour-flush latrines. For mixtures stored at 23°C, 3-$\log_{10}$ reductions were estimated to fall between 1 and 6 months depending on free ammonia, which ranged from 620 to 4,760 mg/L NH_3-N. It was suggested that free ammonia had a greater impact on the duration of the initial lag phase, during which minimal inactivation occurs, rather than on the post-lag phase inactivation rate. Across all studies, lag phases varied considerably and could have significant importance for total treatment time.

Overall, consideration of these studies as a whole suggests that ammonia treatment is a promising strategy for the inactivation of *Ascaris* eggs. The primary inactivation mechanism appears to be free ammonia concentration, because this molecule is known to easily cross organisms' cellular barriers and disrupt internal chemistry (Nordin et al., 2009a). However, these studies also suggest that the treatment time needed to achieve a certain level of inactivation is highly dependent on temperature, with higher temperatures causing faster inactivation. For example, at a lower average temperature of 19.5°C, a free ammonia concentration of at least 2,200 mg/L NH_3-N was required for 2-$\log_{10}$ inactivation in 56 days (McKinley et al., 2012). At a higher temperature of 34°C, a free ammonia concentration of

800 mg/L NH_3-N resulted in 2-log_{10} inactivation after only one week (Nordin et al., 2009a). At an intermediate temperature of 23°C, a free ammonia concentration of 1,162 mg/L NH_3-N resulted in the same level of 2-log_{10} inactivation after 60 days (Fidjeland et al., 2013). Perhaps higher temperature levels enable the free ammonia molecule to cross cell barriers more quickly and easily. In view of free ammonia treatment's temperature dependency, specific temperature conditions must be taken into account when testing this strategy. Nordin et al. (2009) also reported that a concentration of 280 mg/L NH_3-N might be the minimum threshold that is required for any level of egg inactivation to occur.

The two studies that have investigated treatment of feces using stored urine focused on a number of sanitation systems, including composting toilets, pit latrines, vacuum toilets, and pour-flush latrines. However, urine treatment on the dry products of UDDTs has not been studied. While the composting toilet studied by McKinley et al. (2012) is also classified as an Eco-San system and is in some ways similar to an UDDT, the use of sawdust as the primary desiccant resulted in storage conditions different from those observed in Ugandan UDDTs, where highly alkaline wood ash is used. Furthermore, while McKinley et al. (2012) varied the materials that were added to the mixtures, only one mix ratio, based on saturation of the compost, was used for all combinations of compost and urine.

The goal of this research is to determine whether urine treatment of UDDT products is a viable option for ensuring safe recovery of nutrients from excreta in the context of Uganda. A variety of treatment mixtures were studied, with the goal of identifying the most effective and feasible possibilities. Finally, the temperatures that would be achievable when storing the various mixtures were evaluated. Measurements of pH, temperature, and free ammonia concentration were compared to values from McKinley et al. (2012), Fidjeland et al. (2013), and other studies to infer pathogen reduction.

4.2. Research Methods

Multiple stages of experiments were performed to determine which mixtures provided the most effective treatment conditions in the local context. These stages are summarized in Table 10.

Table 10: Ammonia treatment experimental matrix

Experimental stage	Mix ratios studied (urine : fecal products : ash)	Additional test conditions
1	1:1:0, 2:1:0, 3:1:0, 1:0:0, 0:1:0	Stored indoors at ambient temperature for 8 weeks
2	2:1:0, 2:1:0.5, 2:1:1	Stored indoors at ambient temperature for 16 weeks
3	2:1:0, 2:1:0.5 2:1:0	Stored outdoors for 11 weeks Stored indoors for 11 weeks

4.2.1. Sample Collection and Mixture Preparation

An initial set of experiments was used to evaluate the conditions present in various mixtures of fecal products and stored urine. The term "fecal products" refers to the mixture of materials that is present in the toilet's collection vault and includes feces, wood ash, toilet paper, and small amounts of other anal cleansing materials, such as stones and notebook paper. Supplies of stored urine and fecal products for the first experimental stage were collected from a UDDT installed at Kalisizo Muslim Primary School, after the facility had been operating for approximately three months. Additional supplies for use in the second and third stages were collected from the same source after the UDDT had been in operation for approximately six months.

Initial mix ratios were based on theoretical feasibility calculations (Appendix E), which incorporated data regarding the composition and excretion rates of urine and feces, from both Ugandan and international sources, including Esrey et al. (2001), Jonsson et al. (2004), Niwagaba (2009), and Nordin (2010). The results suggested that a 2:1 mixture of stored urine and fecal products, at a pH of 9.0 and a temperature of 25°C, could attain an free ammonia concentration above 800 mg/L NH_3-N, the value estimated to achieve 6-$\log_{10}$ inactivation of Ascaris eggs after approximately four months at 24°C (Nordin et al., 2009a). The mix ratios used in the first stage included three volumetric combinations of urine and fecal products (1:1, 2:1, 3:1), along with two controls, one containing only fecal products and one containing only stored urine. All mix ratios were performed in triplicate. The volume of each mixture was approximately 900 milliliters, and all mixtures were contained in closed, two-liter plastic buckets. All buckets were kept in a closed, dark storage room for a period of 58 days, beginning on January 21, 2014 and ending on March 20, 2014. Physical and chemical tests were performed weekly, while indoor and outdoor ambient temperature readings were normally measured daily at varying times. Moisture content of each mixture was measured after the testing period was completed.

The results of the first experimental stage suggested that the 2:1 mixture of stored urine and fecal products would be the most promising alternative to pursue further. The second stage focused on the effect of adding different amounts of wood ash to the mixture, in an effort to raise pH levels. Two volumetric mixes of stored urine, fecal products, and ash (2:1:0.5, 2:1:1) were included, and the 2:1:0 mixture from Stage 1 was repeated to account for any changes in ambient conditions. Each of these three volumetric mix ratios was performed in triplicate. The volume of each mixture was approximately 400 milliliters, and all mixtures were contained in closed, newly-opened, half-liter plastic bottles. Urine, fecal products, and wood ash were placed in appropriately-sized measuring cups to transfer the correct volume into each bottle. Materials were poured into bottles slowly to minimize spillage. Different storage containers were used in this second stage because significant ammonia volatilization was observed when mixtures in the first stage were opened for testing. The bottles were kept in the same storage room for a period of 113 days, beginning on April 3, 2014 and ending on July 25, 2014, and moisture content was measured after completion of the testing period.

The results of the second stage suggested that the 2:1:0 and 2:1:0.5 mixtures of urine, fecal products, and ash would be the most promising alternatives to continue testing. Free ammonia levels in all three mixtures from the second stage were similar, but, due to the importance of conserving wood ash supplies, the two mixtures with lower ash fractions were selected. The third stage focused on the effect of storing mixtures outdoors, to measure how the temperatures of the mixtures changed. These two volumetric mixes of urine, fecal products, and ash (2:1:0, 2:1:0.5) were stored outside on an iron roof, to minimize the possibility of disturbance by animals or curious individuals, and a control mixture (2:1:0) was stored indoors in the storage room used in the previous two stages. Ambient temperatures at each location were measured. Each mix ratio was performed in triplicate. The 400-milliliter mixtures were kept in their respective locations for a period of 80 days, beginning on August 20, 2014 and ending on November 8, 2014, and moisture content was measured after completion of the testing period.

4.2.2. Physical and Chemical Testing Methods

Detailed procedures for all physical and chemical tests are included in Appendix A. Measurements of pH, temperature, and total ammonia concentration within each mixture were taken at the beginning of the testing period and then once per week until the test period ended using equipment shown in Table 11. During the first stage, each bucket was opened and the mixture was stirred just before the tests were performed. During the two subsequent stages, closed bottles were shaken, allowing the contents to mix prior to opening each bottle for testing.

Table 11: Testing equipment used for physical and chemical measurements

Measurement	Equipment	Range	Precision	Reference
pH	Machery-Nagel pH Indicator Strips	7.0 – 14.0 pH units	0.5 pH units	Mehl et al., 2011
Temperature	Taylor 9842 Waterproof Digital Thermometer	–40.0 – 230.0°C	0.1°C	Standard Method 2550 B (Rice et al., 2012)
Total Ammonia	Seachem Multitest Ammonia Test Kit	0.0 – 6.0 mg/L NH_3	For 0.0 – 0.5 mg/L: 0.01 mg/L NH_3; For 0.5 – 6.0 mg/L: 0.1 mg/L NH_3	Manufacturer's Instructions, based on Standard Method 4500-NH_3 D (Rice et al., 2012)
Moisture Content	American Weigh Scales Digital Pocket Scale	0.0 – 2,000.0 g	0.1 g	Standard Method 2540 G (Rice et al., 2012), modified

Measurements of pH were performed using the method described by Mehl et al. (2011). Samples of fecal products were collected in a container, an approximately equal volume of water was added, the mixture was shaken, and the pH of the supernatant was measured using pH indicator strips.

Temperature measurements were performed according to Standard Method 2550 B (Rice et al., 2012). A single thermometer (Taylor 9842 Digital Waterproof Thermometer) was used for all measurements, but the instrument was cleaned between each use with alcohol swabs (Kendall, 70% isopropyl alcohol). Total ammonia measurements were performed after samples were diluted 1,000 times using local tap water that had been filtered and solar disinfected. Initial estimates of dilution requirements were based on the theoretical calculation of ammonia in urine using a procedure described by Jonsson et al. (2004). Total ammonia measurements were then performed using Seachem Multitest: Ammonia Test Kits according to the manufacturer's instructions. Various quality assurance/quality control (QA/QC) procedures were carried out to assess and confirm the accuracy and precision of the total ammonia tests. These procedures included measurement of total ammonia in dilution water and subsequent correction of sample results, measurement of provided standards, measurement of diluted standards, and spike and recovery tests. Results of QA/QC tests are included in Appendix F. The pH and total ammonia levels of water used for total ammonia sample dilutions and pH tests were measured during each week of data collection. The pH of water was always 7.0, while total ammonia concentration varied between 0.00 and 0.08 mg/L NH_3. The small levels of total ammonia present in the dilution water were taken into account when calculating undiluted total ammonia concentrations of samples. Detailed procedures can be found in Appendix A.

The moisture content of each mixture was measured either after the testing period had been completed (in the case of the first two stages) or during the testing period (for the third stage). The procedure described in Standard Method 2540 G (Rice et al., 2012) was followed; however, samples were heated and dried using a solar oven constructed in-house. An adjustable cardboard panel, covered with aluminum foil, directed sunlight through a clear plastic opening in the top of the oven compartment to heat samples, which were placed on a black platform inside the compartment. The interior walls were also covered with aluminum foil to redirect any stray sunlight toward the platform.

Because solar drying was used, moisture content measurements could only be performed during appropriate weather conditions, and extended drying times (5 to 8 hours per day for 5 to 10 days) were required. While all stages of experiments were being performed, pH, moisture content, and temperature conditions were also monitored in fecal vaults and in stored urine at Kalisizo Muslim Primary School and Saint Andrews Matale Hill Primary School, where demonstration UDDTs had been installed during the previous year.

4.2.3. Calculation of Free Ammonia Concentrations

Free ammonia concentrations in each mixture were calculated for each sampling day, using the measured pH, temperature, and total ammonia concentration on that day. Using acid-base equilibrium relationships for a non-dilute solution and neglecting the small fraction of ammonia present in gaseous form, the aqueous free ammonia concentration can be calculated according to Equation 4.5:

$$[NH_3] = \frac{[NH_{tot}]}{\left[\frac{(\gamma_{NH3})(10^{-pH})}{(\gamma_{NH4+})(10^{-pKa})}+1\right]} \quad (4.5)$$

where $[NH_3]$ represents the free ammonia concentration in moles per liter, $[NH_{tot}]$ is the total ammonia concentration in moles per liter, γ_{NH3} is the activity coefficient of free ammonia, γ_{NH4+} is the activity coefficient of the ammonium ion, and *pKa* is the negative logarithm (base 10) of the acid-base equilibrium constant for ammonia.

The activity coefficient of free ammonia can be calculated according to Equation 4.6, used for nonelectrolytes (Mihelcic and Zimmerman, 2014):

$$\log_{10}(\gamma_{NH3}) = k_s I \quad (4.6)$$

The salting-out coefficient, k_s, is reported to be 0.12 for ammonia at 30°C (Butler, 1998), and the ionic strength, *I*, is given as 0.206 moles per liter for urine (Udert et al., 2003b). Assuming that the salting-out coefficient for ammonia does not change with temperature and that the ionic strength of urine is appropriate for all mixtures, an activity coefficient of 1.06 was calculated for free ammonia.

The activity coefficient for NH_4^+ can be calculated according to Equation 4.7, used for electrolytes when ionic strength is less than 0.5 moles per liter (Aqion, 2013):

$$\log_{10}(\gamma_{NH4+}) = -Az^2\left[\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3I\right] \quad (4.7)$$

At 25°C, the constant *A* is 0.5 (Aqion, 2013), while *z* represents the ionic charge of the compound, which is +1 in the case of the ammonium ion. Assuming that the parameter *A* does not change significantly with temperature, an activity coefficient of 0.75 was calculated for the ammonium ion.

Finally, the negative logarithm of ammonia's acid-base equilibrium constant (*pKa*) in a non-dilute solution can be calculated according to Equation 4.8 (Bell et al., 2007), which shows the equilibrium constant to be dependent on temperature and ionic strength:

$$pKa = 10.0423 - 0.0315536(T) + 0.14737(I_f) \quad (4.8)$$

where *T* represents temperature in degrees Celsius, while I_f stands for formal ionic strength in moles per kilogram. By using the density of urine, reported as 1.024 kilogram per liter (Ogata et al., 1970), the ionic strength of 0.206 moles per liter can be converted into the correct units, resulting in a formal ionic strength of 0.201 moles per kilogram. Equation 4.8 can be used to calculate the equilibrium coefficient corresponding to each measured temperature on a given sampling day.

With the activity coefficients calculated previously, as well as the total ammonia, pKa, and pH values for each mixture on each day of data collection, the free ammonia concentration can be calculated using Equation 4.8. After calculation, the units of the free ammonia concentration were converted to mg/L NH_3-N, to agree with the units of most previous *Ascaris* inactivation studies. After experimentation was completed, the collected data were compared with previously published results to evaluate the potential for pathogen reduction, with special emphasis on inactivation of *Ascaris* eggs.

4.2.4. Data Analysis

Statistical analysis of observed treatment conditions was performed using one-way analysis of variance (ANOVA) tests followed by Tukey's tests for multiple comparisons, conducted with GraphPad

Prism 6.0 (GraphPad Software, San Diego, California, USA, www.graphpad.com). *p* values less than 0.05 were considered statistically significant, while values less than 0.0001 were considered extremely significant. Linear and non-linear regression analyses of temperature data were also performed in GraphPad Prism. Minitab 16 (Minitab Inc., State College, Pennsylvania, USA, www.minitab.com) was used to conduct a multiple linear regression on previously published data, which enabled the estimation of *Ascaris* inactivation based on the treatment conditions observed in this research.

4.3. Results

Complete data sets for all mixtures of stored urine, fecal products, and wood ash, additional temperature measurements, and school UDDT vault conditions are presented in Appendix D. Summaries of the data sets are provided in the following sections.

4.3.1. Treatment Conditions in School UDDTs

In general, the UDDTs at the local primary schools were maintained in good condition for the duration of the monitoring period, which lasted approximately ten months. Compared with the schools' pit latrines, substantial reductions in flies and odors were observed, likely due to an effective urine diversion system and sufficient desiccant use. However, the fecal vaults were not always well-mixed, which contributed to substantial variations in measurements. Results of all measurements are included in Appendix D. A summary of these measurements was presented in Table 9, found in Chapter 3.

Moisture content and pH conditions within UDDT fecal vaults met the recommended storage conditions of pH levels above 9.0 and moisture contents below 25% (Mihelcic et al., 2009), suggesting that many pathogens (with the exception of persistent organisms such as *Ascaris lumbricoides*) would be removed after a storage period of one year (WHO, 2006). The measured values did vary considerably depending on the sampling day and on the location of the sample within the pile. This variation was likely a result of inadequate mixing, which could hinder pathogen reduction in some parts of the pile (Corrales et al., 2006). However, all measured values still reached or surpassed the storage recommendations, and they were also better than vault measurements from previous studies. In China, for instance, moisture contents from 15% to 66% were observed in dry toilets that had been in use for three months (Peasey, 2000). In Panama, composting toilets in which wood ash was used as the desiccant were found to have moisture contents ranging from 29% to 47%, while pH levels in these toilets averaged 8.3 (Mehl et al., 2011). These findings suggest that more ash was being added to the UDDTs in Kalisizo than to the toilets studied in Panama and in China. However, the observed moisture contents were still higher than 5%, the value reported to reliably inactivate *Ascaris* eggs (WHO, 2006).

As shown in Table 9 (found in Chapter 3), the temperature of fecal products within fecal vaults reached a maximum of 34.3°C, which was 15°C higher than the corresponding ambient temperature, but only one other fecal product temperature measurement was above 30°C. The maximum is comparable to the average temperature of 33.9°C observed in fecal piles in Vietnam (Chien et al., 2001), although the ambient temperature there (34.7°C) was much higher than in Uganda. The mean temperature of fecal products (25.6°C) was significantly lower than the maximum but was still higher than the average ambient temperature (p = 0.0191), suggesting that some level of biological activity may have been occurring within the vaults. However, the process was extremely inconsistent, as shown by the wide range of observed temperatures and an average temperature that is far below the maximum. In these UDDTs, it is possible that the decomposition process was related to incomplete mixing. If certain areas of the pile did not exhibit prohibitory levels of pH and moisture content, biological decomposition could have been initiated. On the other hand, the two temperature measurements above 30°C may have simply represented outliers in the data set. If they were removed, average fecal products temperature would drop to 23.6°C, less than two degrees above the average ambient temperature. In any case, the temperatures of fecal products in these UDDT vaults did not reach the required level (42°C) or extend for the required duration (six months) necessary for pathogen inactivation (Mihelcic et al., 2009).

4.3.2. Treatment Conditions in Test Mixtures

A summary of treatment conditions in all mixtures of stored urine, fecal products, and wood ash that were tested over the course of the three experimental stages is provided in Table 12. Moisture content values of test mixtures generally followed expected trends. Mixtures with greater urine fractions exhibited higher moisture levels. A significant discrepancy ($p = 0.0100$) was noted between the moisture content of the 2 U : 1 F : 0 A mixture in stage 1 and the moisture level of the same mixture in stage 2, with the average value in the first stage (78%) being lower than that measured in the second stage (84%). After stage 1, another batch of fecal products, which had a higher average moisture content (18%), were used to generate the mixtures in stages 2 and 3, which explains the discrepancy.

Table 12: Average treatment conditions over the entire experiment for all mixtures

Experimental Stage	Mixture (Urine : Fecal Products : Wood Ash)	Average Results ± Standard Deviation				
		Moisture Content	pH	Temperature (°C)	Total Ammonia (mg/L NH_3)	Free Ammonia (mg/L NH_3-N)
1	0 U : 1 F : 0 A	12 ± 4%	10.4 ± 0.2	23.5 ± 0.7	102 ± 56	73 ± 40
	1 U : 1 F : 0 A	64 ± 2%	10.2 ± 0.3	23.4 ± 0.7	1669 ± 565	1113 ± 343
	2 U : 1 F : 0 A	78 ± 1%	10.0 ± 0.0	23.4 ± 0.7	2194 ± 469	1383 ± 289
	3 U : 1 F : 0 A	84 ± 1%	9.9 ± 0.2	23.3 ± 0.7	2783 ± 436	1586 ± 317
	1 U : 0 F : 0 A	99 ± 0%	9.2 ± 0.3	23.2 ± 0.7	4532 ± 669	1355 ± 579
2	2 U : 1 F : 0 A	84 ± 0%	9.6 ± 0.2	22.2 ± 0.6	2787 ± 379	1204 ± 282
	2 U : 1 F : 0.5 A	76 ± 1%	9.8 ± 0.3	22.2 ± 0.6	2328 ± 302	1279 ± 343
	2 U : 1 F : 1 A	70 ± 4%	10.3 ± 0.3	22.3 ± 0.6	1691 ± 245	1165 ± 208
3	2 U : 1 F : 0 A - in	83 ± 3%	9.6 ± 0.2	22.4 ± 0.9	2804 ± 188	1274 ± 291
	2 U : 1 F : 0 A - out	82 ± 1%	9.6 ± 0.2	35.0 ± 9.7	2814 ± 235	1702 ± 401
	2 U : 1 F : 0.5 A - out	70 ± 3%	10.0 ± 0.2	35.3 ± 10.1	2325 ± 208	1667 ± 280

The pH levels of all experimental mixtures fell between the two pH extremes set by stored urine and fecal products alone, with mixtures with a higher urine fraction exhibiting pH levels that were closer to the stored urine controls. In stages 2 and 3, the 2 U : 1 F : 0.5 A and 2 U : 1 F : 1 A mixtures exhibited pH levels (from 9.8 to 10.3) that were significantly higher ($p < 0.0001$ in all cases) than the pH exhibited by the 2 U : 1 F : 0 A mixtures in those same stages (9.6). In stage 1, the 2 U : 1 F : 0 A mixture exhibited a pH (10.0) that was significantly lower ($p < 0.0001$ in both cases) than the pH of the same mixture in the latter two stages (9.6), which was likely due to the different batch of fecal products used to prepare the mixtures in stages 2 and 3.

The results of previous studies confirm that the inclusion of wood ash in fecal products significantly raises the pH levels of experimental mixtures. For instance, one of the mixtures tested by McKinley et al. (2012) included stored urine and biosolids from a compost toilet, however sawdust, rather than wood ash, had been added to the biosolids during toilet operation. The pH of this mixture ranged from 7.9 to 8.1, significantly below that of the mixtures tested in the present research, since the pH of sawdust is lower than wood ash (Mehl et al., 2011). Similarly, Cruz-Espinoza et al. (2012) combined feces with a mixture of lime and soil to simulate operating conditions of solar toilets in El Salvador. While the pH of a saturated lime solution (12.5 at 25°C) is higher than that of wood ash (Prusinski and Battacharja, 1999), the additive mixture contained very little lime (1 part lime to 60 parts soil), and the pH of the amended feces ranged from 8.0 to 9.0. Finally, in a mix designed to simulate the composition of a pit latrine vault, Fidjeland et al. (2013) combined urine and feces in what was approximately a 2.5 urine : 1 feces volumetric mixture. The pH of this mix fell between 8.9 and 9.1, significantly below the pH levels of the 2 U : 1 F : 0 A and 3 U : 1 F : 0 A mixtures in the present research. The likely explanation for this difference is that the fecal products used to create these mixtures included wood ash.

In addition to the temperature readings of the mixtures, indoor and outdoor ambient temperature measurements were also taken at the same time of day as those from the mixtures (between 9:00 AM and 3:00 PM). These ambient temperature measurements are shown in Table 13. In all three stages, the mixtures stored indoors exhibited temperatures that were not significantly different from indoor ambient temperatures ($p > 0.9999$ in all cases). Some small differences in average temperature were observed across the various stages, but it was concluded that these differences were not critical and were due simply to the small sample size of temperature measurements during experimental tests. For example, a single rainy day with a relatively cold temperature could have had a significant impact on the average temperature.

Table 13: Summary of ambient temperature measurements from all experimental stages

Experimental Stage	Location	Temperature (degrees Celsius)		
		Range	Average	Standard Deviation
1	Ambient Indoor	21.6 - 24.7	23.5	1.0
	Ambient Outdoor	19.3 - 31.0	26.1	4.1
2	Ambient Indoor	21.4 - 23.6	22.3	0.6
	Ambient Outdoor	18.1 - 27.2	23.3	2.9
3	Ambient Indoor	20.6 - 23.7	22.5	0.9
	Ambient Outdoor	20.3 - 29.3	25.2	3.3

The total ammonia concentrations in the stage 1 fecal products control were quite low when compared with the concentrations in the test mixtures, indicating that the UDDT's urine diversion system was functioning effectively. Most of the nitrogen contained in feces is present in organic compounds (Jonsson et al., 2005), the biological degradation of which is inhibited by high pH levels. Also, due to the high pH seen in the fecal products, any ammonia that might have been present initially was likely to volatilize and escape during storage in the collection vault. Conversely, concentrations of total ammonia in the urine were the highest among all materials tested, which was also expected. However, these total ammonia levels were slightly lower than those observed in Uganda by Nordin (2010) and those that were calculated theoretically (see Appendix E) using protein intake data from the FAO (2012) and equations provided in Jonsson et al. (2004). Ammonia volatilization is the likely explanation for this small discrepancy. When the urine control in stage 1 was initially prepared and then opened weekly for measurement, gaseous ammonia could have easily escaped, causing a decrease in the average total ammonia concentration.

Regarding total ammonia concentrations in the test mixtures, all mixtures with different mix ratios exhibited total ammonia concentrations that were significantly different (p values ranged from

<0.0001 to 0.0057). Figure 7 shows these dissimilarities in the first stage's mixtures. In stages 2 and 3, average total ammonia concentrations in the 2 U : 1 F : 0 A mixtures were significantly higher ($p <$ 0.0001) than the first stage's 2 U : 1 F : 0 A mixture. Between the first and second stages, the type of containers used to hold the mixtures was changed to reduce the need for open mixing. The latter two stages used bottles with a twist cap that provided an effective seal, and mixing was accomplished by shaking the closed bottle. In the first stage, small buckets had been used, and these needed to be opened so that the mixtures could be stirred. The two types of containers are shown in Figure 8.

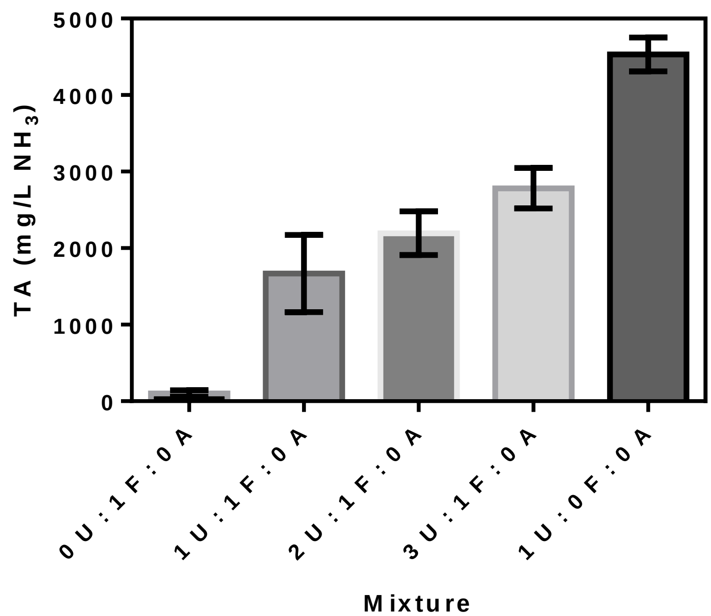

Figure 7: Average total ammonia levels and standard deviations of all mixtures throughout stage 1

After calculating free ammonia concentrations from total ammonia, pH, and temperature, it was observed that the mixtures' free ammonia concentrations were much closer together than their total ammonia concentrations. Mixtures with higher total ammonia levels also exhibited lower pH values, meaning that less ammonia was in the uncharged form. When considering only the mixtures stored indoors, this "balancing" phenomenon effectively pushed all free ammonia concentrations into a similar range, and differences between most mixtures were not statistically significant. For example, in the first stage, the total ammonia concentration of the urine control was much higher than that of all other mixtures. However, its free ammonia concentration is not significantly different from those in other mixtures (*p* values ranged from 0.2395 to 0.9992), due to the urine's lower pH.

Figure 8: Containers used during ammonia treatment tests. (a) Two-liter buckets used during stage 1 (photograph taken by the author); (b) 500-milliliter bottles used during stage 2 (photograph taken by Debra Trimmer).

4.3.3. Additional Temperature Measurements

It is important to note that all temperature measurements reported thus far were collected during the daytime. To consider how temperature variation throughout the day and night might affect ammonia concentration and pathogen inactivation, additional indoor and outdoor ambient temperature measurements were taken at different times of day. The complete data set can be found in Appendix D. Outdoor temperatures varied considerably, ranging from 16.1°C to 32.9°C and averaging 23.1°C, while indoor temperatures were more consistent, ranging from 20.6°C to 25.1°C and averaging 22.8°C.

The third experimental stage showed that the temperatures within mixtures stored outdoors could fluctuate even more widely than surrounding ambient temperatures. To further explore this phenomenon and gain a more representative view of the temperatures seen in the outdoor mixtures throughout the day, fifteen additional temperature readings were collected at various times from one of the mixtures stored outdoors. Indoor and outdoor ambient temperatures were also measured concurrently. A summary of these results is presented in Figure 9.

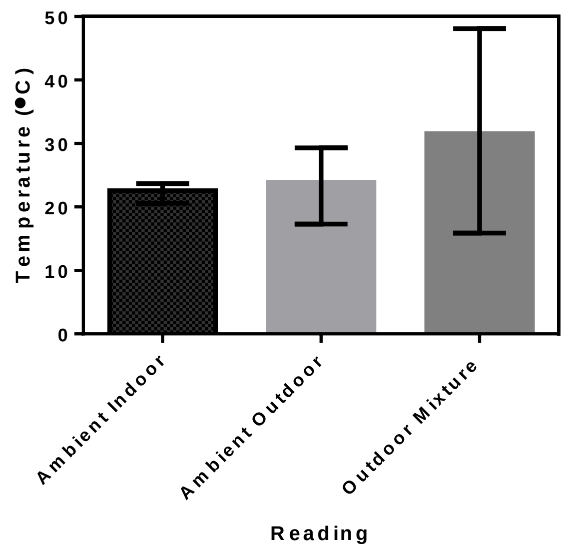

Figure 9: Averages and ranges of ambient and outdoor mixture temperatures

A comparison of these temperatures with those from Table 12 shows that, when various times of day are considered (including the colder nighttime hours), the outdoor mixture exhibits a lower average temperature (31.5°C). However, this average temperature is still approximately 8°C above the average ambient outdoor temperature (23.9°C). The elevated mixture temperature is likely due to its ability to retain heat more effectively than the surrounding air, and, in addition to being positioned in a sunny location, the mixture bottle was placed on top of an iron sheet, which is an effective conductor of heat.

4.4. Discussion

Based on the results of this research, a number of key issues pertaining to the effectiveness and feasibility of ammonia treatment were identified. These issues, estimates of *Ascaris* inactivation, and treatment system recommendations are discussed in the following sections.

4.4.1. Total Ammonia Losses

With the singular exception of the fecal products control, all mixtures exhibited declining trends in total ammonia concentrations over time. Table 14 shows the average daily total ammonia loss in each mixture, which was estimated by performing a linear regression on each mixture's total ammonia concentration over time. The slope of the regression line provided the average daily loss value. A plot of the data used to determine daily losses in the third experimental stage is presented in Figure 10.

Table 14: Average daily losses of total ammonia in all mixtures

Experimental Stage	Experiment Duration (days)	Mixture	Average Daily Total Ammonia Loss (mg NH_3/L/day)
1	58	0 U : 1 F : 0 A	-0.2
		1 U : 1 F : 0 A	21.1
		2 U : 1 F : 0 A	6.5
		3 U : 1 F : 0 A	0.9
		1 U : 0 F : 0 A	0.8
2	113	2 U : 1 F : 0 A	2.8
		2 U : 1 F : 0.5 A	4.2
		2 U : 1 F : 1 A	3.5
3	80	2 U : 1 F : 0 A - in	3.8
		2 U : 1 F : 0 A - out	4.7
		2 U : 1 F : 0.5 A - out	5.7

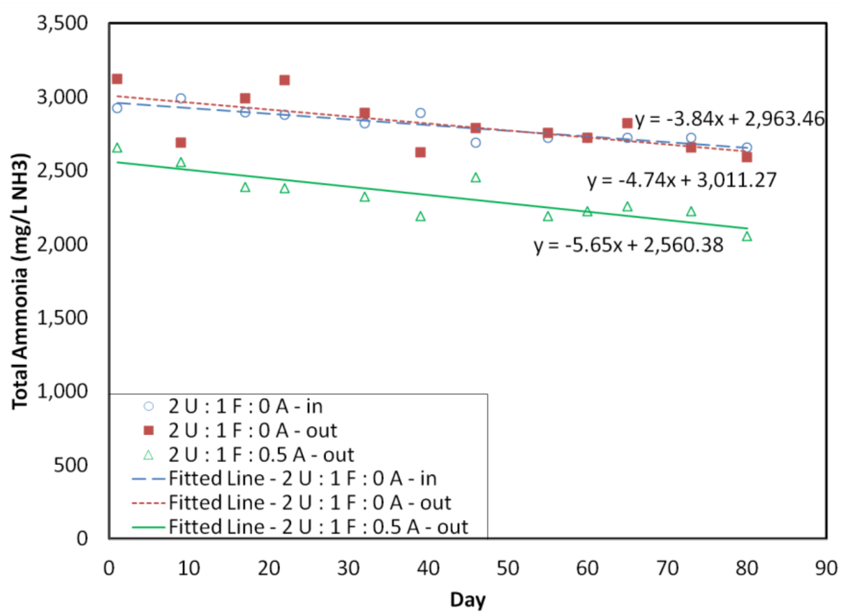

Figure 10: Average total ammonia concentrations over time in stage 3 mixtures with regression lines

The most substantial losses were observed in the first stage's 1 U : 1 F : 0 A mixture. As previously stated, these losses can be explained by the need for open mixing at the beginning of the test duration and periodic opening for additional mixing and sampling. This mixture's high daily loss was likely due to its higher pH, meaning that more of the total ammonia was present as free ammonia. The

2 U : 1 F : 0 A mixture also showed a significant decline in the first stage, but it was substantially less severe than that of the 1 U : 1 F : 0 A mixture. In stages 2 and 3, the effect of the improved storage containers is apparent when comparing daily losses in the 2 U : 1 F : 0 A mixture. This mixture's average daily losses in the second and third stages were significantly lower than its daily loss during the first stage. In the final stage, the average daily loss of the outdoor mixture was slightly higher than that of the indoor mixture. Given the higher average temperature in the outdoor mixture, this discrepancy is likely due to the fact that more ammonia is present as free ammonia when temperature is increased.

Prior studies have also noted ammonia losses over time. Nordin et al. (2009a) observed that total ammonia levels gradually declined in fecal treatments, and these reductions were explained by alkaline conditions and the need to periodically open treatments for sampling. McKinley et al. (2012) also noted reductions in total ammonia over time, but, in this case, a different hypothesis was presented. Because the matrices in which ammonia declines were most significant exhibited relatively low pH levels, the possibility of volatilization was less likely. Instead, the authors suggested that an Anammox reaction may have been occurring. The Anammox process biologically converts ammonium and nitrite ions to nitrogen gas under anoxic conditions (Strous et al., 1999). This reaction is hindered above a pH of 8.3, but, because the matrices in question exhibited pH values below this level (McKinley et al., 2012), the Anammox process could suitably explain the ammonia loss that was observed. However, in the present research, because all measured pH values were significantly higher than 8.3, the Anammox reaction was not likely to be a factor in ammonia loss.

Although ammonia losses constituted an important issue during this research, they are unlikely to be as significant in practical application, since periodic opening would not be required. If the mixture is stored in a sealed container, any ammonia losses should be minor (Nordin et al., 2009a). If significant headspace is present in the container, some transfer of free ammonia into the gaseous phase would occur, but equilibrium between the gas and liquid phases would eventually be reached, and the amount of ammonia in the gaseous phase is likely to be small. In the case of a two-liter container filled with one liter of urine and containing one liter of headspace, initial feasibility calculations (found in Appendix E) showed that less than 1% of total ammonia would be present in the gaseous phase, as long as the container is sealed. This level of volatilization may cause odors, but it would likely not reduce treatment efficiency. Other considerations regarding practical application are discussed below in further detail.

4.4.2. The Effects of Storage Conditions on Free Ammonia "Balancing"

It has been noted that, despite significantly different total ammonia levels, indoor mixtures exhibited similar free ammonia concentrations. This "balancing" phenomenon was explained by the interaction between the high pH of the fecal products fraction and the high total ammonia concentration of the urine fraction within each mixture. However, it is important to note that, if the pH of the fecal products had not been as high, this effect would have been less pronounced. If, for instance, the pH of fecal products had been 9.0, which is similar to the level seen by Mehl et al. (2011) in toilets where wood ash was used as the desiccant, the ratio of stored urine to fecal products would have had little to no effect on the pH of the resulting mixture. In mixtures with no additional wood ash, higher total ammonia concentrations would have led to higher free ammonia concentrations.

When comparing the mixtures stored outdoors with those stored indoors, the "balancing" phenomenon did not apply, due to the significant temperature difference. In stage 3, even the mixture with a lower urine fraction (2 U : 1 F : 0.5 A) exhibited a substantially higher free ammonia concentration than the mixture (2 U : 1 F : 0 A) stored indoors, since the higher temperature shifted equilibrium toward free ammonia. The third stage's free ammonia concentrations over time are shown in Figure 11, and the difference between the concentrations of the indoor mixture and those of the outdoor mixtures is easily seen. The two outdoor mixtures, however, do appear to "balance" with one another.

Free ammonia concentrations exhibited a decreasing trend over time. Losses of total ammonia, discussed in the previous section, explain this behavior. Since these losses are likely to be reduced or eliminated during practical application (Nordin et al., 2009a), declining free ammonia levels are not likely to be a significant problem. A more concerning issue is the variability displayed by the outdoor mixtures. Especially on colder days, free ammonia concentrations decreased substantially, and, in some cases, the concentrations of free ammonia in the outdoor mixtures fell below those of the indoor mixtures. It is uncertain what effect these wide variations would have on overall treatment efficiency. Given the importance of temperature in ammonia treatment (Nordin et al., 2009), a higher overall temperature would be beneficial, and Niwagaba (2009) observed that varying the temperature of stored urine resulted in more effective pathogen removal than if temperature remained constant. However, McKinley et al. (2012) found that ammonia treatment of feces was deterred when the free ammonia concentration was more variable, which would be the case when temperature fluctuates considerably.

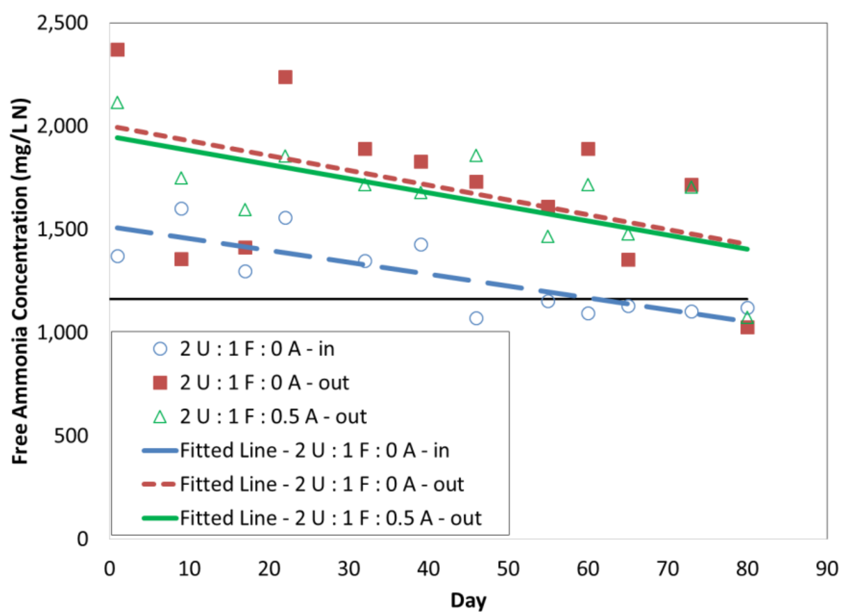

Figure 11: Average free ammonia concentrations over time in stage 3 mixtures. The horizontal black line represents the concentration required to achieve 2-log_{10} inactivation of *Ascaris* eggs in 60 days at a temperature of 23°C (Fidjeland et al., 2013).

4.4.3. Temperature Variability

To account for the variability in temperature observed throughout the year and within a single day, all outdoor and indoor ambient temperature measurements were plotted over a single 24-hour period, as shown in Figure 12. Given that this data set incorporates a variety of weather conditions and other factors, non-linear regressions were used to fit sine wave functions (constrained so that the period of the wave was 24 hours) to both the outdoor and indoor measurements to portray a "typical day" in Kalisizo. Equations 4.9 and 4.10 provide the results of these regressions:

$$T_{outdoor\ amb} = 21.8°C - 4.85°C * sin\left((0.262\ hour^{-1}) * t + 0.796\right) \quad (4.9)$$

$$T_{indoor\ amb} = 22.8°C - 0.559°C * sin\left((0.262\ hour^{-1}) * t - 0.139\right) \quad (4.10)$$

where t is time expressed in hours (for example, 1:30 PM is expressed as 13.5), while $T_{outdoor\ amb}$ and $T_{indoor\ amb}$ are the outdoor and indoor temperatures (°C), respectively. Indoor temperatures exhibit only minor variations during a typical day. Seasonal variations are likely to be more important, while still being relatively insignificant. Mixtures stored indoors, therefore, can likely be assumed to hold a reasonably constant temperature. In contrast, outdoor temperatures vary to a much larger degree over a single day. This level of variation would have profound effects on mixtures stored in outdoor locations.

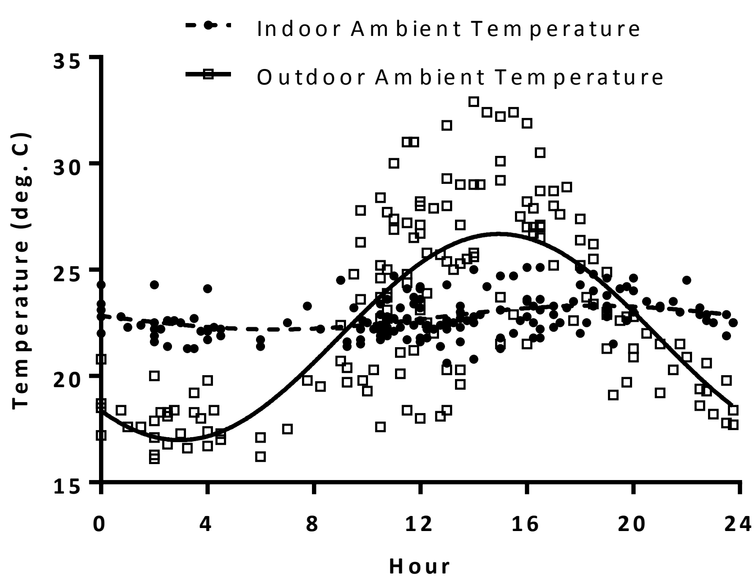

Figure 12: Ambient temperature measurements with "typical day" models over 24-hour period

A comparison of the "typical day" model for outdoor temperature with data recorded on www.climatedata.eu showed the model to be an accurate representation of an average day in the central and southern parts of Uganda. In the case of Kampala, which is approximately 150 kilometers northeast from Kalisizo, the average annual high and low temperatures are reported to be 26.6°C and 17.2°C, respectively, with an overall average of 21.9°C (www.climatedata.eu). Similarly, the "typical day" outdoor model reached a maximum of 26.6°C and a minimum of 17.0°C, and its average temperature was 21.7°C, suggesting that this model provides an accurate picture of an average day in Kalisizo.

These ambient temperature models were then related to mixture temperatures. In both the outdoor and indoor cases, mixture temperatures were plotted as functions of ambient temperatures, and linear regressions were performed. Equations 4.11 and 4.12 show the resulting functions:

$$T_{outdoor\ mix} = 2.63 * T_{outdoor\ amb} - 31.3°C \quad (4.11)$$

$$T_{indoor\ mix} = 0.872 * T_{indoor\ amb} + 2.83°C \quad (4.12)$$

where $T_{outdoor\ mix}$ and $T_{indoor\ mix}$ represent mixture temperatures for given ambient temperature values, expressed in degrees Celsius. Using Equations 4.9 through 4.12, mixture temperatures throughout a "typical day" were modeled. Figure 13 provides a plot of outdoor ambient temperatures and outdoor mixture temperatures over the course of a "typical day". During colder hours, the mixture temperature drops below ambient conditions, while, during warmer hours, the mixture temperature increases to levels considerably higher than ambient temperatures. In the indoor scenario, mixture and ambient temperatures were similar throughout the entire day.

Average mixture temperatures for outdoor and indoor models were calculated to be 25.8°C and 22.7°C, respectively. A comparison of these averages with actual temperatures observed in the mixtures revealed that the outdoor model average was considerably lower than what was observed. Using the model averages in place of measured temperatures when estimating potential *Ascaris* egg inactivation would provide a conservative estimate for outdoor mixtures. Caution is most needed when estimating inactivation in this case, since outdoor conditions can be highly variable.

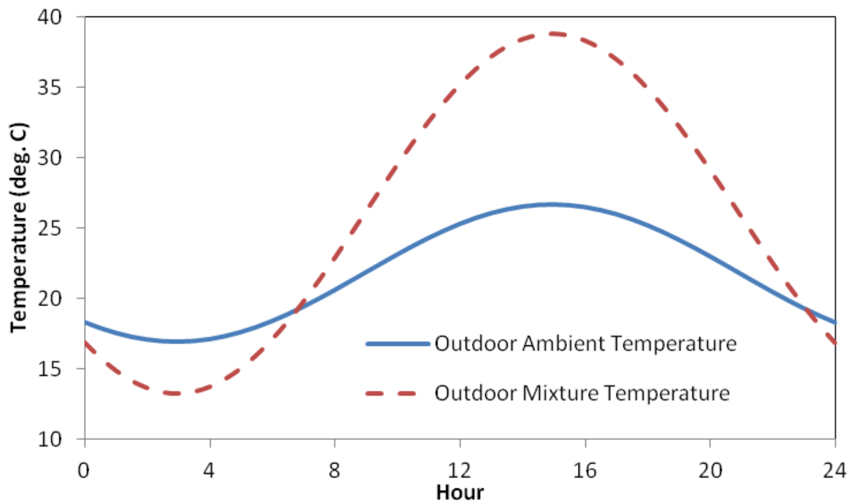

Figure 13: "Typical day" model of outdoor mixture and ambient temperatures

4.4.4. Estimation of *Ascaris* Inactivation Based on Previous Studies

To evaluate the potential for pathogen reduction, data sets from four previous studies that evaluated *Ascaris* inactivation through ammonia treatment (Pecson et al., 2007; Nordin et al., 2009a; McKinley et al., 2012; Fidjeland et al., 2013) were selected based on similarity with conditions in the test mixtures of this research. Two of the studies (McKinley et al., 2012; Fidjeland et al., 2013) used urine as the source of additional ammonia, which further corresponds to this research. All four studies also provided results regarding *Ascaris* egg inactivation kinetics. For the purpose of this research, a 2-$\log_{10}$ *Ascaris* inactivation level was used as the target for ammonia treatment. As stated previously, an overall 4-$\log_{10}$ reduction is needed for safe agricultural reuse in Uganda. However, WHO (2006) reported that "more or less complete inactivation of *Ascaris* eggs" could occur after one year of storage in fecal vaults at ambient temperatures between 20°C and 35°C. Understanding that, based on other studies (Peasey, 2000; Moe and Izurieta, 2003), complete inactivation of *Ascaris* eggs is unlikely given these storage conditions, the phrase "more or less complete inactivation" is assumed to correspond with 2-$\log_{10}$ inactivation. Therefore, a secondary ammonia treatment step will only be required to achieve an additional 2-$\log_{10}$ reduction of *Ascaris* eggs.

Ascaris inactivation is commonly represented using a model that includes an initial lag phase followed by first-order exponential decay (Pecson et al., 2007). The model can be described by Equations 4.13 and 4.14, the first of which shows expected *Ascaris* concentration over time, while the second provides the duration of the lag period before exponential decay begins:

$$N = N_o \left[1 - \left(1 - e^{(-kt)}\right)^m\right] \tag{4.13}$$

$$Lag\ Period = \frac{\ln(m)}{k} \tag{4.14}$$

where N represents the number of active organisms remaining at a given time t, N_o is the initial number of active organisms, k is the first-order inactivation rate constant (day^{-1}), m is the lag constant, and t is the elapsed time, measured in days. One of the studies (Pecson et al., 2007) provided values for the constants (k, m) in each test case. For the other three studies, these two constants were calculated using reported lag periods and inactivation times. All studies except Fidjeland et al. (2013) provided 2-$\log_{10}$ inactivation times. Instead, this study reported 1-$\log_{10}$ inactivation times, so 2-$\log_{10}$ removal times were estimated by using the k and m constants in Equation 4.13, allowing all data sets to be associated with the same level of inactivation. Several sets of the treatment conditions evaluated in these previous studies are shown in Table 15, along with 2-$\log_{10}$ *Ascaris* inactivation times and lag periods.

To develop a predictive equation for *Ascaris* egg inactivation, a multiple linear regression was performed using temperature, pH, and free ammonia data from Table 15. However, after the first iteration of the regression analysis, the effect of pH was found to be insignificant (p = 0.842). Therefore, this factor was eliminated, leaving temperature and free ammonia concentration as the two remaining parameters. This result agrees with the statement made by Nordin et al. (2009a) that temperature and free ammonia are two of the most important factors contributing to *Ascaris* egg inactivation. The second iteration produced a regression equation that was relatively simple, fit the given data reasonably well (R^2 = 74%), and showed that both temperature (p < 0.001) and free ammonia (p = 0.016) had significant impacts on 2-$\log_{10}$ *Ascaris* inactivation time. Equation 4.15 shows the final multiple regression equation:

$$t_{2-log} = 257\ days - \left(6.82\,\frac{days}{°C}\right) * T - \left(0.0232\,\frac{days}{\frac{mg}{L}NH_3-N}\right) * FA \quad (4.15)$$

where $t_{4\text{-}log}$ represents the time required for 4-$\log_{10}$ inactivation of *Ascaris* eggs (days), *T* represents temperature (°C), and *FA* represents free ammonia concentration (mg/L NH_3-N). Given the limits of the data used to develop Equation 4.15, it should be noted that the equation is only valid for certain ranges of temperature (20 to 30°C) and free ammonia concentration (700 to 2,000 mg/L NH_3-N).

Table 15: Selected *Ascaris* egg inactivation data from previous studies

Number	Temperature (°C)	pH	Average Total Ammonia Concentration as N (mg/L NH_3-N)	Average Free Ammonia Concentration (mg/L NH_3-N)	Lag Period (days)	2-$\log_{10}$ Inactivation Time including Lag Period (days)	Reference
1	20	11.5	1,045	1,035	28	132	McKinley et al., 2012
2	20	12.0	1,240	1,235	-	87	Pecson et al., 2007
3	20	11.2	2,545	2,491	-	52.5	McKinley et al., 2012
4	23	8.9	2,100	616	48	86[a]	Fidjeland et al., 2013
5	23	9.0	3,400	1,162	24	42[a]	Fidjeland et al., 2013
6	23	9.0	6,800	2,394	21	28[a]	Fidjeland et al., 2013
7	24	10.5	840	793	-	35	Nordin et al., 2009a
8	24	8.9	6,174	1,825	-	47	Nordin et al., 2009a
9	28	8.9	2,100	784	18	26[a]	Fidjeland et al., 2013
10	28	9.0	3,400	1,456	12	19[a]	Fidjeland et al., 2013
11	28	9.0	6,800	2,982	-	10[a]	Fidjeland et al., 2013
12	30	12.0	1,220	1,218	-	16	Pecson et al., 2007
13	34	8.3	3,458	600	8	21	Nordin et al., 2009a
14	34	12.8	994	994	-	3.7	Nordin et al., 2009a
15	34	12.8	1,008	1,008	-	3.8	Nordin et al., 2009a

[a] 2-$\log_{10}$ inactivation times for data from Fidjeland et al. (2013) were calculated by the author

Ascaris egg inactivation in the mixtures tested in this research was then estimated using Equation 4.15. However, to be more conservative and consistent, the measured mixture temperatures were not included. This modification minimized fluctuations resulting from seasonal variations (more significant indoors) and from daily variations (more significant outdoors). Instead, the averages from the "typical day" model were used. All indoor mixtures were given the average indoor mixture temperature from the model (22.7°C), while the outdoor mixtures were given the model's average outdoor mixture temperature (25.8°C). The model temperatures, along with the measured averages of pH and total ammonia, were used to calculate new average free ammonia concentrations for each mixture. Equation 4.15 was then used to estimate the treatment time required for 2-log_{10} inactivation of *Ascaris* eggs. Table 16 provides the results, along with the adjusted sets of treatment conditions for each mixture. A treatment time for the fecal products control (0 U : 1 F : 0 A) has not been reported, since its free ammonia concentration falls outside of the validity range for Equation 4.15.

Table 16: Estimated treatment times required for 2-log_{10} inactivation of *Ascaris* eggs

Experimental Stage	Mixture	Average pH	Adjusted Temperature (°C)	Average Total Ammonia (mg/L NH_3)	Calculated Free Ammonia (mg/L NH_3-N)	Estimated Time for 2-log_{10} Inactivation (days)
1	0 U : 1 F : 0 A	10.4	22.7	102	74	N/A
	1 U : 1 F : 0 A	10.2	22.7	1,669	1,143	76
	2 U : 1 F : 0 A	10.0	22.7	2,194	1,368	70
	3 U : 1 F : 0 A	9.9	22.7	2,783	1,633	64
	1 U : 0 F : 0 A	9.2	22.7	4,532	1,235	74
2	2 U : 1 F : 0 A	9.6	22.7	2,787	1,271	73
	2 U : 1 F : 0.5 A	9.8	22.7	2,328	1,271	73
	2 U : 1 F : 1 A	10.3	22.7	1,691	1,200	74
3	2 U : 1 F : 0 A - in	9.6	22.7	2,804	1,279	73
	2 U : 1 F : 0 A - out	9.6	25.8	2,814	1,411	48
	2 U : 1 F : 0.5 A - out	10.0	25.8	2,325	1,525	46

4.4.5. Recommended Mixture and Storage Conditions

Given the estimated inactivation times shown in Table 16, a question arises regarding which of the mixtures will be most feasible and effective in the Ugandan context. While all stage 1 mixtures containing fecal products and urine had similar treatment times (64 to 76 days), the 3 U : 1 F : 0 A mixture exhibited the highest free ammonia concentrations and was estimated to have a shorter inactivation time than the 1 U : 1 F : 0 A and 2 U : 1 F : 0 A mixtures. However, some uncertainty exists with regard to the feasibility of the mixture. While global excretion rates suggest that the typical volume of urine produced by one person on a daily basis can be more than ten times the daily volume of feces (Esrey et al., 2001), the largest value in the literature for daily excretion of feces, 0.35 kilograms per person (Niwagaba, 2009), indicates that some locations may exhibit a much lower ratio of urine to feces. The fecal generation rate provided by Niwagaba (2009) is specific to rural areas of developing countries, a description that fits most of Uganda, including the Kalisizo area. When the addition of other materials, including desiccant and toilet paper, are considered along with this large generation rate, the ratio of urine to fecal products is computed to be 2.05 U : 1 F (supporting calculations can be found in Appendix E). Early estimates of urine and fecal production in UDDTs at Kalisizo schools also suggested that a lower generation ratio may be more applicable in this context. For example, at Saint Andrews Matale Hill Primary School, the UDDT was being used by approximately 30 students, most of whom were not in the boarding section. The daily production rate of fecal products was calculated to be roughly three liters per day. Although some urine may not have been counted, due to potential agricultural application between monitoring visits, the observed urine production rate was approximately 6.3 liters per day, resulting in a generation ratio of 2.1 U : 1 F, nearly equal to the ratio calculated theoretically.

Given these theoretical and practical estimates, the 3 U : 1 F : 0 A mixture would not be possible in this case, assuming that all fecal products are to be treated using this method. The 2 U : 1 F : 0 A mixture, on the other hand, would remain feasible even in this extreme case and would not consume all of the available urine. Any remaining urine could be used, after dilution, as a nitrogen-rich liquid fertilizer. Improvements in the yields of various crops, comparable with those caused by commercial fertilizers, have been shown to result from urine application (Richert et al., 2009).

With the conclusion that the 2 U : 1 F : 0 A mixture was the most effective and feasible option from stage 1, the second stage investigated whether additional wood ash should be added to this mixture. When the modeled average temperature for indoor mixtures was used, the "balancing" phenomenon caused the free ammonia concentrations and treatment times of all mixtures to be quite similar. Given that the availability of sufficient supplies of wood ash has occasionally been found to be an issue in multiple areas of Uganda (Kaggwa et al., 2003; Kamuteera et al., 2013), mixtures which incorporate smaller amounts of wood ash are likely to be more feasible. Therefore, the 2 U : 1 F : 0 A and 2 U : 1 F : 0.5 A mixtures were chosen for further testing in stage 3.

The third stage examined the question of whether mixtures should be stored indoors or outdoors. In terms of storage location, even with average temperatures from the "typical day" model that were considerably lower than measured temperatures, the mixtures located outdoors were associated with much shorter inactivation times than the mixtures stored indoors. However, this statement assumes that average temperature and free ammonia levels provide sufficient information to reliably estimate *Ascaris* inactivation. As discussed previously, it is currently unclear whether large fluctuations in temperature and free ammonia levels would improve or inhibit pathogen inactivation. A future study, which directly measures and compares pathogen inactivation in constant temperature conditions and in fluctuating temperature conditions, is needed to adequately investigate this issue. The two storage locations each provide different benefits. Storing mixtures outdoors results in higher temperature and free ammonia levels, but those levels can vary widely. While indoor storage results in lower temperatures and free ammonia concentrations, these values remain more stable throughout the treatment period.

Considering the fact that the outdoor 2 U : 1 F : 0 A and 2 U : 1 F : 0.5 A mixtures exhibited inactivation times that were similar to one another, and that supplying sufficient wood ash may be difficult (Kaggwa et al., 2003; Kamuteera et al., 2013), the 2 U : 1 F : 0 A mixture is recommended as the most effective and feasible option among all of those tested. Based on the estimated inactivation times associated with this mixture, three months of closed indoor storage is likely to result in 2-$\log_{10}$ inactivation of *Ascaris* eggs within the context of Uganda.

By storing the mixture outdoors on a surface that conducts heat (such as metal), the inactivation time estimated in this research suggests that two months of closed storage would provide 2-$\log_{10}$ inactivation. As stated previously, this recommendation is qualified by a significant amount of uncertainty, due to the variability associated with outdoor storage. A future study that evaluates the effects of these fluctuations would help to confirm or correct this recommendation. Table 17 provides a summary of initial ammonia treatment recommendations for indoor and outdoor storage in Uganda. The indoor location is recommended as the primary storage option, due to its greater consistency, practicality, and safety. Outdoor storage could present potential hazards to curious children and to local livestock or other wildlife. However, if the mixture could be kept isolated, and if fluctuating treatment conditions prove not to be a hindrance for pathogen inactivation, outdoor storage would provide a fast and effective option for ammonia treatment. If storage space is at a premium, as it might be in a growing small town, the decreased time requirement could be a key advantage of outdoor storage.

Table 17: Recommendations for ammonia treatment of fecal products after UDDT vault storage

Number	Mixture	Storage Location	Storage Time	Additional Comments
1	2 U : 1 F : 0 A	Indoors	3 months	Indoor storage provides consistent temperature conditions
2	2 U : 1 F : 0 A	Outdoors on a metal surface	2 months	Further study is needed regarding fluctuating temperature conditions

If users find that the 2 U : 1 F : 0 A mixture requires too much urine, or if users simply wish to use more of the produced urine as a liquid fertilizer on its own, the 1 U : 1 F : 0 A mixture would also be a feasible option. Estimated 2-$\log_{10}$ inactivation times in Table 16 show that it would be slightly less effective than the 2 U : 1 F : 0 A mixture, but the difference in treatment time is small. The mixture with the smaller urine fraction could be a useful alternative mixture in certain situations.

4.4.6. Treatment System Recommendations and Practical Feasibility

In many areas of Uganda, Eco-San systems and UDDTs remain a relatively new and unfamiliar approach to sanitation. However, as detailed in Chapter 3, well-directed sensitization and education efforts can transform those not acquainted with these systems into knowledgeable and effective UDDT operators and advocates. Discussion and observation of the benefits of the system, such as its permanence, reduction of flies and odors, and production of agricultural amendments, can convince potential users of its utility and value. The ammonia treatment system is likely to produce agricultural amendments of better hygienic quality than the UDDT's conventional dehydration process, while also retaining the other advantages of this type of system. The mixture of urine and fecal products may produce an agricultural amendment that is more complete than either of these materials on their own. Urine is extremely high in nitrogen, while fecal material is high in organic matter, and both contain significant amounts of phosphorus, potassium, and various micronutrients (Jonsson et al., 2004). Alternatively, the mixture could be added to a compost pile containing other types of organic waste, with the final product being used as a soil amendment. Given these added advantages, ammonia treatment seems to have a strong chance of acceptance in Uganda when coupled with an effective sensitization and education effort.

For ammonia treatment, an appropriately-sized container that could be sealed for an extended period of time is needed to store the mixture. For example, several types of black, cylindrical plastic containers with removable lids, ranging in volume from 100 to 500 liters, are available for purchase in many Ugandan towns. The appropriate container volume could be related to the size of the household or institution. To accommodate the 2 U : 1 F : 0 A mixture, the bottom third of the container could be marked off. Once the collected fecal products fill this bottom third, the container could be moved to the storage location, stored urine added to fill the container, and a wooden stick or pole used to mix the contents. Based on Table 17, indoor storage would extend for three months. If outdoor storage were deemed to be feasible, it would last for two months. In the outdoor case, the container could be placed on a piece of scrap metal, widely used in Uganda to fabricate products such as boxes and rainwater gutters. Figure 14 provides an overall summary of the recommended ammonia treatment process.

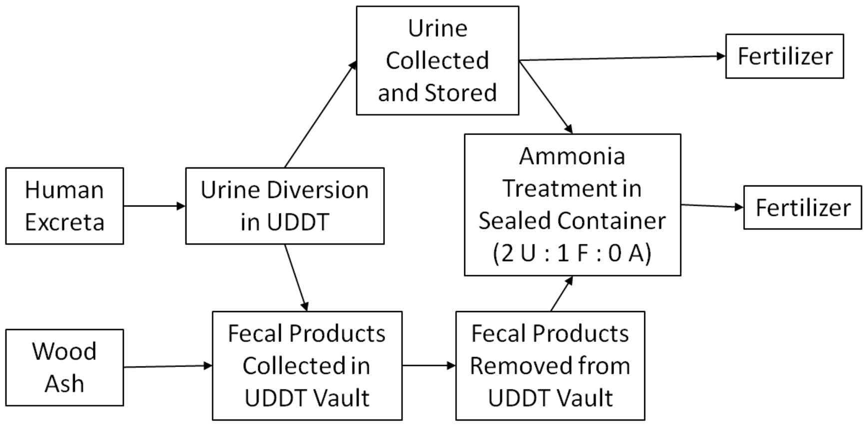

Figure 14: Recommended ammonia treatment process diagram

Regarding economic feasibility, the ammonia treatment system would constitute only a small additional cost on top of the double-vault UDDT. A preliminary cost analysis of the additional materials needed for ammonia treatment shows that this additional treatment step would require an additional expenditure that is approximately 11% of the construction cost of the double-vault UDDT (see Appendix G for cost estimates associated with each system). These additional expenses would include materials such as a container for closed storage of the mixture, shovels to fill or empty the container, and a pole for mixing. It would be sensible to move the container to its storage location before urine is added, since the liquid will add weight.

Ideally, the ammonia treatment system could eventually be offered by local construction companies and sanitation providers as a complete package, perhaps incorporating the construction of the toilet facility and provision of the other necessary materials and information into a single product. Additionally, they could provide regular maintenance of the system, as well as collection and centralized processing services. However, at this early stage in its development, it is more likely to be implemented on a piecemeal basis by interested individuals, households, or organizations. Further research on pathogen inactivation under fluctuating treatment conditions and in a full-scale system could help to propel this alternative forward.

4.5. Conclusions

The results of this research provide insight into both the current operation of UDDTs in Kalisizo, Uganda and the possibility of an alternative fecal treatment system in which ammonia levels are elevated through the addition of stored urine. The two UDDTs recently installed in Kalisizo schools were operated effectively, attaining the pH (above 9.0) and moisture content (below 25%) recommended for these systems. However, the problem of persistent pathogens, such as *Ascaris lumbricoides*, remained a concern, since pH and moisture content did not meet the extreme conditions needed for complete inactivation of *Ascaris* eggs. However, the results of ammonia treatment tests showed that this alternative is a promising and feasible strategy for inactivating *Ascaris* eggs in fecal products. The 2 U : 1 F : 0 A mixture was estimated to provide 2-$\log_{10}$ inactivation of *Ascaris* eggs after three months of indoor storage, or after two months of outdoor storage, if storage in an outdoor location were deemed to be feasible. However, treatment conditions during outdoor storage were found to be quite variable, and the effect of these fluctuations on treatment efficiency is currently unclear. Social acceptance of the treatment system appears to be possible with proper sensitization and education efforts, and the system would constitute a relatively minor cost in comparison with a double-vault UDDT facility.

Moving forward, several opportunities for future work are suggested by this research. Some possible topics include the following:

- Pathogen inactivation studies focusing on the effects of fluctuating treatment conditions
- Testing of a full-scale (at least 100 liters) ammonia treatment system to identify issues not apparent in the small-scale mixtures evaluated in this research, and to determine whether outdoor storage would be feasible on a larger scale
- Qualitative studies focusing on the acceptance and feasibility of ammonia treatment

- Analysis of the agricultural value of fecal product/stored urine mixtures and comparison with the improved agricultural yields from urine alone that are discussed in Shaw (2010) and Richert (2009)

This research provides a promising starting point from which further study and refinement of ammonia treatment can be accomplished. In the future, this treatment strategy could prove to be an alternative that improves the hygienic safety and agricultural value of fecal products being produced by UDDTs.

CHAPTER 5: OVERALL CONCLUSIONS AND RECOMMENDATIONS

Overall, this research investigated two topics of concern related to Ecological Sanitation (Eco-San) and Urine-Diverting Dry Toilets (UDDTs) in Uganda: (1) effective promotion to improve local knowledge and attitudes and to ensure correct operation of the facilities; and (2) effective treatment of collected fecal material to ensure that resistant and endemic pathogens, such as *Ascaris lumbricoides*, are being inactivated prior to agricultural reuse. With regard to the first topic, the efficacy of installing demonstration UDDTs at primary schools in Kalisizo, Uganda was studied using qualitative methods that assessed knowledge and attitudes within the school communities, both before installation of the facilities and after several months of operation. The facilities were also monitored to assess operational performance. In general, the strategy was successful in improving knowledge and opinions among students and teachers and in empowering students to become compelling advocates for Eco-San systems. Key findings included the following:

- Students, including those who were not using the facilities, exhibited a marked increase in knowledge regarding UDDT principles and operation after installation, and pre-existing local knowledge was applied to certain aspects of the system (addition of local herbs to collected urine)
- Although initial attitudes toward UDDTs in the school communities were predominantly negative, opinions after installation of the facilities were strongly positive, with emphasis being placed on the advantages of the system over pit latrines (permanence of the structure, reduced flies and odors, general hygienic improvements, economic value of agricultural products)
- After installation, participants' views on the use of UDDT fertilizers improved significantly and was likely influenced by initial observations of the benefits of urine application on school crops

- With the introduction of improved sanitation systems that highlight the importance and value of sanitation, other hygienic improvements (hand-washing stations, provisions for washing and disposing of menstrual pads) have been installed at the schools, fostering an environment that is safer, empowering girls to effectively manage menstruation without feelings of humiliation or shame, and demonstrating to students that they are valued and respected.

Recommendations for future areas of study include: the long-term success of demonstration UDDTs and full-scale systems in Kalisizo; future uptake of UDDTs in the area; developing attitudes toward reuse of UDDT products as the materials are used; the effects of UDDTs on long-term economic and health status of users; and alternative urine treatment methods using local materials.

Regarding the second topic, an alternative fecal treatment mechanism that elevates free ammonia levels through the addition of stored urine was studied. Treatment conditions (pH, temperature, ammonia concentration) were measured in various mixtures of stored urine, fecal products, and wood ash, and the results of those measurements were compared with previously published data on *Ascaris* egg inactivation to estimate required treatment times. Treatment conditions in fecal vaults were also measured to determine the efficacy of the alkaline dehydration process that is currently used as primary treatment in UDDTs. In general, ammonia treatment through urine addition was shown to be a promising and feasible strategy. Key findings included the following:

- Demonstration UDDTs recently installed in Kalisizo schools were operated effectively, attaining the recommended pH (above 9.0) and moisture content (below 25%), but persistent pathogens remained an issue, since pH and moisture content did not meet the extreme conditions needed for inactivation of *Ascaris* eggs
- All ammonia treatment mixtures achieved treatment conditions that would inactivate *Ascaris* eggs over a period of several months, with the 2 U : 1 F : 0 A mixture selected as the most effective and feasible option among those tested

- The 2 U : 1 F : 0 A mixture was estimated to provide 2-$\log_{10}$ inactivation of *Ascaris* eggs after three months of indoor storage, or after two months of outdoor storage, if storage in an outdoor location were deemed to be feasible
- Given estimated production rates of urine and feces, as well as wood ash requirements, in UDDTs, the 2 U : 1 F : 0 A mixture has the capacity to treat all feces collected from a UDDT using the urine produced in the same facility, while also minimizing the need for additional supplies of wood ash
- Treatment conditions during outdoor storage were found to be quite variable, due to daily temperature cycles, and the effect of these fluctuations on treatment efficiency is currently unknown

Recommendations for future areas of study include: the effects of fluctuating treatment conditions on pathogen inactivation; testing of a full-scale (at least 100 liters) ammonia treatment system; the acceptance of ammonia treatment in Uganda and other countries; and analysis of the agricultural value of fecal product/stored urine mixtures.

Overall, this research has provided possible solutions for enhancing the promotion and acceptance of UDDTs in Uganda through school-based demonstration facilities, and for improving the treatment of UDDT fecal products by using low-cost urine treatment. In the future, these solutions could play a part in helping Uganda to address current trends related to growing population density, declining soil fertility and food security, human health and hygiene, and environmental conservation. As part of a larger strategy, these strategies could help Uganda to achieve its “Vision 2040”, in which the country is transformed into an industrialized, middle-income nation where all Ugandans are ensured of a high quality life in a clean and healthy environment.

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APPENDICES

Appendix A: Detailed Physical and Chemical Testing Procedures

This appendix provides detailed testing procedures used during ammonia treatment experiments. Temperature, pH, total ammonia, and moisture content measurements are included.

A.1. Temperature

A single thermometer was used for all measurements, but the instrument was cleaned between each use with alcohol swabs (Kendall, 70% isopropyl alcohol). The thermometer's probe was immersed in the mixture until the temperature reading held constant. This process generally required between ten and twenty seconds for each mixture.

A.2. pH

After the contents of each container were completely mixed, a fresh pH indicator strip was submerged in the mixture until the color change was complete. Usually, approximately one to three seconds were required. Because the first stage's fecal product controls were dry mixtures, a small amount (approximately 10 ml) was removed from the bucket using a plastic spoon and mixed with treated water from Kalisizo's piped system (approximately 10 ml) in a plastic, 30-ml medicine cup (McKesson, 5-ml graduations). After gently shaking to mix, the solids were allowed to settle, and the pH of the supernatant could be measured. This procedure conforms to that used by Mehl et al. (2011) in Panama.

A.3. Total Ammonia

Due to the ammonia test kit's low measurement range, dilutions needed to be prepared from samples of each mixture before testing for total ammonia concentration. Using a plastic, 3-ml graduated transfer pipette (Karter Scientific, 0.5-ml graduations), a one milliliter sample from each mixture was obtained and deposited in a plastic 15-ml graduated test tube (Lake Charles Manufacturing, 0.5-ml graduations). After all samples had been collected, a series of three 1:10 dilutions was performed on each sample. Water from Kalisizo's piped system, which had been treated by filtration through a ceramic candle filter and solar disinfection, was added to the test tube until the total volume reached ten milliliters, and, after capping the tube and shaking it to ensure adequate mixing, one milliliter from the dilution was transferred to a second test tube. This process was repeated until a third test tube held a 1:1000 dilution of the original sample. Using a procedure from Jonsson et al. (2004), along with data from FAO statistics, Esrey et al. (2001), Niwagaba (2009), Ogata et al. (1970), and Putnam (1971), a total ammonia concentration for stored urine in Uganda was estimated to be approximately 5,460 mg/L NH3. Supporting calculations can be found in Appendix C. Similarly, Nordin (2010) recorded total ammonia concentrations in Uganda of 5,100 mg/L NH3, so a 1:1000 dilution would be expected to fall within the test kit's measurement range.

Following dilution of all samples, approximately 0.5 milliliters of each were dispensed into the cavity of a small testing plate. Using forceps, a gas exchange ammonia sensor disc, provided in the test kit, was also placed in the cavity, and one drop of the kit's total ammonia reagent was added. Over the course of fifteen minutes, the sensor undergoes a color change that correlates to the total ammonia concentration in the sample. To determine this concentration, the sensor's color is compared to a continuous color scale ranging from 0.0 mg/L NH3 (yellow) to 6.0 mg/L NH3 (dark blue). For a more sensitive reading, the sensor can be left in the sample for thirty minutes and then compared to the color scale. However, since the sensor's color continues to change during the second fifteen minute period, the thirty minute scale only ranges from 0.0 to 3.0 mg/L NH3. Although details regarding the exact cause of the sensor's color change are not provided by the kit manufacturer, it is assumed that the addition of the reagent serves to increase the sample's pH, converting any ammonia into the uncharged form. Then, the gas exchange sensor directly measures the ammonia gas being released to the atmosphere over time, which can be correlated to the aqueous concentration of ammonia in the sample. Sensors in all samples were read using the color scale after fifteen minutes, and, with the exception of diluted samples in which the total ammonia concentration was above 3.0 mg/L NH3, sensors were read again after thirty minutes. If discrepancies between the two readings were observed, the lower one was kept.

A total ammonia test was also conducted on the dilution water used on each testing day, to identify any background ammonia concentration that might have an effect on the dilutions. After testing was completed on each day, the background concentration in that day's dilution water was used in Equation A.1 to calculate the actual, undiluted total ammonia concentration of each mixture:

$$C_m = \frac{C_s(F_w+F_m)-C_wF_w}{F_m} \qquad \text{(A.1)}$$

In the above equation, C_m represents the actual total ammonia concentration in the mixture, C_s signifies the measured total ammonia concentration in the diluted sample, and C_w is the measured total ammonia concentration in the dilution water, with all concentrations being expressed as mg/L NH_3. Additionally, F_w represents the fraction of dilution water in the diluted sample (999/1000), while F_m stands for the fraction of the mixture in the diluted sample (1/1000).

For quality control purposes, total ammonia tests were also performed on the 1 mg/L NH_3 standard provided in the test kit, and a spike recovery test, which used this standard solution in conjunction with actual mixture samples, was also performed. For the spike recovery test, a mixture sample was spiked by using the standard solution in place of water for the final 1:10 dilution in the series of three. The concentration in the spiked sample was compared to the concentration in a fully diluted sample of the same mixture, to determine if the spike was being registered by the test method. Results of quality control tests are included in Appendix E.

A.4. Moisture Content

The moisture content of each mixture was measured either after the testing period had been completed (in the case of the first two stages) or during the testing period (for the third stage). After each test matrix was thoroughly mixed, a sample of at least 25 milliliters was collected and deposited in a plastic, 30-ml medicine cup (McKesson, 5-ml graduations). The mass of the empty cup had previously been measured using the digital scale, and the filled cup's mass was subsequently recorded. Each filled cup was then placed in a solar oven, which had been fabricated using locally-available scrap materials. On days in which the weather was appropriate, the oven was positioned outside for a period of five to eight hours, and the mass of the cup was measured at the end of the each day. When the decrease in mass from the previous day was 0.1 gram or less, drying was assumed to be complete, and the final mass was recorded. The drying process commonly required between five and ten days. Moisture content for each sample could then be calculated according to Equation A.2:

$$Moisture\ Content = \frac{(m_{wet} - m_{dry})}{(m_{wet} - m_{cup})} \times 100\% \qquad \text{(A.2)}$$

where m_{wet} represents the initial wet mass of the sample and cup, m_{dry} stands for the final dry mass of the sample and cup, and m_{cup} is the mass of the empty cup.

Appendix B: Qualitative Research Tools and UDDT Evaluation Guide

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FOCUS GROUP DISCUSSION GUIDE – PHASE 1

Introduction:

1. What is the importance of using pit latrines/toilets in our environment (homes, schools, public places)?

2. What different types of pit latrines/toilets exist in this community? Which ones have you heard exist in other places around?

Knowledge:

3. Have you ever heard of/seen/used Eco-San systems (UDDTs)?
   a. *If "Yes":*
      i. From where have you heard/seen/used these UDDT toilets?
      ii. When did you first hear of/see/use the UDDT toilets?
      iii. What are the major differences between Eco-San toilets and the commonly used pit latrines?
      iv. What do you think are the major benefits in using UDDTs over pit latrines?
         Probe for:
         - lack of flies, odors, permanent structures
         - treated feces and urine are used as nutrients and organic matter for plants which are consumed by humans and animals
         - natural resource protection
      v. What do you think are the major disadvantages in using UDDTs over pit latrines?
         - getting sufficient desiccant
         - bothersome to add desiccant after every use
         - collection of urine
      vi. What are the different steps taken in operation of UDDTs?
         - initial operation
         - treatment processes
         - emptying of vaults
         - nutrient reuse
   b. *If "No":*
      (Provide some minimal education at this point, and then follow up with attitude questions)

Attitudes:

4. *Perceptions of UDDTs*
   a. Tell me about your experiences or what you have seen/heard are people's experiences in using Eco-San toilets.
   b. What do you think are the major advantages in using Eco-San toilets over other types of toilets/latrines?
   c. What are the major challenges in using Eco-San toilets compared with other types of toilets/ latrines?

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5. *Perceptions of UDDTs – continued*
    a. What are your thoughts and feelings about the whole process of handling of urine and feces in Eco-San systems?
        Probe for:
        - Risks and dangers
        - Beneficial uses
        - Potential value
    b. Do you think, if introduced, community members will be receptive to installing UDDTs in their homes instead of ordinary pit latrines? Explain.
    c. What are the anticipated challenges in installation and operation of UDDTs in ordinary homesteads?
        - Do you think people in homes will be willing to learn about the principles of the system?
        - Will they be willing to follow operational procedures?
        - Will they be willing to reuse urine and feces after treatment?
            Probe for:
            - Potential effects on crops
            - Benefits and risks
            - Willingness to handle urine and feces
    d. What about among school communities and other general public places? Do you think they will be receptive to install these UDDTs in schools and other public places instead of ordinary pit latrines? Please explain.
    e. What are the anticipated challenges in installation and operation of UDDTs in schools and other public places?
        - Do you think school and other public communities will be willing to learn about the principles of the system?
        - Will they be willing to follow operational procedures?
        - Will they be willing to reuse urine and feces after treatment?
            Probe for:
            - Potential effects on crops
            - Benefits and risks
            - Willingness to handle urine and feces

6. *Perceptions of Crops*
    a. What do you think would be people's thoughts about crops that have been fertilized by treated urine and feces?
    b. Will they take as important the nutritional value of the treated feces and urine? Please explain.
    c. Will they consider the consumption of the fertilized crops to be risky? Please explain.
    d. Will they be willing to consume these crops fertilized with feces and urine? Please explain.

7. What are your thoughts about what can be done to overcome the above challenges if the Eco-San project is to succeed?

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KEY INFORMANT INTERVIEW GUIDE – PHASE 1

Facility Installation

1.) In what year was your Eco-San system installed?
2.) Why was an Eco-San system chosen instead of a traditional pit latrine or other sanitation system?
3.) Who or what organization installed this Eco-San system?
4.) Did you receive training when the facility was installed?
    a. If so, what topics were included in this training?

Facility Use and Operation

5.) Is the Eco-San system only used by members of one household, or do neighbors and/or the general public also use the facility?
6.) Do children use the Eco-San system? If yes, what challenges do they experience when using the facility?
7.) Are desiccating materials added to the vault?
    a. If so, what materials are added?
    b. When are they added, and what amount is added?
    c. What challenges are experienced in adding desiccants?
8.) How long are feces stored in the vault before emptying?
9.) How long is urine stored before use or disposal?
10.) Would it be acceptable to use treated feces and urine for agriculture in your community?
11.) Are treated urine and feces ever used? If yes, in what way are they used?

    Probe for agriculture, other uses/purposes

User Satisfaction

12.) Do the users prefer this Eco-San system over other types of latrines and sanitation systems?
    a. Why?
    b. What are the advantages of this facility over other types of latrines?
    c. What are the disadvantages when compared to other types of latrines?
13.) What challenges have been experienced in using this facility?
    a. What has been done to address those problems?
    b. What suggestions do you give as a way of addressing these challenges?

Recommendation

Another group of people is planning to set up Eco-San systems to serve schools and possibly neighboring communities. What advice would you give to this group if their project is to succeed?

Probe for who should be included in project planning/implementation, structural recommendations, mobilization message content

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FGD AND KII OBJECTIVES AND QUESTIONS – PHASE 2

1. *Evaluate changes in knowledge and attitudes toward Eco-San toilets among members of intervention communities*
    a. Do community members (students and staff) have a better understanding of the principles of Eco-San systems?
        i. Nutrient reuse (using human excreta as fertilizer)
        ii. Sanitization of feces (adding wood ash after every use)
        iii. Benefits of Eco-San (permanent structures, can be built anywhere, economic gains, odor/fly reduction, etc.)
    b. Do community members feel that Eco-San toilets are an appropriate and beneficial sanitation option (in schools and/or in households)?
        i. Has seeing the Eco-San toilets at the schools changed community members' perceptions of this technology?

2. *Evaluate acceptance of the facilities within the school communities and the experiences of users*
    a. What benefits have members of the school community (users and non-users) seen as a result of the Eco-San toilet?
    b. What disadvantages have community members seen?
    c. Have any problems been identified? (ash availability/addition, urine/feces mixing, blockage of urine piping, cleanliness of facility, structural problems, storage and reuse of urine/feces, etc.)
    d. How does use of ecosan toilets generally compare with use of pit latrines and water/flush toilets?
    e. What changes could be made to address any issues with ecosan toilets?
    f. Would members of the school community recommend that more Eco-San toilets be constructed at their school, and at other local schools?

Additional KII questions will be asked of participants, especially with regard to personal experiences about how easy or difficult it is to use the facility and how this compares with pit latrines. The issue of use of fertilizers on crops for home consumption will also be probed.

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Urine-Diverting Dry Toilet (UDDT) Operational Checklist

School ______________________________ Date ____________________

Estimated number of toilet users ____________

List any problems that users are experiencing:

Answer the following questions with "Yes" or "No" and list any problems below each question:

Does urine appear to be completely separated from feces? ______________ (Yes/No)

Problems:

Does sufficient ash appear to be added to the feces? ______________ (Yes/No)

Problems:

Does the front door appear to be in good condition? ______________ (Yes/No)

Problems:

Do the rear access panels appear to be in good condition? ______________ (Yes/No)

Problems:

Do the vent pipes appear to be in good condition? ______________ (Yes/No)

Problems:

Do the urine diverters appear to be in good condition? ______________ (Yes/No)

Problems:

Do the buckets and cups appear to be in good condition? ______________ (Yes/No)

Problems:

Does the urine piping appear to be in good condition? ______________ (Yes/No)

Problems:

Rate the following on a scale of 1 to 5:

Cleanliness of the latrine: ______________ 1 = very clean; 5 = very dirty

Presence of flies: ______________ 1 = no flies; 5 = full of flies

Presence of odor: ______________ 1 = no odor; 5 = terrible odor

Moisture content of feces/ash pile: ______________ 1 = very dry; 5 = very wet

Estimate the following:

Volume of feces/ash collected since last inspection: ______________ liters

Volume of urine collected since last inspection: ______________ liters

Volume of desiccant used since last inspection: ______________ liters

Appendix C: IRB Exemptions, Approvals, and Approved Consent Forms

The following pages include the USF IRB exemption, approval letters from the UVRI-SEC and UNCST in Uganda, and the final consent forms approved for use.

Gmail by Google

John Trimmer <jtrimmer87@gmail.com>

IRB Question

Hart, Olivia <olivia@usf.edu> Mon, Jun 24, 2013 at 4:28 PM
To: "Ergas, Sarina" <sergas@usf.edu>
Cc: "Mihelcic, James" <jm41@usf.edu>, "jtrimmer87@gmail.com" <jtrimmer87@gmail.com>

Dear Dr. Ergas,
Julie Martin forwarded me your email below for a response. After reviewing the email and attached documents, I would make the same determination Julie made regarding Tricia Wilbur's project. To reiterate, as defined by the federal regulations, a human subject is a living individual about whom an investigator conducting research obtains data through intervention or interaction with the individual or identifiable private information. Research is defined as a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge. For a project to include human subjects research which is reviewable by the USF IRB and requires approval per the federal regulations, both of the definitions outlined above must be met.

Mr. Trimmer's project is collecting information related to the Eco-san toilets and not the individuals. As such, I do not feel that this meets the definition of human subjects research requiring USF IRB approval. Should you need additional assistance, please feel free to contact me.

Thank you,

Olivia Hart, MPA, CIP
IRB Education Coordinator
Research Integrity & Compliance
Phone: (813) 974-7454
FAX: (813) 974-7091
USF IRB website: http://www3.research.usf.edu/dric/hrpp/

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REPUBLIC OF UGANDA

Our Ref: GC/127/13/06/27

Your Ref: ……

24th June 2013

Dr. John Trimmer,

RE: UVRI SEC review of protocol titled **"Brick by Brick Uganda Primary School Ecological Sanitation (Eco-San) Pilot in Kalisizo Town."**

Thank you for your responses to the queries addressed to you by UVRI SEC during the SEC meeting of 13th June 2013.

This is to inform you that your responses dated 19th June 2013 were reviewed and met the requirements of the UVRI Science and Ethics Committee.

UVRI SEC annual approval has been given for you to conduct your research up to 24th June 2014. Annual progress report and request for extension should be submitted to UVRI SEC prior to the expiry date, to allow timely review.

The reviewed and approved documents included;

1. UVRI-SEC application form
2. Project Protocol
3. Consent forms
4. Data collection guides
5. Letters from key collaborators
6. CVs of project personnel

You can now continue with your study after registration with the Uganda National Council for Science and Technology (UNCST).

Note: UVRI SEC requires you to submit a copy of the UNCST approval letter for the above study before commencement.

Yours sincerely,

Mr. Tom Lutalo
Chair, UVRI SEC
C.C Secretary, UVRI SEC

Uganda National Council for Science and Technology

(Established by Act of Parliament of the Republic of Uganda)

UNCST

27/08/2013

Our Ref: SS 3197

Mr. John Thomas Trimmer
Brick by Brick Uganda
P.O Box 133
Kampala

Re: Research Approval: Brick by Brick Uganda Primary School Ecological Sanitation Pilot in Kalisizo Town

I am pleased to inform you that on **12/07/2013**, the Uganda National Council for Science and Technology (UNCST) approved the above referenced research project. The Approval of the research project is for the period of **12/07/2013** to **12/07/2014**.

Your research registration number with the UNCST is **SS 3197**. Please, cite this number in all your future correspondences with UNCST in respect of the above research project.

As Principal Investigator of the research project, you are responsible for fulfilling the following requirements of approval:

1. All co-investigators must be kept informed of the status of the research.
2. Changes, amendments, and addenda to the research protocol or the consent form (where applicable) must be submitted to the designated local Institutional Review Committee (IRC) or Lead Agency for re-review and approval **prior** to the activation of the changes. UNCST must be notified of the approved changes within five working days.
3. For clinical trials, all serious adverse events must be reported promptly to the designated local IRC for review with copies to the National Drug Authority.
4. Unanticipated problems involving risks to research subjects/participants or other must be reported promptly to the UNCST. New information that becomes available which could change the risk/benefit ratio must be submitted promptly for UNCST review.
5. Only approved study procedures are to be implemented. The UNCST may conduct impromptu audits of all study records.
6. A progress report must be submitted electronically to UNCST within four weeks after every 12 months. Failure to do so may result in termination of the research project.

Below is a list of documents approved with this application:

	Document Title	Language	Version	Version Date
1	Research proposal	English	N/A	N/A
2	Consent forms	English, Luganda	N/A	N/A
3	Data Collection Guides	English	N/A	N/A

Yours sincerely,

[redacted]

Leah Nawegulo
for: Executive Secretary
UGANDA NATIONAL COUNCIL FOR SCIENCE AND TECHNOLOGY

Cc Chair, Uganda Virus Research Institute SEC, Entebbe

LOCATION/CORRESPONDENCE

Plot 6 Kimera Road, Ntinda
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COMMUNICATION

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Brick by Brick

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INFORMED CONSENT FORM
IN-DEPTH INTERVIEWS AND FOCUS GROUP DISCUSSIONS

RESEARCH STUDY TITLE: Brick by Brick Uganda Primary School Ecological Sanitation (Eco-San) Pilot in Kalisizo Town.

PRINCIPAL INVESTIGATOR: John Trimmer, United States Peace Corps Volunteer, Brick by Brick Uganda.

Co-Investigators: Robert Ssekubugu, Rakai, Kalisizo, Neema Nakyanjo, Rakai, Kalisizo, Max Ssenyonga, Brick by Brick Uganda.

SPONSOR: Brick by Brick Uganda, (an NGO), and Brick by Brick Partners, a Non-Profit Organization based in the United States.

INFORMATION SHEET

Hello, my name is ______________________________________. I work with Brick by Brick, a Non Government Organisation in Kalisizo - Rakai district, which collaborates with Brick by Brick Partners, a Non-Profit Organization in the United States.

INTRODUCTION:

Brick by Brick Uganda was established in 2003. Its major goal is to improve lives and futures of children in Uganda. Among other ways, this is by supporting the delivery of quality education, improving the physical infrastructure of school communities and encouraging sustainable economic development.

Through its work, Brick by Brick Uganda has realized that there is great need for more sustainable sanitation systems, more specifically, Ecological Sanitation (Eco-San). It is believed that use of UDDTs can be an environmentally sound option that moves toward the main goal.

Brick by Brick Uganda wants to carry out a research study assessing the **acceptability** and **utilization** of Eco-San systems (use of UDDTs) in a school setting within and near Kalisizo and the neighboring fishing village where Eco-San systems have been installed in the past, in order to provide a point of comparison.
………………

UGANDA VIRUS RESEARCH INSTITUTE ENTEBBE
SCIENCE & ETHICS COMMITTEE
04 JUL 2013

[redacted]

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DEPARTMENT OF AFRICAN LANGUAGES
01 JUL 2013
MAKERERE UNIVERSITY
P. O. BOX 7062, KAMPALA

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WHAT YOU SHOULD KNOW ABOUT THIS STUDY:

- You are (your child is) being asked to join a research study.
- This consent form explains the research study and your (your child's) part in the study.
- Please read it carefully and take as much time as you need.
- Please ask questions at any time about anything you do not understand.
- If you (your child) join the study, you (he/she) can change your (his/her) mind later. You (Your child) can decide not to take part or you (your child) can quit at any time. There will be no penalty or loss of benefits if you (your child) decide to quit the study.
- During the study, we will tell you (your child) if we learn any new information that might affect whether you (your child) wish to continue to be in the study.
- Ask the study team to explain any words or information in this informed consent that you do not understand.

PURPOSE:

I would like to ask you (your child) to participate in a research study to assess acceptability and utilisation of Eco-San systems (UDDTs) in a school setting and neighboring fishing village where Eco-San systems have been installed in the past.

The objectives of the study are:

1. to assess the current attitudes and levels of knowledge regarding various aspects of Eco-San systems.
2. to re-assess knowledge and attitudes in Kalisizo after UDDTs have been in operation for one year.
3. to assess knowledge and attitudes in a neighboring fishing village where UDDTs have previously been installed.
4. to compare knowledge and attitudes in Kalisizo before and after the pilot project, and compare Kalisizo results with the results in fishing village(s), in order to determine the success of the project with respect to community education.

You (your child) were selected for this study because you (your child) live(s) in Rakai district where Brick by Brick Uganda operates and where pilot testing of the Eco-San system (UDDTs) is to undergo/ongoing, that is Kalisizo or Kasensero landing site.

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STUDY PROCEDURES:

We shall conduct a total of about 16 focus group discussions (FGDs) and about 12 In-depth interviews (IDIs), in order to cover those different topics among different categories of participants. These FGDs and IDIs will be audio-recorded to ensure that all important points are captured. Each FGD will be conducted in a central private place, containing between 7 and 9 participants and lasting between an hour and one and a half. FGD participants will include residents of Rakai district school girls and school boys, male and female parents and men and women residing in Kasensero fishing village.

Each in-depth informant interview will in turn be conducted with one person at a time, will be in private and will last about one hour. Participants will include Rakai district school teachers, district education representatives, local leaders and parents.

In-depth Interviews with owners of Eco-San systems are estimated to be between 20 and 30.

Today, you (your child) are/is being asked to participate in an IDI/FGD. The entire discussion will be tape-recorded, and you (your child) will be identified by name only on the tape. The tape will be privately maintained in locked files at Brick by Brick offices. The information recorded is considered confidential, and no one else except the study investigators will have access to the tapes.

CONFIDENTIALITY:

- Any identifying information shared during our discussion will remain confidential and will be privately maintained in locked files in the offices of Brick by Brick. The tape recordings and written records will be privately maintained in locked files in the offices of Brick by Brick. Long term records will be stored securely in locked files of Brick by Brick , and will not have your (your child's) name or other individual identification on them. No information linked to your (your child's) name(s) will be released to anyone else without your (your child's) permission.

PARTICIPATION IS VOLUNTARY:

- Your (your child's) participation in this KII/IDI is completely voluntary. You (your child) are (is) free to withdraw from the discussion at any time. You (your child) will not be forced to stay in the discussion, and you (your child) will not be penalized if you (your child) decide to leave. Such a decision (not to participate or to leave the discussion early) will not affect you (your child) in any way.

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RISKS FROM BEING IN THE STUDY:

The risks due to being in the study are minimal. These risks include:

- Some amount of discomfort you (your child) may feel due to embarrassment when discussing human excreta. These feelings should be minimal since the discussions focus on general attitudes within the community, rather than personal beliefs and opinions.

- Some questions may be hard for you (your child) to answer and may make you (your child) self-conscious. You (your child) will not be required to answer any question that you (your child) do not want to. You (your child) can stop at any time during the interview. Or, you (your child) can refuse to participate in the study altogether.

- All in all, we will interview you (your child) in private, and keep all information safe and confidential. No information linked to your (your child's) name will be released to anyone else without your (your child's) permission.

BENEFITS:

There are no direct benefits to you (your child) for participating in the study. However, the information you (your child) provide(s) could assist your (your child's) community by helping us to learn about the attitudes and beliefs of the community members towards the Eco-San system.

You (your child) will be compensated for participation and travel expenses with a flat rate of 10,000 Ugandan shillings .

QUESTIONS/POINTS OF CONTACT:

If you have any questions, please ask, and we shall do our best to answer them fully and honestly. If you have additional questions or if you need to discuss any other aspect of the study, you can contact: the study Principal Investigator John Trimmer, Brick by Brick Uganda (tel. 0705385867) or Robert Ssekubugu (tel. 0772425401) or Neema Nakyanjo (tel. 0772484147) both of Kalisizo town council or Max Ssenyonga of Brick by Brick Uganda (tel. 0772551615).

If you have any questions concerning your (your child's) rights as a participant in this research, please contact Mr. **Tom Lutalo,** Chairman of the Science and Ethics Committee (SEC) of the Uganda Virus Research Institute (UVRI) (tel. 041-320776) or the Secretary of the UVRI-SEC (tel. 041-320776).

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CONSENT OF PARENT OR GUARDIAN IF PARTICIPANT IS AN UNEMANCIPATED MINOR UNDER AGE 18.

I have been asked whether my son/daughter/ward may participate in an in-depth interview/focus group discussion assessing the **acceptability** and **utilization** of Eco-San systems (use of UDDTs) in Rakai. The study representative _______________________________, has explained the significance of the research, the in-depth interview/focus group discussion in which my child/ward will participate, all of the methods to be used and the risks that my child/ward may take. The information above has been read to me.

I have been given an opportunity to ask questions about this research project. All questions were answered in a way that I understand. If I have other questions about this study, I can ask the study representative ____________________________________ or John Trimmer whose contact I have been given.

I understand that my agreement to let my child/ward participate is voluntary, and that I can decline to let my child/ward participate or ask that my child/ward leave the study at any time, without any penalty to myself or my child/ward. I also understand that he/she has the right to voluntarily refuse to participate in all or part of the study. I'm signing my name (or making my thumb print) below to indicate my consent for my child/ward to participate in this study.

****

_______________________________ ____________________

SIGNATURE OF PARENT/GUARDIAN DATE

(thumb print if illiterate)

_______________________________ ______________________________

PRINTED NAME OF PARENT/GUARDIAN ADDRESS OF PARENT /GUARDIAN

_______________________________ ____________________

SIGNATURE OF INVESTIGATOR DATE

ELICITING CONSENT

****

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STATEMENT OF CONSENT

Assessing the **acceptability** and **utilization** of Eco-San systems (use of UDDTs) in Rakai district.

I,______________________________age_______________have been asked to participate in an IDI/FGD about assessment of the **acceptability** and **utilization** of Eco-San systems (use of UDDTs) in Rakai district.

The study representative _________________________has explained the significance of the research, the duration of the project, the IDI/FGD in which I will participate, all of the methods to be used, and the risks that I may take.

I have been given an opportunity to ask questions about this research project. All questions were answered in a way that I understand. If I have other questions about this research, I can ask the study representative ____________________ or John Trimmer, a Peace Corps volunteer working with Brick by Brick Uganda in Kalisizo, whose contact I have been given. If I have any questions concerning my rights as a participant in this study, I can contact Mr. Tom Lutalo Chairman of the Science and Ethics Committee of Uganda Virus Research Institute, tel. 041-320776 or the Secretary of the UVRI-SEC (tel. 041-320776).

I understand that my participation is voluntary, that I can decline to be in the study or leave the study at any time, and that if I decline to join the study or if I leave the study, I will not be penalized in any way.

I am signing my name (or making my thumb print) to indicate my consent to participate in this study. I will be given a copy of the signed consent form.

______________________________ _______________

SIGNATURE OF PARTICIPANT
(Thumb print if illiterate) DATE

______________________________ _______________

Name of participant Address of participant

___________________ ______________________ _______________

SIGNATURE OF WITNESS
(If participant is illiterate) PRINTED NAME OF WITNESS DATE
(Same as participant)

-- -------------------------

SIGNATURE OF INVESTIGATOR ELICITING CONSENT DATE

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Appendix D: Complete Data Sets for All Physical and Chemical Measurements

Table D.1: Stage 1 moisture content measurements

Mixture	Cup Mass (g)	Initial Wet Mass (g)	Final Dry Mass (g)	Moisture Content	Mixture Averages
0 U : 1 F (A)	1.5	17.2	15.2	13%	12 ± 4%
0 U : 1 F (B)	1.5	16.5	14.2	15%	
0 U : 1 F (C)	1.4	17.1	15.8	8%	
1 U : 1 F (A)	1.5	32.0	12.2	65%	64 ± 2%
1 U : 1 F (B)	1.5	34.7	13.1	65%	
1 U : 1 F (C)	1.5	32.4	13.2	62%	
2 U : 1 F (A)	1.5	29.9	7.8	78%	78 ± 1%
2 U : 1 F (B)	1.5	30.5	7.7	79%	
2 U : 1 F (C)	1.5	28.2	7.5	78%	
3 U : 1 F (A)	1.5	28.6	5.6	85%	84 ± 1%
3 U : 1 F (B)	1.5	30.4	6.2	84%	
3 U : 1 F (C)	1.5	29.6	6.2	83%	
1 U : 0 F (A)	1.5	27.6	1.8	99%	99 ± 0%
1 U : 0 F (B)	1.5	27.1	1.7	99%	
1 U : 0 F (C)	1.4	29.3	1.8	99%	

Table D.2: Stage 2 moisture content measurements

Mixture	Cup Mass (g)	Initial Wet Mass (g)	Final Dry Mass (g)	Moisture Content	Mixture Averages
2U:1F:0A (A)	1.5	29.6	6.1	84%	84 ± 0%
2U:1F:0A (B)	1.4	28.9	5.9	84%	
2U:1F:0A (C)	1.5	27.8	5.7	84%	
2U:1F:0.5A (A)	1.5	31.7	8.7	76%	76 ± 1%
2U:1F:0.5A (B)	1.4	35.2	9.5	76%	
2U:1F:0.5A (C)	1.4	31.8	9.2	74%	
2U:1F:1A (A)	1.5	34.8	10.4	73%	70 ± 4%
2U:1F:1A (B)	1.5	35.0	11.4	70%	
2U:1F:1A (C)	1.5	38.9	14.4	66%	

Table D.3: Stage 3 moisture content measurements

Mixture	Cup Mass (g)	Initial Wet Mass (g)	Final Dry Mass (g)	Moisture Content	Mixture Averages
2U:1F:0A (A) - in	1.5	27.9	5.6	84%	83 ± 3%
2U:1F:0A (A) - in	1.5	29.3	7.2	79%	
2U:1F:0A (A) - in	1.5	27.6	5.7	84%	
2U:1F:0A (A) - out	1.4	30.8	6.9	81%	82 ± 1%
2U:1F:0A (A) - out	1.4	30.1	6.8	81%	
2U:1F:0A (A) - out	1.4	30.1	6.3	83%	
2U:1F:0.5A (A) - out	1.5	31.4	10.4	70%	70 ± 3%
2U:1F:0.5A (B) - out	1.5	34.3	10.3	73%	
2U:1F:0.5A (C) - out	1.5	32.6	11.6	68%	

Table D.4: Additional moisture content measurements for second batch of fecal products

Mixture	Cup Mass (g)	Initial Wet Mass (g)	Final Dry Mass (g)	Moisture Content	Average
feces/ash control - A	1.4	18.0	14.9	19%	18 ± 1%
feces/ash control - B	1.5	16.7	14.1	17%	
feces/ash control - C	1.5	16.4	13.5	19%	

Table D.5: Stage 1 pH measurements

Mixture	Day									Mixture Averages
	2	10	17	24	31	37	45	50	58	
0 U : 1 F (A)	10.5	10.5	10.5	10.0	10.5	10.5	10.5	10.5	10.5	
0 U : 1 F (B)	10.5	10.5	10.0	10.5	10.0	10.5	10.5	10.0	10.0	10.4 ± 0.2
0 U : 1 F (C)	10.5	10.5	10.5	10.0	10.5	10.0	10.5	10.5	10.5	
1 U : 1 F (A)	10.0	10.0	10.0	10.0	10.5	10.0	10.5	10.5	10.5	
1 U : 1 F (B)	10.0	10.0	10.0	10.0	10.5	10.5	10.5	10.5	10.5	10.2 ± 0.3
1 U : 1 F (C)	10.0	10.0	10.0	10.0	10.0	10.5	10.5	10.0	10.0	
2 U : 1 F (A)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
2 U : 1 F (B)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0 ± 0.0
2 U : 1 F (C)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
3 U : 1 F (A)	9.5	10.0	9.5	9.5	9.5	10.0	10.0	10.0	10.0	
3 U : 1 F (B)	9.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.9 ± 0.2
3 U : 1 F (C)	9.5	9.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
1 U : 0 F (A)	9.0	9.0	9.0	9.0	9.0	9.5	9.0	9.5	9.5	
1 U : 0 F (B)	9.0	9.0	9.0	9.0	9.5	9.5	9.5	9.5	9.5	9.2 ± 0.3
1 U : 0 F (C)	9.0	9.5	9.0	9.5	9.0	9.0	9.5	9.5	9.0	

Table D.6: Stage 2 pH measurements

Mixture	Day																	Mixture Averages
	1	8	15	23	30	35	42	49	59	63	70	78	85	92	99	106	113	
2 U : 1 F : 0 A (A)	9.5	9.5	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0 A (B)	10.0	10.0	9.5	9.5	9.5	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.6 ± 0.2
2 U : 1 F : 0 A (C)	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0.5 A (A)	10.0	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.0	9.5	
2 U : 1 F : 0.5 A (B)	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.5	10.0	9.5	10.0	10.0	9.5	9.5	9.5	9.5	9.8 ± 0.3
2 U : 1 F : 0.5 A (C)	10.0	10.0	10.0	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
2 U : 1 F : 1 A (A)	10.5	10.0	10.0	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.5	10.0	10.0	10.0	
2 U : 1 F : 1 A (B)	10.0	10.0	10.5	10.5	10.5	10.5	10.0	10.5	10.0	10.5	10.0	10.5	10.0	10.0	10.5	10.0	10.5	10.3 ± 0.3
2 U : 1 F : 1 A (C)	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.0	

Table D.7: Stage 3 pH measurements

Mixture	Day 1	9	17	22	32	39	46	55	60	65	73	80	Mixture Averages
2 U : 1 F : 0 A - in (A)	9.5	10.0	9.5	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0 A - in (B)	10.0	10.0	10.0	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.6 ± 0.2
2 U : 1 F : 0 A - in (C)	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0 A - out (A)	9.5	9.5	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0 A - out (B)	10.0	10.0	9.5	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.6 ± 0.2
2 U : 1 F : 0 A - out (C)	10.0	10.0	9.5	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
2 U : 1 F : 0.5 A - out (A)	10.5	10.0	10.0	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
2 U : 1 F : 0.5 A - out (B)	10.0	10.5	10.0	10.0	10.0	10.0	10.0	9.5	10.0	10.0	10.0	9.5	10.0 ± 0.2
2 U : 1 F : 0.5 A - out (C)	10.0	10.5	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	

Table D.8: Stage 1 temperature measurements (°C)

Mixture	Day 2	10	17	24	31	37	45	50	58	Mixture Averages
0 U : 1 F (A)	22.5	24.4	22.7	23.7	23.9	22.7	24.2	23.1	24.5	
0 U : 1 F (B)	22.3	24.4	22.7	23.7	23.8	22.7	24.1	23.1	24.3	23.5 ± 0.7
0 U : 1 F (C)	22.4	24.4	22.6	23.6	23.7	22.6	24.1	23.1	24.3	
1 U : 1 F (A)	22.4	24.3	22.5	23.5	23.6	22.4	24.1	23.4	24.3	
1 U : 1 F (B)	22.6	24.1	22.5	23.5	23.6	22.5	24.1	23.5	24.2	23.4 ± 0.7
1 U : 1 F (C)	22.6	24.1	22.5	23.5	23.6	22.5	24.2	23.6	24.3	
2 U : 1 F (A)	22.4	24.1	22.4	23.4	23.5	22.3	24.0	23.4	24.2	
2 U : 1 F (B)	22.6	24.1	22.4	23.4	23.5	22.5	24.1	23.6	24.2	23.4 ± 0.7
2 U : 1 F (C)	22.7	24.1	22.5	23.4	23.6	22.6	24.1	23.7	24.2	
3 U : 1 F (A)	22.4	24.1	22.3	23.3	23.5	22.3	23.9	23.4	24.1	
3 U : 1 F (B)	22.5	24.0	22.3	23.3	23.5	22.4	24.0	23.6	24.1	23.3 ± 0.7
3 U : 1 F (C)	22.6	23.9	22.4	23.3	23.5	22.6	24.1	23.6	24.1	
1 U : 0 F (A)	22.4	23.8	22.3	23.2	23.4	22.3	23.9	23.4	24.0	
1 U : 0 F (B)	22.4	23.8	22.3	23.2	23.4	22.4	24.0	23.5	24.0	23.2 ± 0.7
1 U : 0 F (C)	22.4	23.8	22.3	23.2	23.5	22.5	24.1	23.5	24.0	
Ambient T_{in}	21.6	24.7	23.2	24.1	24.2	22.7	24.1	22.5	24.1	23.5 ± 1.0
Ambient T_{out}	20.3	30.0	28.0	27.1	28.2	27.4	23.4	19.3	31.0	26.1 ± 4.1

Table D.9: Stage 2 temperature measurements (°C)

Mixture	Day																	Mixture Averages
	1	8	15	23	30	35	42	49	59	63	70	78	85	92	99	106	113	
2 U : 1 F : 0 A (A)	23.5	23.4	22.4	22.6	22.1	21.5	22.6	22.1	22.8	22.4	21.6	22.6	21.8	21.3	21.2	22.0	22.6	22.2 ±0.6
2 U : 1 F : 0 A (B)	23.5	23.4	22.4	22.5	22.2	21.6	22.5	22.1	22.7	22.3	21.5	22.6	21.6	21.3	21.2	22.0	22.6	
2 U : 1 F : 0 A (C)	23.5	23.3	22.4	22.6	22.2	21.7	22.5	22.1	22.6	22.4	21.6	22.6	21.6	21.3	21.2	22.0	22.6	
2 U : 1 F : 0.5 A (A)	23.6	23.4	22.3	22.6	22.1	21.4	22.4	22.1	22.7	22.3	21.6	22.6	21.6	21.3	21.1	22.0	22.5	22.2 ±0.6
2 U : 1 F : 0.5 A (B)	23.6	23.3	22.4	22.6	22.2	21.6	22.4	22.1	22.6	22.4	21.5	22.6	21.7	21.3	21.1	22.0	22.6	
2 U : 1 F : 0.5 A (C)	23.6	23.2	22.4	22.5	22.2	21.7	22.3	22.1	22.6	22.4	21.6	22.6	21.6	21.3	21.2	22.0	22.6	
2 U : 1 F : 1 A (A)	23.6	23.4	22.3	22.6	22.2	21.6	22.5	22.2	22.7	22.5	21.7	22.6	21.6	21.3	21.1	22.0	22.6	22.3 ±0.6
2 U : 1 F : 1 A (B)	23.7	23.3	22.5	22.5	22.2	21.7	22.3	22.2	22.7	22.3	21.6	22.6	21.6	21.4	21.2	22.0	22.5	
2 U : 1 F : 1 A (C)	23.6	23.3	22.5	22.6	22.2	21.7	22.3	22.2	22.6	22.5	21.6	22.5	21.7	21.4	21.3	22.0	22.5	
Ambient T_{in}	23.6	23.4	22.2	22.6	22.3	21.4	22.4	22.2	22.6	22.4	21.6	22.6	21.7	21.5	21.4	22.1	22.6	22.3 ±0.6
Ambient T_{out}	25.0	26.5	18.4	26.7	19.6	18.1	25.7	22.0	25.5	23.7	23.1	27.2	24.8	23.6	19.7	22.7	23.7	23.3 ±2.9

Table D.10: Stage 3 temperature measurements (°C)

Mixture	Day												Mixture Averages
	1	9	17	22	32	39	46	55	60	65	73	80	
2 U : 1 F : 0 A - in (A)	22.0	21.8	20.3	22.0	22.6	23.0	22.0	23.7	22.3	23.1	22.5	23.6	22.4 ± 0.9
2 U : 1 F : 0 A - in (B)	22.1	21.8	20.3	22.0	22.6	23.0	22.0	23.6	22.2	23.2	22.4	23.6	
2 U : 1 F : 0 A - in (C)	22.2	21.8	20.3	22.0	22.5	23.0	22.0	23.7	22.3	23.1	22.5	23.6	
2 U : 1 F : 0 A - out (A)	48.1	19.2	21.8	40.6	37.2	42.4	37.1	36.1	47.3	28.2	40.0	22.4	35.0 ± 9.7
2 U : 1 F : 0 A - out (B)	48.0	18.9	22.1	41.0	37.5	42.2	38.9	34.9	46.3	27.3	41.2	21.9	
2 U : 1 F : 0 A - out (C)	48.6	19.4	22.5	41.6	37.4	43.0	38.8	34.5	44.8	27.1	40.8	21.3	
2 U : 1 F : 0.5 A - out (A)	49.9	19.2	23.0	42.7	36.8	44.1	40.1	34.2	44.6	26.7	42.2	21.4	35.3 ± 10.1
2 U : 1 F : 0.5 A - out (B)	48.8	19.6	23.2	42.7	37.8	42.5	40.0	34.0	43.5	25.7	42.5	20.4	
2 U : 1 F : 0.5 A - out (C)	50.1	20.3	23.8	43.6	36.4	41.8	41.0	33.2	44.5	24.8	44.5	20.3	
Ambient T_{in}	22.2	21.6	20.6	22.1	22.5	22.9	22.2	23.6	22.4	23.2	22.6	23.7	22.5 ± 0.9
Ambient T_{out}	27.9	20.4	20.3	26.9	25.0	29.0	22.5	26.7	28.0	24.8	29.3	21.2	25.2 ± 3.3

Table D.11: Additional outdoor mixture temperature measurements

Date	Time	Temperature (°C)		
		Ambient Indoors	Ambient Outdoors	Outdoor Mixture (2 U : 1 F : 0 A)
21-Aug-2014	12:30	22.2	27.9	48.1
29-Aug-2014	9:15	21.6	20.4	19.2
6-Sep-2014	13:00	20.6	20.3	21.8
11-Sep-2014	11:00	22.1	26.9	40.6
21-Sep-2014	13:15	22.5	25.0	37.2
28-Sep-2014	14:15	22.9	29.0	42.4
5-Oct-2014	12:15	22.2	22.5	37.1
14-Oct-2014	12:00	23.6	26.7	36.1
19-Oct-2014	13:00	22.4	28.0	47.3
24-Oct-2014	9:30	23.2	24.8	28.2
1-Nov-2014	13:00	22.6	29.3	40.0
7-Nov-2014	7:45	23.3	19.8	18.5
8-Nov-2014	11:45	23.7	21.2	22.4
8-Nov-2014	21:00	23.2	19.2	18.4
9-Nov-2014	4:30	22.2	17.3	15.9
Average		23.1 ± 0.6	19.4 ± 1.9	18.8 ± 8.0

Table D.12: Additional ambient temperature measurements

Date	Time	Temperature (°C)		Weather Conditions
		Ambient Indoors	Ambient Outdoors	
23-Jan-2014	13:30	21.6	20.3	Cloudy, scattered rain
31-Jan-2014	11:00	24.7	30.0	sunny, warm
7-Feb-2014	12:00	23.2	28.0	cloudy, but warm
14-Feb-2014	12:00	24.1	27.1	sunny, a little breezy
21-Feb-2014	12:00	24.2	28.2	sunny, warm
22-Feb-2014	14:00	25.0	32.9	sunny, hot
23-Feb-2014	16:00	25.1	31.9	sunny, hot
24-Feb-2014	11:30	22.7	18.4	light rain
25-Feb-2014	18:00	24.3	27.4	sunny, warm
26-Feb-2014	17:45	23.5	22.6	sunny, breezy; but cloudy earlier
27-Feb-2014	11:00	22.7	27.4	sunny, warm
28-Feb-2014	10:30	23.4	28.4	sunny, warm
2-Mar-2014	16:30	25.1	27.1	partly cloudy
3-Mar-2014	13:00	24.3	31.8	sunny, hot
4-Mar-2014	15:00	24.7	32.2	sunny, hot
5-Mar-2014	7:00	22.5	17.5	partly cloudy
6-Mar-2014	9:00	24.5	20.7	light drizzle
7-Mar-2014	12:00	24.1	23.4	sunny
7-Mar-2014	18:00	25.0	26.4	sunny
7-Mar-2014	20:00	24.6	22.8	Clear
7-Mar-2014	22:00	24.5	20.9	Clear
8-Mar-2014	0:00	24.3	20.8	Clear
8-Mar-2014	2:00	24.3	20.0	Clear
8-Mar-2014	4:00	24.1	19.8	clear

Table D.12 (continued)

8-Mar-2014	15:30	24.7	32.4	sunny, hot
10-Mar-2014	9:00	24.5	22.4	partly cloudy
11-Mar-2014	10:30	22.9	17.6	rainy
12-Mar-2014	10:00	22.5	19.3	overcast
13-Mar-2014	9:50	22.6	19.8	light drizzle
16-Mar-2014	17:00	23.3	25.2	sunny, rain earlier
17-Mar-2014	8:20	22.2	19.5	sunny
19-Mar-2014	19:00	24.6	24.9	sunny
20-Mar-2014	11:30	24.1	31.0	sunny
22-Mar-2014	18:30	24.8	26.2	sunny
24-Mar-2014	19:45	24.2	22.8	rain morn, sun afternoon
25-Mar-2014	19:00	23.8	23.0	partly cloudy
26-Mar-2014	19:30	24.1	22.6	partly cloudy
27-Mar-2014	14:30	24.2	32.4	sunny
4-Apr-2014	10:45	23.6	25.0	partly cloudy
5-Apr-2014	11:15	23.2	20.1	drizzle
7-Apr-2014	10:45	22.8	22.7	cloudy
9-Apr-2014	16:30	23.6	30.5	sunny
10-Apr-2014	13:30	23.3	29.0	sunny
11-Apr-2014	11:45	23.4	26.5	sunny
14-Apr-2014	16:00	23.5	28.2	sunny
15-Apr-2014	13:30	23.0	25.3	sun, rain earlier
16-Apr-2014	15:00	23.1	30.1	sunny
17-Apr-2014	16:00	23.6	27.0	sun, rain earlier
18-Apr-2014	13:00	22.2	18.4	rainy
19-Apr-2014	16:30	22.2	27.0	sun, rain earlier
22-Apr-2014	19:00	23.1	22.9	sunny
24-Apr-2014	19:00	23.3	21.3	sunny
25-Apr-2014	11:30	22.6	24.4	partly cloudy
26-Apr-2014	12:00	22.6	26.7	sunny
29-Apr-2014	18:30	24.0	25.5	sunny
30-Apr-2014	15:00	23.1	21.5	cloudy, rain earlier
2-May-2014	11:15	22.3	21.1	cloudy, rain earlier
3-May-2014	13:30	22.3	19.6	rainy
5-May-2014	18:30	23.3	23.4	sun, rain earlier
6-May-2014	14:00	22.8	25.8	partly cloudy
8-May-2014	12:45	21.4	18.1	rainy, cloudy
12-May-2014	15:00	21.8	23.7	sun, rain earlier
13-May-2014	16:30	21.8	26.5	sunny
14-May-2014	17:15	22.5	27.6	sunny
15-May-2014	12:45	22.4	25.7	partly cloudy
16-May-2014	19:00	22.8	21.2	sunny
21-May-2014	10:45	22.2	23.1	partly cloudy
22-May-2014	12:30	22.2	22.0	cloudy, rain earlier
1-Jun-2014	13:45	22.6	25.5	sunny
5-Jun-2014	10:30	22.4	23.7	cloudy
12-Jun-2014	12:00	21.6	23.1	partly cloudy
13-Jun-2014	18:15	22.5	23.7	sun, cloudy earlier

Table D.12 (continued)

16-Jun-2014	14:00	22.5	29.0	sunny
17-Jun-2014	17:00	22.9	28.7	sunny
18-Jun-2014	17:30	23.2	28.9	sunny
19-Jun-2014	16:15	23.3	27.9	sunny
20-Jun-2014	11:30	22.6	27.2	sunny
21-Jun-2014	16:00	22.8	21.5	partly cloudy, rain earlier
23-Jun-2014	15:30	22.0	22.9	cloudy, rain earlier
24-Jun-2014	19:15	21.5	19.1	sun, cloudy earlier
25-Jun-2014	16:15	21.8	27.0	sun
26-Jun-2014	12:15	21.8	23.9	partly cloudy
27-Jun-2014	11:30	21.7	24.8	partly cloudy
28-Jun-2014	12:15	22.4	25.8	sun
3-Jul-2014	10:30	21.7	24.6	sun
4-Jul-2014	9:45	21.5	23.6	sun
7-Jul-2014	10:30	21.9	25.2	sun
8-Jul-2014	10:45	22.0	23.9	cloudy
9-Jul-2014	10:45	21.9	27.7	sun
11-Jul-2014	9:15	21.4	19.7	cloudy
14-Jul-2014	9:45	21.7	26.3	sun
17-Jul-2014	16:15	22.5	26.7	sun
18-Jul-2014	10:30	22.1	22.7	sun
19-Jul-2014	16:30	23.1	28.7	sun
19-Jul-2014	20:00	24.0	20.9	clear
19-Jul-2014	22:30	23.2	19.4	clear
20-Jul-2014	0:00	23.1	18.5	clear
20-Jul-2014	2:00	22.5	17.1	clear
22-Jul-2014	13:30	22.7	27.1	sun
24-Jul-2014	15:45	22.6	27.5	sun
25-Jul-2014	10:45	22.6	23.7	partly cloudy
21-Aug-2014	12:30	22.2	27.9	partly cloudy
29-Aug-2014	9:15	21.6	20.4	sun
31-Aug-2014	10:15	22.2	20.3	cloudy
1-Sep-2014	9:45	22.2	27.8	partly cloudy
3-Sep-2014	13:00	22.6	25.4	cloudy
4-Sep-2014	10:45	22.3	23.8	cloudy
5-Sep-2014	12:00	21.8	18.0	rain
6-Sep-2014	13:00	20.6	20.3	drizzle
7-Sep-2014	14:00	20.8	25.6	partly cloudy
8-Sep-2014	15:00	21.3	29.2	partly cloudy
9-Sep-2014	18:00	22.0	25.2	partly cloudy
10-Sep-2014	2:00	21.9	16.1	clear
10-Sep-2014	17:00	22.3	28.0	partly cloudy
11-Sep-2014	3:30	21.3	18.3	partly cloudy
11-Sep-2014	11:00	22.1	26.9	partly cloudy
12-Sep-2014	2:30	22.6	18.1	clear
12-Sep-2014	11:45	22.4	31.0	partly cloudy
13-Sep-2014	2:30	22.6	18.3	clear
15-Sep-2014	0:00	22.8	18.5	partly cloudy

Table D.12 (continued)

16-Sep-2014	1:00	22.3	17.6	cloudy
17-Sep-2014	3:00	22.5	17.3	clear
17-Sep-2014	23:00	22.5	18.2	clear
18-Sep-2014	1:30	22.4	17.6	clear
19-Sep-2014	3:30	22.7	19.2	clear
21-Sep-2014	4:00	21.7	16.7	clear
21-Sep-2014	13:15	22.5	25.0	cloudy
21-Sep-2014	22:45	22.6	20.6	clear
22-Sep-2014	2:15	22.2	18.3	clear
24-Sep-2014	2:30	21.4	16.8	clear
24-Sep-2014	23:30	21.9	17.8	clear
25-Sep-2014	3:15	21.3	16.6	clear
26-Sep-2014	2:00	22.2	17.9	clear
26-Sep-2014	6:00	21.7	17.1	clear
27-Sep-2014	4:00	22.1	17.4	clear
27-Sep-2014	21:45	23.0	21.5	clear
28-Sep-2014	3:45	22.1	18.0	clear
28-Sep-2014	14:15	22.9	29.0	partly cloudy
29-Sep-2014	21:00	23.3	21.5	clear
2-Oct-2014	20:30	23.5	22.0	clear
3-Oct-2014	20:00	23.0	21.3	drizzle
3-Oct-2014	22:45	22.9	19.3	partly cloudy
4-Oct-2014	0:45	22.8	18.4	partly cloudy
4-Oct-2014	2:45	22.6	18.4	clear
4-Oct-2014	19:45	22.6	19.7	partly cloudy
5-Oct-2014	0:00	22.0	17.2	clear
5-Oct-2014	2:00	21.6	16.3	clear
5-Oct-2014	6:00	21.4	16.2	clear
5-Oct-2014	12:15	22.2	22.5	partly cloudy
13-Oct-2014	21:30	23.5	20.3	clear
14-Oct-2014	0:00	23.4	18.7	Clear
14-Oct-2014	12:00	23.6	26.7	partly cloudy
15-Oct-2014	22:30	22.9	18.6	Clear
16-Oct-2014	4:15	22.3	18.4	Cloudy
17-Oct-2014	23:30	22.9	19.8	Clear
18-Oct-2014	23:45	22.5	18.4	Clear
19-Oct-2014	4:30	21.9	17.0	Clear
19-Oct-2014	13:00	22.4	28.0	partly cloudy
24-Oct-2014	9:30	23.2	24.8	partly cloudy
1-Nov-2014	13:00	22.6	29.3	partly cloudy
1-Nov-2014	23:45	22.5	17.7	Clear
7-Nov-2014	7:45	23.3	19.8	Overcast
8-Nov-2014	11:45	23.7	21.2	Drizzle
8-Nov-2014	21:00	23.2	19.2	Clear
9-Nov-2014	4:30	22.2	17.3	partly cloudy
Average		22.8 ± 0.9	23.1 ± 4.3	

Table D.13: Stage 1 total ammonia measurements (mg/L NH_3)

Mixture	Day									Mixture Averages
	2	10	17	24	31	37	45	50	58	
0 U : 1 F (A)	50	170	20	60	110	50	10	120	180	102 ± 56
0 U : 1 F (B)	150	70	20	160	150	70	40	110	150	
0 U : 1 F (C)	50	170	120	160	190	130	90	40	120	
1 U : 1 F (A)	1950	2170	1520	1960	1550	1350	390	1480	1580	1669 ± 565
1 U : 1 F (B)	2350	1970	1920	2360	1850	1150	890	1680	780	
1 U : 1 F (C)	2150	2670	2420	1360	1950	1950	590	1580	1480	
2 U : 1 F (A)	2550	1870	1920	2760	2950	2150	1490	1580	1980	2194 ± 469
2 U : 1 F (B)	2350	1870	2920	1660	1750	2350	1790	2380	1680	
2 U : 1 F (C)	2550	2370	1920	1960	2750	3350	1990	2180	2180	
3 U : 1 F (A)	2350	2170	2520	3160	3150	2950	2190	2980	2980	2783 ±436
3 U : 1 F (B)	3550	3170	2720	2460	2950	2950	1990	3180	2380	
3 U : 1 F (C)	2950	3470	1920	2960	2550	2750	2590	2780	3380	
1 U : 0 F (A)	4450	4970	4920	3960	3550	2950	3990	4980	4980	4532 ± 669
1 U : 0 F (B)	4950	3970	5120	5160	5150	5150	4990	5380	4980	
1 U : 0 F (C)	3950	4970	4120	4460	5150	4950	3190	3980	3980	

Table D.14: Stage 2 total ammonia measurements (mg/L NH_3)

Mixture	Day																	Mixture Averages
	1	8	15	23	30	35	42	49	59	63	70	78	85	92	99	106	113	
2 U : 1 F : 0 A (A)	2,780	3,180	3,590	2,990	2,300	3,000	3,000	2,800	2,900	2,590	2,600	2,790	2,750	2,700	2,500	2,190	2,290	2787 ± 379
2 U : 1 F : 0 A (B)	2,380	2,980	2,590	2,290	3,500	2,500	2,500	2,500	2,300	1,990	2,800	2,490	2,450	2,600	1,800	2,790	2,590	
2 U : 1 F : 0 A (C)	2,980	2,780	3,190	2,990	3,200	3,400	2,800	3,000	3,000	3,190	3,200	3,190	2,950	3,000	3,000	3,390	2,890	
2 U : 1 F : 0.5 A (A)	2,480	2,980	2,590	2,590	2,300	2,800	2,500	2,600	2,400	1,990	2,400	1,990	2,250	1,900	1,900	1,890	1,890	2328 ± 302
2 U : 1 F : 0.5 A (B)	1,580	2,380	2,290	1,990	2,700	2,800	2,400	2,200	2,300	1,890	2,200	2,290	2,250	2,100	2,600	2,090	2,090	
2 U : 1 F : 0.5 A (C)	2,380	2,580	2,790	2,990	2,400	2,600	2,600	2,400	2,500	2,190	2,300	2,190	2,050	2,400	2,400	2,390	1,990	
2 U : 1 F : 1 A (A)	1,680	1,980	1,590	1,590	1,600	2,100	1,800	1,400	1,500	1,590	1,800	1,490	1,650	1,600	1,600	1,290	1,590	1691 ± 245
2 U : 1 F : 1 A (B)	1,980	1,980	2,190	2,190	1,800	2,000	1,400	2,000	1,800	1,590	1,400	1,490	1,750	1,800	1,500	1,590	1,290	
2 U : 1 F : 1 A (C)	1,880	1,780	1,990	1,990	2,000	1,600	1,700	1,600	1,600	1,290	1,200	1,590	1,650	1,300	1,800	1,690	1,990	

Table D.15: Stage 3 total ammonia measurements (mg/L NH_3)

Mixture	Day												Mixture Averages
	1	9	17	22	32	39	46	55	60	65	73	80	
2 U : 1 F : 0 A - in (A)	2,990	2,990	2,990	3,080	2,790	2,490	2,590	2,790	2,790	2,690	2,690	2,390	2804 ± 188
2 U : 1 F : 0 A - in (B)	2,790	2,790	2,910	2,580	2,790	3,290	2,690	2,790	2,790	2,590	2,790	2,690	
2 U : 1 F : 0 A - in (C)	2,990	3,190	2,790	2,980	2,890	2,890	2,790	2,590	2,590	2,890	2,690	2,890	
2 U : 1 F : 0 A - out (A)	3,190	2,790	2,990	3,380	2,790	2,490	2,790	2,690	2,690	2,590	2,690	2,390	2814 ± 235
2 U : 1 F : 0 A - out (B)	2,990	2,490	3,190	2,780	2,890	2,490	2,690	2,790	2,590	2,690	2,590	2,790	
2 U : 1 F : 0 A - out (C)	3,190	2,790	2,790	3,180	2,990	2,890	2,890	2,790	2,890	3,190	2,690	2,590	
2 U : 1 F : 0.5 A - out (A)	2,690	2,490	2,390	2,280	2,290	1,990	2,690	1,990	2,090	2,290	2,390	1,990	2325 ± 208
2 U : 1 F : 0.5 A - out (B)	2,490	2,790	2,490	2,380	2,290	2,190	2,390	2,190	2,390	2,190	2,190	2,190	
2 U : 1 F : 0.5 A - out (C)	2,790	2,390	2,290	2,480	2,390	2,390	2,290	2,390	2,190	2,290	2,090	1,990	

Table D.16: Stage 1 free ammonia concentrations (mg/L NH_3-N)

Mixture	Day									Mixture Averages
	2	10	17	24	31	37	45	50	58	
0 U : 1 F (A)	37	129	15	38	83	37	8	90	136	73 ± 40
0 U : 1 F (B)	112	53	13	120	95	52	30	69	96	
0 U : 1 F (C)	37	129	90	101	143	81	68	30	91	
1 U : 1 F (A)	1210	1390	945	1239	1166	837	294	1112	1193	1113 ± 343
1 U : 1 F (B)	1463	1258	1193	1492	1391	859	671	1263	589	
1 U : 1 F (C)	1338	1705	1504	860	1235	1456	445	1001	948	
2 U : 1 F (A)	1582	1194	1191	1742	1865	1331	950	997	1267	1383 ± 289
2 U : 1 F (B)	1463	1194	1811	1048	1107	1460	1143	1507	1075	
2 U : 1 F (C)	1590	1514	1193	1237	1742	2085	1271	1383	1394	
3 U : 1 F (A)	951	1386	1016	1321	1326	1827	1394	1881	1903	1586 ± 317
3 U : 1 F (B)	1441	2021	1684	1550	1865	1830	1269	2014	1520	
3 U : 1 F (C)	1202	1481	1191	1865	1612	1712	1654	1761	2159	
1 U : 0 F (A)	857	1034	942	797	722	1189	834	2089	2133	1355 ± 579
1 U : 0 F (B)	953	826	981	1039	2160	2083	2138	2265	2133	
1 U : 0 F (C)	761	2114	789	1857	1054	959	1371	1675	837	

Table D.17: Stage 2 free ammonia concentrations (mg/L NH_3-N)

Mixture	Day																	Mixture Averages
	1	8	15	23	30	35	42	49	59	63	70	78	85	92	99	106	113	
2 U : 1 F : 0 A (A)	1,170	1,334	2,227	1,861	1,419	1,173	1,222	1,120	1,190	1,048	1,021	1,137	1,088	1,048	966	873	933	
2 U : 1 F : 0 A (B)	1,505	1,881	1,048	930	1,405	1,528	1,015	1,000	941	802	1,095	1,015	962	1,009	696	1,112	1,055	1204 ± 282
2 U : 1 F : 0 A (C)	1,884	1,162	1,290	1,218	1,285	1,340	1,137	1,200	1,222	1,290	1,256	1,300	1,158	1,164	1,160	1,351	1,178	
2 U : 1 F : 0.5 A (A)	1,571	1,881	1,604	1,612	920	1,091	1,011	1,040	981	802	942	811	883	737	732	1,164	767	
2 U : 1 F : 0.5 A (B)	1,188	1,500	1,420	1,239	1,669	1,712	1,489	1,357	937	1,172	860	1,426	1,378	815	1,001	833	852	1279 ± 343
2 U : 1 F : 0.5 A (C)	1,507	1,623	1,731	2,233	1,483	1,592	1,610	1,481	1,556	1,358	1,406	1,363	1,253	1,459	1,456	1,472	1,239	
2 U : 1 F : 1 A (A)	1,264	1,250	985	1,188	989	1,284	1,119	865	935	988	1,102	928	1,009	1,185	969	794	990	
2 U : 1 F : 1 A (B)	1,256	1,248	1,635	1,635	1,341	1,485	867	1,490	1,123	1,186	856	1,113	1,070	1,096	1,110	979	963	1165 ± 208
2 U : 1 F : 1 A (C)	1,414	1,336	1,486	1,487	1,490	1,188	1,268	1,192	1,196	963	890	1,187	1,225	963	1,333	1,258	1,237	

Table D.18: Stage 3 free ammonia concentrations (mg/L NH_3-N)

Mixture	Day												Mixture Averages
	1	9	17	22	32	39	46	55	60	65	73	80	
2 U : 1 F : 0 A - in (A)	1,191	1,835	1,116	1,897	1,137	1,029	1,032	1,183	1,124	1,116	1,092	1,010	
2 U : 1 F : 0 A - in (B)	1,721	1,712	1,735	1,589	1,737	2,062	1,072	1,179	1,120	1,079	1,128	1,136	1274 ± 291
2 U : 1 F : 0 A - in (C)	1,200	1,262	1,042	1,188	1,173	1,195	1,112	1,098	1,044	1,199	1,092	1,221	
2 U : 1 F : 0 A - out (A)	2,264	996	1,835	2,181	1,698	1,651	1,694	1,602	1,894	1,270	1,719	967	
2 U : 1 F : 0 A - out (B)	2,343	1,442	1,276	2,110	2,145	1,903	1,688	1,621	1,804	1,284	1,687	1,108	1702 ± 401
2 U : 1 F : 0 A - out (C)	2,505	1,633	1,133	2,422	1,826	1,932	1,810	1,607	1,978	1,513	1,741	1,005	
2 U : 1 F : 0.5 A - out (A)	2,185	1,451	1,498	1,834	1,691	1,535	2,031	1,439	1,616	1,521	1,826	1,212	
2 U : 1 F : 0.5 A - out (B)	1,956	2,039	1,566	1,823	1,704	1,676	1,804	1,247	1,838	1,434	1,676	820	1667 ± 280
2 U : 1 F : 0.5 A - out (C)	2,201	1,756	1,724	1,908	1,760	1,822	1,738	1,712	1,692	1,479	1,615	1,186	

Table D.19: Temperature, pH, and moisture content measurements from UDDTs

Number	Storage Location Ambient Temperature (°C)	Fecal Products			Stored Urine	
		Temperature (°C)	pH	Moisture Content (%)	Temperature (°C)	pH
1	21.6	22.5	10.5	13%	22.4	9.0
2	21.6	22.3	10.5	15%	22.4	9.0
3	21.6	22.4	10.5	8%	22.4	9.0
4	21.2	31.4	10.5	(not measured)	21.2	9.0
5	19.7	34.3	10.0	(not measured)	21.7	9.0
6	23.9	26.7	9.0	19%	20.0	9.0
7	21.2	24.8	9.5	17%	20.4	9.0
8	23.6	23.9	10.5	19%	23.6	8.5
9	22.2	22.3	10.5	(not measured)	22.2	9.0

Appendix E: Ammonia Treatment Feasibility Calculations

The addition of urea has been shown to be an effective alternative for sanitizing source-separated feces. When added, the urea is enzymatically degraded to produce ammonia, which is toxic to many pathogens (Nordin et al., 2009). However, for people in resource-limited settings, the purchase of urea may be expensive and is not a viable option. Another potential source of ammonia is human urine. Fresh urine contains a large amount of urea (Putnam, 1971), which is converted to ammonia during storage (Udert et al., 2003a). These calculations were performed in an attempt to determine if the ammonia concentrations present in stored urine might be sufficient to sanitize fecal matter, and if urine is produced in large enough quantities relative to feces for this treatment method to be a viable option. The calculations themselves can be found in the pages following this summary and explanation.

To begin, the nitrogen concentration of urine in Uganda was estimated based on equations provided by Jonsson et al. (2004) and data collected in 2011 on dietary protein consumption in Uganda from the Food and Agricultural Organization of the United Nations (Section 1 of the Calculations). The result, 5.0 grams of nitrogen per liter of urine, was multiplied by 90%, estimated using data from Putnam (1971) to be the fraction of nitrogen present in either ammonia or urea. A total ammonia nitrogen (TAN) value of 4.5 grams per liter NH_3-N was calculated. This value was compared to data from Putnam (1971) and Nordin (2010), and was found to be similar (Section 2 of the Calculations).

The next several sections of calculations deal with estimating the concentration of uncharged ammonia likely to be present in the urine, since this form is the one responsible for pathogen inactivation (Pecson et al., 2007). Assuming a temperature of 25°C, the equilibrium reactions and equilibrium constants for ammonium ions (NH_4^+), uncharged aqueous ammonia ($NH_{3(aq)}$), and uncharged gaseous ammonia ($NH_{3(g)}$) were used to derive an equation that would calculate the $NH_{3(aq)}$ concentration for a given total ammonia concentration and pH level. At this point, it was assumed that the solution is dilute, so that the activity of aqueous species is equivalent to their molar concentrations

(Calculations Section 3). The derived equation was then used to calculate the uncharged ammonia concentration, given the estimated concentration of total ammonia present in urine from Uganda and a pH of 9.0, which is the approximate pH in urine after urea has degraded (Udert et al., 2003a). This calculation shows that, if the loss of volatilized ammonia is minimal in the storage container, then the amount of ammonia lost to the gaseous phase is insignificant, suggesting that the derived equation could be simplified by eliminating the portion related to the partitioning of the aqueous and gaseous phases of uncharged ammonia (Calculations Section 4). After this simplification, the final $NH_{3(aq)}$ concentration present in urine was calculated to be 1,633 mg/L NH_3-N. This value is significantly higher than 800 mg/L, which was estimated to result in 6-$\log_{10}$ removal of *Ascaris* eggs in feces within four months at 24°C (Nordin et al., 2009a). It should be noted that another study found significantly longer inactivation times for *Salmonella* Typhimurium bacteriophage 28B, but this virus does not affect humans, its genome structure is different from the structure of many enteric viruses, and these enteric viruses are reported to have shorter inactivation times (Nordin et al., 2009b). Considering these points, the uncharged ammonia concentration calculated here should be sufficient to sanitize undiluted urine in Uganda (Calculations Section 5).

The same calculation was then performed for a mixture consisting of two parts urine to one part fecal products obtained from a UDDT vault. To be conservative, it was assumed that any ammonia previously present in the feces was lost due to volatilization during storage at high pH levels. Only the urine, then, contributes to the total amount of ammonia present. It was also assumed that the addition of fecal products does not cause any pH change, resulting in a pH of 9.0 in the overall mixture. The calculated uncharged ammonia concentration for this case was 1,092 mg/L NH_3-N, still higher than the target concentration of 800 mg/L (Calculations Section 6). Then, urine excretion rates (1.2 kg/cap-d, from Esrey et al., 2001), fecal generation rates (0.35 kg/cap-d, from Niwagaba, 2009), the moisture content of feces (80 – 83%, from Nordin, 2010), the average density of urine (1.024 kg/L, from Ogata et al., 1970), and the average density of feces (1.0 kg/L, from Ferreira, 2005), were used to estimate the average volumes of urine and fecal products that would be produced in one day. It was found that enough urine is produced so that a 2 urine : 1 fecal products mixture is feasible, and it should be noted that the fecal generation rate used was the highest value found in all of the literature that was searched, suggesting that this estimated generation rate might be higher than the actual rate (Calculations Section 7). So far, the calculations suggest that treatment of feces using ammonia from urine could be a feasible option in Uganda.

However, it is acknowledged that the dilute solution assumption may be inappropriate, since Udert et al. (2003b) reports that urine has an average ionic strength of 0.206 M. This value results in an activity coefficient for NH_4^+ of 0.75 and a coefficient of 1.06 for NH_3, which could certainly have a significant impact on the results. To account for ionic strength, these activity coefficients were incorporated into the derived equation (Calculations Section 8). This revised equation was then used to recalculate the uncharged ammonia concentrations in urine and in the 2 urine : 1 fecal products mixture. In urine alone, the concentration was calculated to be 1,288 mg/L NH_3-N, but, for the mixture, the concentration was found to be 854 mg/L NH_3-N , which is only slightly above the target (Calculations Section 9).

Finally, three additional scenarios were considered to determine how changing certain conditions would affect the final TAN concentration. First, if the pH is raised to 9.1, the ammonia concentration increases to 1,000 mg/L NH_3-N. Second, if the temperature is increased from 25°C to 26°C (with the original pH of 9.0), a concentration of 900 mg/L NH_3-N is obtained. Third, if a 3 urine : 1 fecal products mixture is used (at original temperature and pH levels), the calculated ammonia concentration is 970 mg/L NH_3-N . Although this mixture would not be feasible with the assumed fecal generation rate, the fact that this rate may be conservatively high has already been discussed (Calculations Section 10). Additionally, it is also possible that the feces could still contain ammonia when added to the mix, raising the total ammonia concentration. Moreover, if sufficient ash was used during latrine operation, adding fecal products might raise the pH significantly, and, by storing the mixture of urine and feces in a sealed container in the sun, high temperatures might be achieved. In practice, actual observed conditions might create a scenario in which higher concentrations are achieved or might provide additional insight into an effective method for achieving higher concentrations.

Scanned copies of these calculations are provided on the following pages.

1.) Calculation of total ammonia nitrogen (TAN) concentration in urine for Uganda

Ugandan Protein Intake, 2011 (FAO, 2014)

Total Protein Intake:	51.7 grams per person per day

From Jonsson et al. (2004):

Total nitrogen excreted in urine and feces = 0.13 * (total protein intake)

Total nitrogen excreted:	6.7 grams per person per day
	2.5 kilograms per person per year

Total Nitrogen Concentrations in Urine

Assumed urine excretion:	1.2 kilograms per person per day (Esrey et al., 2001)
Assumed urine density:	1.024 kilograms per liter (Ogata et al., 1970)

Total Nitrogen	
Total Excretion	6.7 grams per person per day
Percent in Urine	88% Source: Jonsson et al. (2004)
Urine Excretion	5.9 grams per person per day
Urine Concentration	5.0 grams per liter

Ammonia Fraction of Total Nitrogen

Based on data from Putnam (1971):	87% - 93% of excreted nitrogen is present in urea or ammonia
Assumptions:	90% of excreted nitrogen is present in urea or ammonia
	Besides urea, no other compounds degrade to ammonia during storage
	Ammonia volatilization is negligible during closed storage (Pecson et al., 2007)
Total Ammonia Nitrogen	**4.5 grams per liter NH_3-N**
	324 millimoles per liter

2.) Comparison with other estimates and measurements

Data from Putnam (1971) on fresh urine composition

Urea concentration, low estimate:	9.3 grams per liter
Ammonia concentration, low estimate:	0.2 grams per liter

Urea is degraded by urease, which is produced by bacteria in soil, aquatic systems, and human intestines (Udert et al., 2003a):

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^-$$

Molar mass of urea:	60 grams per mole
Molar mass of ammonium ion:	18 grams per mole
Moles of ammonium per moles of urea:	2
Ammonium ions produced from urea:	5.6 grams per liter NH_4^+
Total Ammonia Concentration:	5.8 grams per liter NH_4^+
Total Ammonia Nitrogen:	4.5 grams per liter NH_3-N

From Nordin (2010)

Total Ammonia Nitrogen, measured in Uganda:	4.2 grams per liter NH_3-N

Estimated/Measured TAN Concentration (g/L)	Source
4.5	Putnam, 1971
4.2	Nordin, 2010
4.5	Present Calculations

3.) Acid-Base Equilibrium and Partitioning between Aqueous and Gaseous Phases
(with dilute solution assumption)

Acid-Base Equilibrium

$$NH_4^+{}_{(aq)} \leftrightarrow NH_{3(aq)} + H^+{}_{(aq)} \qquad K_a = \frac{[NH_3][H^+]}{[NH_4^+]}$$

Nordin (2010):

$$pK_a = \frac{2729.92}{T} + 0.09018$$

Gas Phase Equilibrium

$$NH_{3(aq)} \leftrightarrow NH_{3(g)} \qquad H = \frac{P_{NH_{3(g)}}}{\left[NH_{3(aq)}\right]}$$

Combined Aqueous and Gas Phases

$$\left(moles\ of\ NH_{(tot)}\right) = \left(moles\ of\ NH_4^+{}_{(aq)}\right) + \left(moles\ of\ NH_{3(aq)}\right) + \left(moles\ of\ NH_{3(g)}\right)$$

$$NH_{(tot)} = \left[NH_4^+{}_{(aq)}\right]V_l + \left[NH_{3(aq)}\right]V_l + \left[NH_{3(g)}\right]V_g$$

$$K_a = \frac{[NH_3][H^+]}{[NH_4^+]} \quad \rightarrow \quad [NH_4^+] = \left[NH_{3(aq)}\right]\frac{[H^+]}{K_a}$$

$$H = \frac{P_{NH_{3(g)}}}{\left[NH_{3(aq)}\right]} \quad \rightarrow \quad P_{NH_{3(g)}} = \left[NH_{3(aq)}\right]H$$

Ideal Gas Law:

$$PV = nRT$$

$$\left[NH_{3(g)}\right] = \frac{n}{V} = \frac{P}{RT}$$

$$\left[NH_{3(g)}\right] = \frac{P_{NH_{3(g)}}}{RT} \quad \rightarrow \quad \left[NH_{3(g)}\right] = \frac{\left[NH_{3(aq)}\right]H}{RT}$$

$$NH_{(tot)} = \left[NH_{3(aq)}\right]\frac{[H^+]}{K_a}V_l + \left[NH_{3(aq)}\right]V_l + \left[NH_{3(aq)}\right]\frac{H}{RT}V_g$$

$$NH_{(tot)} = \left[NH_{3(aq)}\right]\left(\frac{[H^+]}{K_a}V_l + V_l + \frac{H}{RT}V_g\right)$$

$$\left[NH_{3(aq)}\right] = \frac{NH_{(tot)}}{V_l\left(\frac{[H^+]}{K_a} + 1\right) + V_g\left(\frac{H}{RT}\right)}$$

Parameter	Symbol	Units	Assumed/Calculated Value
Temperature	T	K	298
Equilibrium Constant	K_a	-	$10^{-9.25}$
Henry's Constant	H	atm-m^3/mol	1.6×10^{-5}
Ideal Gas Constant	R	atm-m^3/mol-K	8.2057×10^{-5}

4.) Example Calculation of Ammonia Partitioning

Scenario: one liter of urine stored in sealed container, one liter of air in headspace above urine

After urea degradation, pH ≈ 9.0 (Zhigang et al., 2008) $\rightarrow$ $[H^+] = 10^{-9}\,M$

$$NH_{(tot)} = [NH_{tot}]V_l = (324\,mM)(1\,L) = 324\,mmol$$

$$\left[NH_{3(aq)}\right] = \frac{324\,mmol}{(1\,L)\left(\frac{10^{-9}}{10^{-9.25}} + 1\right) + (1\,L)\left(\frac{1.6\,x\,10^{-5}\ \frac{atm - m^3}{mol}}{\left(8.2057\,x\,10^{-5}\ \frac{atm - m^3}{mol - K}\right)(298\,K)}\right)}$$

Ammonia Phase	Millimoles	Percentage
$NH_4^+{}_{(aq)}$	207.3	64%
$NH_{3(aq)}$	116.6	36%
$NH_{3(g)}$	0.076	0%

Gaseous ammonia is insignificant, therefore can neglect gaseous phase

5.) Simplified Ammonia Partitioning Model

$$[NH_{3(aq)}] = \frac{NH_{(tot)}}{V_l\left(\frac{[H^+]}{K_a}+1\right) + V_g\left(\frac{H}{RT}\right)} \qquad V_g\left(\frac{H}{RT}\right) \approx 0$$

$$[NH_{3(aq)}] = \frac{NH_{(tot)}}{V_l\left(\frac{[H^+]}{K_a}+1\right)} = \frac{NH_{(tot)}/V_l}{\left(\frac{[H^+]}{K_a}+1\right)} \quad \rightarrow \quad [NH_{3(aq)}] = \frac{[NH_{(tot)}]}{\left(\frac{[H^+]}{K_a}+1\right)}$$

Scenario from Section 4 (urine stored alone):

$$[NH_{3(aq)}] = \frac{324\,mM}{\left(\frac{10^{-9}}{10^{-9.25}}+1\right)}$$

Ammonia Phase	Conc. (mM)	Conc. (mg/L as N)	Percentage
$NH_4^+{}_{(aq)}$	207.4	2,903	64%
$NH_{3(aq)}$	116.6	1,633	36%

Uncharged ammonia concentration is greater than 800 mg/L N

Nordin et al. (2009a):
Four months of storage with at least 800 mg/L NH_3-N at 24°C results in 6-$\log_{10}$ reduction of *Ascaris suum* eggs

6.) Example Calculation of Uncharged Ammonia Concentration in Fecal Products/Urine Mixture

Scenario: two parts urine, one part fecal products by volume

Assume all nitrogen from feces has volatilized during storage - feces do not contribute additional ammonia

$$[NH_{(tot)}] = \frac{C_uV_u + C_fV_f}{V_u + V_f} = \frac{(324\,mM)(2\,L) + (0\,mM)(1\,L)}{(2\,L + 1\,L)} = 216\,mM$$

Assume urine buffers any pH change caused by fecal products, so that pH ≈ 9.0

$$[NH_{3(aq)}] = \frac{216\,mM}{\left(\frac{10^{-9}}{10^{-9.25}}+1\right)} = 78\,mM = 1{,}092\frac{mg}{L}NH_3 - N$$

Uncharged ammonia concentration is greater than 800 mg/L N

7.) Is this mixture feasible?

Source	Parameter	Value	Explanation
Niwagaba (2009)	Fecal generation rate	0.35 kg/cap-d	for rural areas of developing countries (larger than for other areas)
Nordin (2007)	Water content of feces	80% - 83%	before desiccation
Ferreira (2005)	Density of feces	1 kg/L	average value

Assume initial water content of 80% decreases to 20% during storage and desiccation - total mass of feces decreases by 60%

$$\left(0.35\ {}^{kg}/_{cap-d}\right)(1-0.6) = 0.14\ {}^{kg}/_{cap-d} = 0.14\ {}^{L}/_{cap-d}$$

Assume volume of ash = 0.35 L/cap-d = wet volume of feces (agrees with recommendation in Mihelcic et al., 2009)
Assume volume of toilet paper = 0.08 L/cap-d (calculated using data from Jonsson et al., 2004)
Total volume of fecal mixture = 0.14 + 0.35 + 0.08 = 0.57 L/cap-d

$$Required\ urine\ volume = \left(0.57\ {}^{L}/_{cap-d}\right)(2) = 1.14\ {}^{L}/_{cap-d}$$

$$Available\ urine = \left(1.2\ {}^{kg}/_{cap-d}\right)\left(\frac{1\,L}{1.024\,kg}\right) = 1.17\ {}^{L}/_{cap-d}$$

Available urine provides the necessary volume of urine, and the estimated volume of the fecal mixture is conservatively high

8.) Dilute solution assumption may be inappropriate

Udert et al. (2003b)
Ionic strength of urine = 0.206 M

$$K_a = \frac{\{NH_3\}\{H^+\}}{\{NH_4^+\}} \qquad pH = -log\{H^+\} \rightarrow \{H^+\} = 10^{-pH}$$
$$\{NH_4^+\} = (\gamma_{NH_4^+})[NH_4^+]$$
$$\{NH_3\} = (\gamma_{NH_3})[NH_3]$$

For electrolytes, when ionic strength is less than 0.5 M:

$$\log_{10}(\gamma_{NH_4^+}) = -Az^2\left[\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3I\right]$$

A = 0.5 at 25°C (Aqion, 2013)
z = ionic charge, +1 for NH_4^+

$$\log_{10}(\gamma_{NH_4^+}) = -0.5(1)^2\left[\frac{\sqrt{0.206}}{1+\sqrt{0.206}} - 0.3(0.206)\right] \rightarrow \gamma_{NH_4^+} = 0.75$$

For nonelectrolytes:

$$\log_{10}\gamma_{NH_3} = k_s I$$ (Mihelcic and Zimmerman, 2010)

k_s = salting-out coefficient, 0.12 for NH_3 at 30°C (Butler, 1998)
Assume k_s is relatively constant with temperature

$$\log_{10}\gamma_{NH_3} = (0.12)(0.206) \rightarrow \gamma_{NH_3} = 1.06$$

$$K_a = \frac{\gamma_{NH_3}[NH_3](10^{-pH})}{\gamma_{NH_4^+}[NH_4^+]} \rightarrow [NH_4^+] = \frac{\gamma_{NH_3}[NH_3](10^{-pH})}{(\gamma_{NH_4^+})(K_a)}$$

$$NH_{(tot)} = [NH_4^+]V_l + [NH_3]V_l = \frac{\gamma_{NH_3}[NH_3](10^{-pH})}{(\gamma_{NH_4^+})(K_a)}V_l + [NH_3]V_l$$

$$\frac{NH_{(tot)}}{V_l} = [NH_3]\left[\frac{(\gamma_{NH_3})(10^{-pH})}{(\gamma_{NH_4^+})(K_a)} + 1\right] \rightarrow [NH_3] = \frac{[NH_{(tot)}]}{\left[\frac{(\gamma_{NH_3})(10^{-pH})}{(\gamma_{NH_4^+})(K_a)} + 1\right]}$$

9.) Calculation of Uncharged Ammonia Concentration

For urine stored alone:

$$[NH_3] = \frac{324\ mM}{\left[\frac{(1.06)(10^{-9})}{(0.75)(10^{-9.25})} + 1\right]} = 92\ mM = 1{,}288\frac{mg}{L}NH_3 - N$$

For 2 urine : 1 fecal products mixture:

$$[NH_3] = \frac{216\ mM}{\left[\frac{(1.06)(10^{-9})}{(0.75)(10^{-9.25})} + 1\right]} = 61\ mM = 854\frac{mg}{L}NH_3 - N$$

Uncharged ammonia concentration is just above 800 mg/L N

10.) Possibilities to raise uncharged ammonia concentration

Approach	Description
Raise pH (add wood ash)	If pH = 9.1, uncharged ammonia concentration rises to 1,000 mg/L N
Raise temp. (store in sun)	If T = 26°C, pK_a = 9.22, uncharged ammonia concentration rises to 900 mg/L N
Change mixture	If 3 urine : 1 fecal products mix, uncharged ammonia concentration rises to 970 mg/L N

*Note: a 3 to 1 mixture may be possible if actual fecal generation rate is less than the conservative estimate

Appendix F: Quality Control Data – Total Ammonia Tests

Table F.1: Total ammonia tests on 1 mg/L NH_3 standard solution provided in test kit

Test Number	Date	Expected Standard Concentration (mg/L NH_3)	Measured Standard Concentration (mg/L NH_3)	Percent Difference
1	14-Feb-2014	1.0	1.1	10%
2	7-Mar-2014	1.0	1.0	0%
3	18-Apr-2014	1.0	1.0	0%
4	20-Jun-2014	1.0	0.9	-10%
5	6-Sep-2014	1.0	1.1	10%

Table F.2: Dilution test results

Solution	Measured Total Ammonia Concentration (mg/L NH_3)
Standard 1 mg/L NH_3 Solution	1.1
Dilution Water	0.04
1:10 Dilution of 1 mg/L Standard	0.14
Back-Calculated 1 mg/L Standard Concentration (accounting for total ammonia in dilution water)	1.04
Percent Difference	*5.5%*

Table F.3: Spike and recovery test results

Solution	Measured Total Ammonia Concentration (mg/L NH_3)
1:1000 Dilution of Original Mixture (2 U : 1 F : 0 A)	2.6
Spike Amount	0.9
Spiked Matrix	3.6
Percent Recovery	*111%*

Appendix G: Estimated Material Quantities and Prices of Urine-Diverting Dry Toilets

Table G.1 provides a material and cost estimate for a double-vault UDDT, which contains two vaults that are to be used in an alternating fashion. The estimate includes the materials and labor required to complete the following:

- Fecal collection vaults (brick walls, concrete floor, metal access panels);
- The superstructure (brick walls, elevated concrete floor slab, wooden door, corrugated iron roofing, timber roof supports);
- Urine-diversion system with associated piping;
- Wash hole for anal cleansing and associated piping;
- Ventilation piping.

Table G.2 provides a material list and preliminary cost estimate for the additional equipment required for ammonia treatment at the household level, based on an average household size of five (Uganda Bureau of Statistics and ICF International Inc., 2012), while Table G.3 compares the cost of the double-vault UDDT with the cost of the equipment required for the ammonia treatment system. The following general points should also be noted:

- These estimates were prepared using the pricing structure of Brick by Brick Construction, a construction company founded by Brick by Brick Uganda, and include provision for general conditions, contingency, and company profit/overhead.
- The use of Interlocking Stabilized Soil Bricks (ISSBs), as opposed to traditional burned bricks, is assumed for the superstructure of each toilet. Due to their environmental benefits, ISSBs are promoted by Brick by Brick and used in the organization's construction projects.
- All costs are shown as Ugandan shillings (UGX). From 2012 to 2014, average quarterly exchange rates have fluctuated between 2,400 and 2,800 UGX per U.S. dollar (Bank of Uganda, 2015).

Table G.1: Estimated material quantities and costs of double-vault UDDT

Item	Unit	Unit Cost	Quantity	Total Cost
ISSB Production				
Cement	bag	UGX 32,000	5	UGX 160,000
Murram	trip	UGX 70,000	1.5	UGX 105,000
Polythene Sheets	meter	UGX 2,500	3	UGX 7,500
Water	jerry can	UGX 400	20	UGX 8,000
Oil	total	UGX 5,000	1	UGX 5,000
Labor	brick	UGX 100	600	UGX 60,000
Construction				
Burned Bricks	each	UGX 100	700	UGX 70,000
Ventilator Bricks	each	UGX 500	8	UGX 4,000
Cement	bag	UGX 32,000	15	UGX 480,000
Sand	trip	UGX 100,000	2	UGX 200,000
Aggregate	trip	UGX 140,000	1	UGX 140,000
Water	jerry can	UGX 400	40	UGX 16,000
Iron Bars	each	UGX 30,000	4	UGX 120,000
Iron Rings	each	UGX 3,000	1	UGX 3,000
Wire Mesh	each	UGX 30,000	1	UGX 30,000
Polythene Sheet	meter	UGX 2,500	3	UGX 7,500
Roofing Timber	piece	UGX 6,000	8	UGX 48,000
Iron Sheets	each	UGX 30,000	4	UGX 120,000
Wooden Doors (3' x 6')	each	UGX 100,000	1	UGX 100,000
Metal Access Panels (2' 3" x 2' 3")	each	UGX 80,000	2	UGX 160,000
Varnish	tin	UGX 54,000	1	UGX 54,000
Varnish Coloring	tin	UGX 5,000	1	UGX 5,000
4" PVC Vent Pipe	foot	UGX 1,300	20	UGX 26,000
4" PVC Caps	each	UGX 8,000	2	UGX 16,000
3" PVC Drain Pipe	foot	UGX 1,300	10	UGX 13,000
3" PVC Corners	each	UGX 6,000	3	UGX 18,000
2" PVC Urine Pipe	foot	UGX 1,300	8	UGX 10,400
2" PVC Corners	each	UGX 6,000	2	UGX 12,000
2" PVC Tee	each	UGX 10,000	1	UGX 10,000
PVC solvent	tin	UGX 6,000	1	UGX 6,000
Plastic Funnel	each	UGX 500	1	UGX 500
Eco-Pans (urine diversion devices)	each	UGX 25,000	2	UGX 50,000
Wooden cover for Eco-Pan	each	UGX 10,000	1	UGX 10,000
Ordinary Nails	kg	UGX 6,000	5	UGX 30,000
Roofing Nails	kg	UGX 7,000	2	UGX 14,000
Binding Wire	kg	UGX 7,000	2	UGX 14,000
Timber formwork	piece	UGX 6,000	15	UGX 90,000
Iron Strips	roll	UGX 40,000	0.2	UGX 8,000
Sisal String	roll	UGX 4,000	1	UGX 4,000
Poles	each	UGX 6,000	10	UGX 60,000
Jerry Can (for urine collection)	each	UGX 6,500	1	UGX 6,500
Material Transport	total	UGX 100,000	1	UGX 100,000
Skilled Labor	person-day	UGX 20,000	40	UGX 800,000
Total Labor and Materials				UGX 3,201,400
General Conditions	5%	of labor and materials		UGX 160,070
Contingency	5%	of labor and materials		UGX 160,070
Profit/Overhead	20%	of labor and materials		UGX 640,280
Total Price				**UGX 4,161,820**

Table G.2: Materials and estimated costs of ammonia treatment equipment

Item	Unit	Unit Cost	Quantity	Total Cost
200-Liter Plastic Tanks	each	UGX 80,000	4	UGX 320,000
Metal for Outdoor Storage	piece	UGX 20,000	2	UGX 40,000
Poles for Mixing	each	UGX 5,000	2	UGX 10,000
20-Liter Jerry Cans for Transporting Urine	each	UGX 6,000	10	UGX 60,000
Markers	pack	UGX 5,000	1	UGX 5,000
Shovels	each	UGX 15,000	2	UGX 30,000
Overall Total Cost				**UGX 465,000**

Table G.3: Cost comparison of double-vault UDDT and ammonia treatment system

Element	Double-Vault UDDT	Ammonia Treatment Equipment
Total Installation Cost	UGX 4,161,820	UGX 465,000
as percentage of Double-Vault UDDT	100%	11%

Appendix H: List of Acronyms and Notation

Eco-San	Ecological Sanitation
UDDT	Urine-Diverting Dry Toilet
VIP	Ventilated Improved Pit
CLTS	Community-Led Total Sanitation
ODF	Open Defecation Free
FGD	Focus Group Discussion
KII	Key Informant Interview
TA	Total Ammonia (mg/L NH_3)
FA	Free Ammonia (mg/L NH_3-N)
QA/QC	Quality Assurance/Quality Control
$t_{2\text{-log}}$	Time Required for 2-$\log_{10}$ Inactivation of *Ascaris* eggs (days)
t	Time
pH	Negative Logarithm of Hydrogen Ion Concentration
I	Ionic Strength (mol/L)
I_f	Formal Ionic Strength (mol/kg)
K_a	Acid-Base Equilibrium Coefficient
pK_a	Negative Logarithm of Acid-Base Equilibrium Constant
H	Henry's Law Constant (atm-m^3/mol)
γ_{NH3}	Activity Coefficient of Free Ammonia
γ_{NH4+}	Activity Coefficient of Ammonium Ion
k_s	Salting-Out Coefficient for Nonelectrolytes
A	Davies Equation Constant
z	Ionic Charge
T	Temperature
$T_{indoor\ amb}$	Indoor Ambient Temperature
$T_{outdoor\ amb}$	Outdoor Ambient Temperature
$T_{indoor\ mix}$	Indoor Mixture Temperature
$T_{outdoor\ mix}$	Outdoor Mixture Temperature

sin	Sine function
N_0	Number of initial viable *Ascaris* eggs at time 0
N	Number of viable *Ascaris* eggs at time t
k	First-Order Rate Constant
m	Lag Constant