A Proposed Sustainable Sanitation System for the Zwelitsha section of Langrug Informal Settlement in Stellenbosch Municipality South Africa

A Thesis
submitted to the Faculty
of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Master of Science
in Environmental Engineering

by

Edwin Muñiz
May 2013

APPROVED:

Professor Jeanine D. Plummer, Major Advisor

Professor Scott Jiusto, Interdisciplinary Advisor

Abstract

Globally, inadequate access to safe water and sanitation services, coupled with poor hygiene practices, kills and sickens thousands of children every day and leads to impoverishment and diminished opportunities for thousands more. The United Nations (UN), has recognized water, sanitation and hygiene (WaSH) as major issues that greatly affect the global poor. Under its Millennium Development Goals, the UN has set targets for addressing these issues. Namely, the UN aims to reduce by 50% the proportion of the global population without sustainable access to safe drinking water and basic sanitation by 2015. In 2010, the target of halving the proportion of people without access to improved sources of water was met five years ahead of schedule. Despite progress, 2.5 billion people in developing countries still lack access to improved sanitation facilities. As a result, the vision of WaSH is incomplete. Often, lack of access to basic sanitation is a daily reality for persons residing in informal settlements. The focus of this thesis was an area called Zwelitsha in the informal settlement of Langrug. Located in Stellenbosch Municipality near Cape Town, South Africa, Zwelitsha currently has few functional toilets for its 604 residents. As a result, persons resort to open defecation, contributing to environmental contamination and possible disease transmission throughout the settlement. Thus, sanitation is a significant need for Zwelitsha. Advancing the work of the Cape Town Project Centre (CTPC) – a center location within the Interdisciplinary and Global Studies Division of Worcester Polytechnic Institute – this thesis aimed to address the shortcomings in the provision of sanitation services within Zwelitsha. Through research, urine divergent dehydration and composting toilet systems were found to be the most technically feasible and applicable for meeting the sanitation needs of Zwelitsha. Favorable characteristics of these systems include independence from a connection to water pipes, sewerage, and energy sources and the generation of usable agricultural products. Both household level and community level options were proposed in this thesis. Proposed systems can be integrated into a large-scale WaSH facility with additional services such as water taps, sinks, toilets, showers, laundry stations, recreational areas, gardens, and salons for local business.

Acknowledgments

I would like to thank Professor Jeanine D. Plummer, Environmental Engineering Program Director and Associate Professor of the Civil and Environmental Engineering Department who has served as my Major Advisor over the past year. Professor Plummer has provided invaluable feedback throughout the process. Her deliberation, critical thinking, and attention to detail have been integral to the formation of this thesis. I would also like to thank Professor Scott Jiusto, Cape Town Project Centre Director and Associate Professor of the Interdisciplinary & Global Studies Division who has served as my Interdisciplinary Advisor. Professor Jiusto has shared his past work and experiences in Cape Town, which along with his ardent vision have inspired the research of this thesis. I would like to thank Worcester Polytechnic Institute and the Civil and Environmental Department for providing me with all its resources including a desk to conduct my research. Lastly, I would like to thank all my family and friends who have supported and bolstered me toward this final product.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

The focus of thesis was the selection of a technically-feasible and sustainable sanitation system for application in the informal settlement of Zwelitsha, located in Cape Town, South Africa. This chapter introduces the global water, sanitation, and hygiene (WaSH) deficit, informal settlements, and Cape Town, South Africa to orient the reader to the WaSH problem. Then, WaSH problems in Zwelitsha, an informal settlement in Cape Town, are discussed. Lastly, the goals of this thesis are presented. The remaining chapters present sanitation systems and propose a system for use in Zwelitsha.

1.1 Water, Sanitation and Hygiene (WaSH)

Beginning in 1990, the United Nations (UN) lead a decade-long series of conferences focused on issues of the global poor. In an effort to end extreme poverty globally by 2015, the UN agreed on eight goals Millennium Development Goals at the Millennium Summit in 2000. These goals, which built on the UN-led conferences commenced in 1990 included:

1. Eradicate extreme poverty and hunger;
2. Achieve universal primary education;
3. Promote gender equality and empower women;
4. Reduce child mortality;
5. Improve maternal health;
6. Combat HIV/AIDS, malaria and other diseases;
7. Ensure environmental sustainability; and
8. Global partnership for development (UN, 2013).

The UN realized that in order to meet these goals, several interim targets must be met. Under the seventh goal of ensuring environmental sustainability, a target was set to reduce by 50% the proportion of the population without sustainable access to safe drinking water (UN, 2013). World leaders failed to recognize sanitation as a target at the Summit. In reaction, the Global WaSH (Water Sanitation and Hygiene) Campaign was launched in 2001 (WSCC, 2013). Inadequate access to safe water and sanitation services, coupled with poor hygiene practices, kills and sickens thousands of children every day and leads to impoverishment and diminished opportunities for thousands more (UNICEF, 2013). Recognition of this linkage among water, sanitation, and hygiene led to the 2001 Campaign which sought to mobilize support for bringing sanitation and hygiene to the global agenda along with safe water access.

As a result of the WaSH Campaign, sanitation, initially left out of the plan, was added as a target to the Millennium Development Goals at the 2002 World Summit for Sustainable Development (WSCC, 2013). Specifically, sanitation was coupled with the safe drinking water target under the seventh goal of ensuring environmental sustainability. The target was set to reduce by 50% the proportion of the population without sustainable access to safe drinking water and basic sanitation by 2015 (UN, 2013) Through the UN, Millennium Development Goals were agreed upon by world leaders in 1990. As a result, targets are set with respect to the global rates of 1990. Even though it was added following the 2002 World Summit for Sustainable Development, the target of reducing by 50% the proportion of the population without sustainable access to basic sanitation is also set against the 1990 global rate. The 1990 global rates were 76% and 49% for the portion of the population with sustainable access to safe drinking water and basic sanitation, respectively (UN, 2012; WHO, 2013a). Thus, to achieve the targets, 88% and 75% of the global population would need to have sustainable access to safe drinking water and basic sanitation by 2015.

In 2010, the target of halving the proportion of people without access to improved sources of water was met five years ahead of schedule. Between 1990 and 2010, more than two billion people gained access to improved drinking water sources. The proportion of people using an improved water source rose from 76% in 1990 to 89% in 2010. Over 40% of all people without improved drinking water live in sub-Saharan Africa. Eleven percent of the global population—783 million people—remains without access to an improved source of drinking water. At the current pace of investment and barring additional interventions, 605 million people will still lack coverage in 2015 (UN, 2012). Access to improved sanitation facilities increased from 36% in 1990 to 56% in 2010 in developing regions as a whole. The greatest progress was achieved in Eastern and Southern Asia.

Despite progress, 2.5 billion in developing countries still lack access to improved sanitation facilities. As a result, the vision of WaSH is incomplete. Working together, Governments, the UN family, the private sector and civil society are making significant advances in providing improved sources of drinking water, but sanitation, and consequently hygiene, are seeing less progress. At current rates of investment and without additional interventions, by 2015, it is estimated that 67% of the global population will have sanitation coverage, well short of the 75% needed to achieve the Millennium Development Goals target (UN, 2012).

Daily, entire communities are exposed to the considerable health and environmental hazards of inadequate human waste disposal (UN, 2012). About 2 million people die every year due to diarrhoeal diseases; most of them are children less than 5 years of age. The most affected are the populations in developing countries, living in extreme conditions of poverty, normally peri-urban dwellers or rural inhabitants (WHO, 2013b).

There are a number of factors that contribute to WaSH issues. These include lack of priority by responsible parties (such as governments, politicians, and utility providers) given to WaSH-related issues, lack of financial resources, lack of sustainability of water supply and sanitation services, poor hygiene behaviours, and inadequate sanitation in public places including hospitals, health centers and schools. Providing access to sufficient quantities of safe water, the provision of facilities for sanitary disposal of excreta, and introducing sound hygiene behaviours are of capital importance to reduce the burden of disease caused by these risk factors (WHO, 2013b).

1.2 Informal Settlements

The UN Habitat Program defines informal settlements as:

1. residential areas where a group of housing units has been constructed on land to which the occupants have no legal claim, or which they occupy illegally; and
2. unplanned settlements and areas where housing is not in compliance with current planning and building regulations (WHO, 1999).

Other widely used terms for informal settlements include unplanned settlements, squatter settlements, marginal settlements, unconventional dwellings, non-permanent structures, inadequate housing, and slums (WHO, 1999).

Rapid urbanization and inadequate capability to meet the housing needs of people in urban areas have contributed to the development of informal settlements on a global scale (WHO, 1999). Persons residing within these informal settlements often face challenging living conditions. Sanitation, hygiene behaviour, food storage facilities and drinking water quality are often poor, exposing inhabitants to a wide range of pathogens. Houses may even act as breeding grounds for insect vectors, posing great health risks. Additionally, access to healthcare and other services are often limited (WHO, 1999). Furthermore, since informal settlements are unguided by urban planning, street grids, roads, and utility infrastructure are often nonexistent and, if present, are inadequately provisioned contributing to the issues of overcrowding. Overcrowding can contribute to stress, violence and increased problems of drugs and other social problems (WHO, 1999). The poor conditions within informal settlements have many contributing factors that must be addressed to improve living standards for inhabitants.

The reality of informal settlements is so dismal that world leaders (through the UN) believe that changing this reality is an integral step in ending extreme global poverty. Consequently, the UN made improving the lives of informal settlement dwellers a target under the environmental sustainability Millennium Development Goal. Namely, the target is to achieve, by 2020, a significant improvement in the lives of at least 100 million slum (informal settlement) dwellers (UN, 2013). In 2012, this target was met. Between 2000 and 2012, the share of urban slum residents in the developing world declined from 39% to 33%. Over 200 million residents gained access to improved water sources, improved sanitation facilities, or durable or less crowded housing, exceeding the Millennium Development Goal target. Still, 863 million people were estimated to be living in slums in 2012 (UN, 2013). In addition, some sources (HDA, 2012; Carr-Hill, 2013) suggest that estimates of slum populations are significantly undercounted.

1.3 Cape Town

According to a 2011 census conducted by Statistics South Africa, nearly 15% of the South African population of 51 million people lives in informal settlements (StatsSA, 2011; ECSECC, 2012). South Africa is subdivided into nine provinces: Eastern Cape; Free State; Gauteng; KwaZulu-Natal; Limpopo; Mpumalanga; Northern Cape; North West; and Western Cape. The legislative capital of South Africa is Cape Town, which is located in the Western Cape province. Cape Town is home to the largest informal settlement in Africa, Khayelitsha with over 40,000 informal shack dwellings. Enumeration projects estimate that there are approximately 300 informal settlements like Khayelitsha within the City of Cape Town alone (Rodriques *et al.*, 2006; HDA, 2012). According to census data obtained by the Strategic Development Information and GIS Department of the City of Cape Town in 2011, there are approximately 235,000 informal shack dwellings in the informal settlements of Cape Town. The data estimated an average household size of 3.5 persons, which means that approximately 823,000 live in the informal settlements of Cape Town (CCT, 2012a). Despite being the second largest contributor to the South African Gross Domestic Product, Cape Town struggles with the challenges of informal settlements (CCT, 2012b). Among the challenges found in these settlements is the provision of WaSH services.

Through the Water and Sanitation Services Department of the Western Cape Province, the City of Cape Town has both the constitutional responsibility for water services and the operational responsibility, as the Water Services Provider (CCT, 2012b). Therefore, the City of Cape Town is responsible for the provision of basic water supply and sanitation for the province. According to the Water and Sanitation Services Department, "basic water supply" comprises of the following:

1) The provision of appropriate education in respect of effective water use;
2) A minimum quantity of potable water of 25 litres per person per day;
3) At a minimum flow rate of not less than 10 litres per minutes;
4) Within 200 metres of a household; and
5) With an effectiveness of not more than 7 days interruption supply to any consumer per year.

Similarly, the department states that "basic sanitation" has two components. The first is the provision of appropriate health and hygiene education. The second is a toilet which is safe, reliable, environmentally sound, easy to keep clean, provides privacy and protection against the weather, is well ventilated, keeps smells to a minimum and prevents the entry and exist of flies and other disease-carrying pests (CCT, 2012c). Regarding water supply and sanitation, standard provision target levels are one functional water tap per 25 households and one functional waterborne [flush] toilet per 5 households (CCT, 2012c).

The service level profile of the department states that, as of January 2012, 99% of all households in the city were serviced with water supply and 93% were serviced with sanitation at the provision target levels. In reference to households within the city's informal settlements, 92% were stated as being serviced with water supply and 59% with sanitation. Still, the department recorded that it met the basic sanitation provision target level [of 1 toilet per 5 households] with an average of 5.76 households per working toilet. The department fell short of the water supply provision target level [of 1 tap per 25 households] with an average of 27.03 households per tap (CCT, 2012c).

The department recognizes significant backlogs for water supply (14,551 taps) and sanitation (80,364 toilets) within informal settlements (Table 1). Still, overall percentages for water and sanitation provision do not demonstrate the disproportionality of services rendered across regions (CCT, 2012c). Formal households have either a metered water connection to the house or to a water tap adjacent to a yard toilet. In addition, formal households generally have waterborne sewer connections for conveyance of sanitation wastes from the home. On the contrary, informal settlements typically have shared toilets and communal standpipes from which sanitation service and free water is provisioned (CCT, 2012c).

Table 1. Sanitation and Water Targets and Current Conditions in the Informal Settlements of Cape Town, South Africa (CCT, 2012a; CCT, 2012c)

Parameter	Water	Sanitation
Estimated Informal Settlement Population	823,000	823,000
Estimated Household Size	3.5	3.5
Estimated Number of Households	235,000	235,000
Provision per Household Target	1 per 25	1 per 5
Reported 2012 Provision in Informal Settlements	1 per 27	1 per 5.7
Number of taps/toilets Target	21,727	114,041
2012 Informal Settlement Number	7,176	33,677

Communal WaSH systems in informal settlements are often misused, vandalised, and inadequately maintained, contributing to poor conditions and dysfunctional systems. Additionally, densely populated settlements typically do not have a grid layout, roads, or any robust infrastructure so areas can be rendered inaccessible to service vehicles and personnel. Lastly, inequitable and unjust political agendas, disproportionate fiscal allocation, and financial restraints lead to intermittent if any provision in informal areas. Thus, many informal settlement residents experience daily service levels well under the city provision standard (Brooks *et al.*, 2012; IIUD, 2013).

1.4 Zwelitsha

One of the informal settlements of Cape Town where residents encounter substandard WaSH provision is Langrug. Formed in the 1990s, Langrug is situated on the slope of a mountain in the small town of Franschhoek within the winelands of the Stellenbosch municipality of the Western Cape province. According to the 2011 Langrug Settlement Enumeration Report, Langrug has a population of 4,088 persons, all of whom live in shacks (ISN *et al.*, 2011). The report enumerated 1,858 shacks, translating to an average household size of 2.2 persons. The population of Langrug is spread out into the settlement's three zones: Nkanini, Mandela Park, and Zwelitsha.

Sanitation and water provision in Langrug is lacking. Among the three zones, there are 91 toilets of which 83 are functional (non-functional toilets are due to vandalism and/or poor drainage). As a result, there is one functional toilet for every 49 persons. It has been reported that there are no toilets within any individual household; thus, all systems are part of communal toilet blocks (ISN *et al.*, 2011). Additionally, there are only 57 taps, of which 45 are working. This brings the provision level to 91 persons per tap (ISN *et al.*, 2011). Similar to the disparate provision of services between formal dwellings in major cities like Cape Town and households in neighboring informal settlements, provision within settlements can be disproportionate as well. For the 604 persons who reside in Zwelitsha, there is one functional tap and no functional toilets. As a result, persons resort to open defecation, contributing to environmental contamination and possible disease transmission throughout the settlement. According to the

Langrug Settlement Enumeration Report, 15% of those surveyed depend on the bush (open defecation) for toilet service (ISN *et al.*, 2011). The municipality has struggled to meet the needs of the informal settlement.

In efforts to satisfy the extensive needs of the Langrug settlement, the Stellenbosch Municipality has entered into an unprecedented partnership with the community. After much deliberation, in 2010, the Stellenbosch Municipality became the first local authority in the world to enter into an agreement with Shack Dwellers International (SDI), an umbrella non-profit organization aiming to improve the living conditions of the urban poor (IIUD, 2013; Vandenberg, 2013). Two entities of ISD are Community Organisation Resource Centre (CORC) and Informal Settlement Network (ISN) which have also been introduced to the Stellenbosch Municipality to aide in upgrading Langrug. Traditionally, municipalities assume complete responsibility and execution of upgrading projects. Through its partnership with SDI, the Stellenbosch municipality is enlisting the help of the community toward finding innovative approaches for solving the community's issues (IIUD, 2013; SDI, 2013; Vandenberg, 2013).

Unlike many governmental agencies, the Stellenbosch Municipality realizes that it cannot meet all the needs of the informal settlements without the input of community members. The partnership has already seen the completion of an enumeration report (Langrug Enumeration Report), including crucial information for improving service provision (IIUD, 2013; SDI, 2013; Vandenberg, 2013). In addition to water and sanitation needs there is an urgent need for electricity with 60% of households in Langrug reporting no electricity provision. Most depend on paraffin and some on gas for lighting and other domestic usages. Families residing in Zwelitsha comprise the largest portion of paraffin dependent energy users without access to electricity (ISN *et al.*, 2011). Also, there is an urgent need for more streets to improve access into and out of the settlement. Due to heavy rains in the winter, poor drainage and storm water system provision and management, the settlement is often flooded. Residents experience fires which can spread to adjacent shacks in the densely-packed settlement. Accompanying the disasters of floods and fires, rampant social problems throughout the settlement include crime and drug abuse (ISN *et al.*, 2011).

In addition to better information gathering and reporting, the alliance has assumed a unique approach to upgrading the settlements known as re-blocking (Brooks *et al*., 2012). According to SDI, re-blocking rearranges shacks in densely-packed settlements to create common public space, develop access roads, and install basic service infrastructure (IIUD, 2013). This process is conducted incrementally, block-by-block. Communities rebuild on the land where they live, avoiding resettlement and preserving social and economic ties that would otherwise be lost by the more traditional methods of uprooting and relocation. This "in-situ" community upgrading means that at any one time only a few infrastructure and household improvements would be taking place, preserving daily rhythms and avoiding mass dislocation (IIUD, 2013). As part of the partnership agreement, the Municipality will contribute R4 million and SDI will contribute R2 million for informal settlement upgrading.

1.5 Knowledge Gap/Thesis Goals

In 2011, Worcester Polytechnic Institute (WPI) informally entered into the Stellenbosch municipality-Langrug community partnership. Since 2007, the Cape Town Project Centre (CTPC) – a center location within the Interdisciplinary and Global Studies Division of WPI – has sent student groups to complete projects aimed at improving the living conditions of informal settlement residents. Projects over the CTPC tenure have included objectives such as revitalizing the local economy, addressing greywater management issues, and strategizing human developments that preserve culture, solve social issues and practice sustainability. Most recently, in 2012, one project team joined the Stellenbosch Municipality and the Langrug community in innovative upgrading of the settlement. The team assisted with initial reblocking efforts, finalized designs and plans for the implementation of a community centre, improved upon current greywater management processes, and designed and began construction of an innovative, communal Water, Sanitation, and Hygiene (WaSH) facility in the subdivision of Zwelitsha (Brooks *et al*., 2012).

This thesis advances the work of the project center with hopes of forming the foundation for future work by the CTPC within the Stellenbosch Municipality-Langrug community partnership. Specifically, this thesis aimed to address the shortcomings in the provision of WaSH services within Zwelitsha. The CTPC has envisioned the development of a multipurpose WaSH facility complete with functioning taps, sinks, toilets, showers, laundry stations, recreational areas, gardens, and salons for local business. Combining each of these amenities in one facility has understandable social benefits including improved health, economic status, and autonomy. The knowledge gap exists in the technical understanding of such a facility. The current situation in Zwelitsha demonstrates a dire need for sanitation systems within the settlement. Meeting this need requires both social consideration and technical expertise, and this thesis focused predominantly on the technical aspects of the sanitation system component of such a WaSH facility.

Integral to this work was the evaluation of sanitation system options for Zwelitsha. Thus, the major objectives of this thesis were: (1) to evaluate possible sanitation systems and (2) to select a sustainable and technically feasible toilet system to meet the sanitation needs of Zwelitsha as part of a WaSH facility. The provision of both water and sanitation services is poor within Zwelitsha. Therefore, sanitation systems that do not require water were a primary focus. Both household level and community level options were explored, with consideration of safety, cost, and potential to generate useable products. The following chapters investigate and compare toilet system options, select and discuss salient features of the chosen system, propose final system design, and provide final recommendations for ensuring that the proposed system alleviates the WaSH deficit in Zwelitsha.

Chapter 2: Toilet System Evaluation

In efforts to meet the sanitation needs of particular regions with particular conditions, many toilet systems have been developed. The available toilet systems were reviewed and shortlisted based on their potential applicability to Zwelitsha conditions. In this way, only systems that appeared promising for meeting the particular needs and conditions of Zwelitsha were investigated further.

The following sections provide general information for each potentially applicable system. These systems included urine diversion toilets and composting toilets. Then, the systems are compared for technical feasibility and applicability within the particular conditions of Zwelitsha, South Africa.

2.1 Composting Toilet Systems

Composting toilet systems use the aerobic decomposition of human feces by microorganisms found in feces to generate a reusable product in the form of compost. Although the physical system can have several designs, the treatment process for the entering human waste is rudimentarily the same for all composting systems where aerobic decomposition is employed. After an individual defecates into the composting toilet, the waste travels down a chute into a reaction chamber usually via gravity. The waste accumulates in this chamber upon each use (defecation) where it undergoes aerobic decomposition. Following an adequate period of waste decomposition, typically 6 months to 12 months or longer in some systems, a “humus” resembling soil remains in the reaction chamber (NSFC, 2000). This humus can be reused for agricultural purposes. Figure 1 illustrates a typical single chambered composting toilet system.

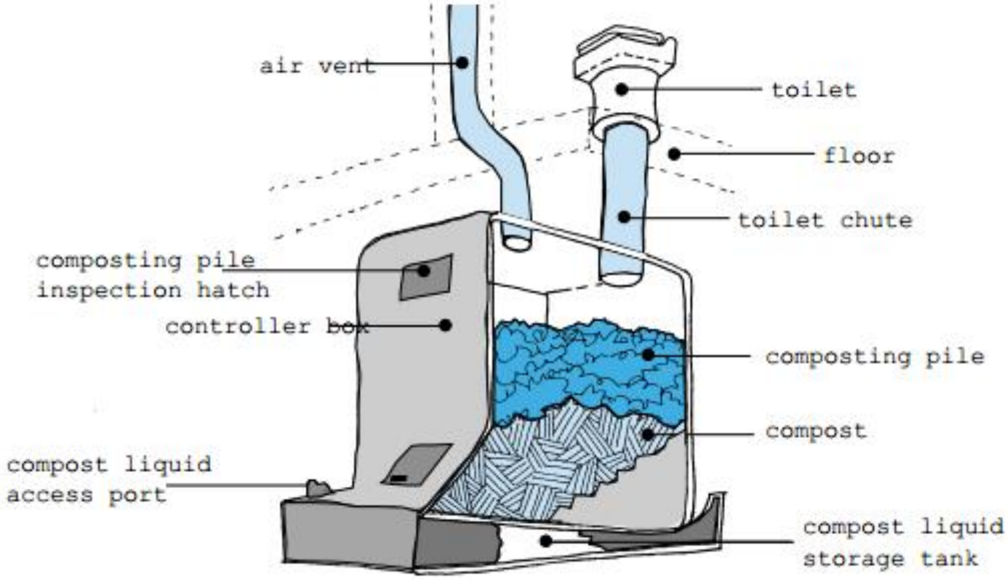


Figure 1. Diagram of a Typical Single-Chambered Composting Toilet System (NSFC, 2000)

Composting toilet systems consist of waterless toilets and are usually self-contained systems such as the one shown in Figure 1. The reaction chamber, which acts as a holding tank, retains human excrement, toilet paper, and any organic (carbon-based) bulking agents placed into the toilet units. Aside from urine, the tank must not contain liquids so as to promote the growth of aerobic organisms that decompose the waste material (NSFC, 2000). In addition, the waste material must be exposed to air for microbial growth. Therefore, the system requires ventilation to circulate air throughout the tank. The purpose of the ventilation system is two-fold, also serving as an odor redirecting mechanism expelling unfavorable odors from the decomposing waste material within the system out of the composting unit and into the air outside. Some models utilize an exhaust system driven by a fan to vent odors as well as carbon dioxide and moisture from the reaction chamber to the outdoors. Screens are placed at the discharging end of the exhaust system to prevent the entrance of insects into the composting system.

Another concern for a composting system is the temperature within the reaction chamber. High temperatures may inhibit microbial growth and thus slow the decomposition process, which is an exothermic process itself generating heat from microbial activity. Correspondingly, low temperatures can also inhibit microbial activity. Temperatures lower than 5˚C may cease the process altogether. The optimal temperature for composting activity is between 25.6˚C and 45˚C (NSFC, 2000).

Although the composting toilet is a dry waterless toilet system, the moisture within the system is still a major concern. Thorough decomposition usually occurs at a moisture content between 45 to 65%, which in most systems is maintained by the urine entering the toilet (NSFC, 2000; Berger, 2011). Some designs have a built-in electric-powered sprayer that draws up liquid collected in the bottom of the reaction chamber to rewet the composting pile to remedy an over-dry condition (NSFC, 2000). For regions with an unreliable or non-existent supply of electricity, systems can be designed to enable user access to the reaction chamber for wetting of the compost with water. Without a moisture content of at least 40%, the decomposition will slow down considerably or may cease.

In addition to maintaining a desirable moisture content, the system must incorporate a turning mechanism or process that will rotate the compost material. Rotating the material keeps the compost pile porous and aerated so that the aerobic organisms can decompose the waste (NSFC, 2000).

Depending on volume and reaction chamber conditions, the compost pile can be left to decompose for 6 to 12 months or even longer before the compost is ready for removal and reuse. Storage time begins after the last use; no additional fecal waste should be introduced to the compost pile during storage. Systems typically produce a final material that is 10 to 30% of its original volume; thus, waste reduction can be as high as 90% of the original volume (NSFC, 2000; Berger, 2011).

There are many different types and models of composting toilet systems offered by manufacturers and dealers in many countries. The cost depends on complexity of the design, the number of units needed, transport costs, production and economic conditions. Costs vary widely, ranging from self-built units as low as $10 to commercially manufactured units as high as $10,000. Owner-built toilets are usually lower in cost than manufactured toilet systems, particularly if local materials are used and labour costs are low (Berger, 2011; Parkinson *et al.,* 2012)

2.2 Urine Diversion Toilet Systems

Urine diversion toilet systems have two separate collection systems: one for urine and one for feces. The purpose of urine diversion toilets is to ensure that urine and feces never mix from the point of human excretion up to the collection stage and eventual disposal. Urine diversion toilets may mix water and feces, or some water and urine. The nutrient value of urine is harnessed by collecting and treating diverted urine. In these systems, the fecal fraction can either be composted or disposed of via sewerage separate from diverted urine. Systems using urine diversion toilets typically have one or more of the following four objectives: to reduce odor, to prevent production of wet fecal sludge, to reduce water consumption and to collect pure urine for use as fertilizer in agriculture (Münch and Winker, 2011). Additionally, urine diversion toilet systems minimize excreta-related groundwater pollution, can be used indoors in areas where pit latrines are the common alternative, and allow users enhanced control over micro-pollutants discharged to the environment. Challenges to implementing these systems include social acceptance, user cooperation, urine reuse or disposal issues, and urine precipitation (Münch and Winker, 2011). There are two main types of urine diversion toilets: (1) UD toilets without flush water, or urine diversion dehydration toilets (UDDTs) and (2) UD toilets with flush water, or UD toilets. These two are described in the following sections.

2.2.1 Urine Diversion Dehydration Toilet (UDDT) Systems

Urine diversion dehydration toilet (UDDT) systems consist of waterless toilets which divert urine and feces into separate receptacles within an enclosed structure. UDDTs do not require additional wastewater disposal or treatment systems. If users want to use water instead of toilet paper for anal cleaning, UDDTs can be designed with a third separate drain hole for anal washwater (Münch and Winker, 2011). When an individual urinates into the toilet, his/her urine is captured in a bowl which is integrated in the front of the toilet pedestal or squatting pan. The urine is then drained off to a storage container located below the system (Münch and Winker, 2011). Following defecation, the feces drop down a chute located behind the urine capturing bowl. The feces are collected in a vault or bin placed below the UDDT system. While composting does not take place in the UDDT system, a ventilation pipe is included to remove odor from the system and to facilitate drying of the feces (Münch and Winker, 2011). The collected feces are removed from the UDDT system. They can be disposed of or treated via composting. A UDDT system designed with a third outlet for users who practice anal cleansing with water must collect and treat the anal washwater separately from urine and feces. The anal washwater can be infiltrated in a gravel filter or treated together with greywater in a subsurface constructed wetland (Hoffmann *et al.*, 2011; Münch and Winker, 2011). If the end goal of the system is to reuse urine as a fertilizer, it is best to avoid mixing anal washwater and/or feces with urine to keep pathogen levels within the urine at a minimum. Figure 2 provides examples of two UDDT systems: one with a front urine collection bowl and a posterior drop chute for feces (left) and the second with an additional third hole for anal washwater collection (right).

Figure 2. Left: Indoor UDDT (pedestal type) in Johannesburg, South Africa (Münch, 2006 from Münch and Winker, 2011). Right: UDDT Squatting Pan in Bangalore, India, with three holes: the area in the front is for anal washing; middle is for feces and back is for urine (Schafer, 2008 from Münch and Winker, 2011).

Urine diversion dehydration systems also include waterless urinals. With proper use (e.g. users do not defecate or place other non-urine items into the urinals), waterless urinals allow for the collection of pure, undiluted [by water] urine. They are connected to a urine storage tank unlike urinals using water that are connected to a sewer or treatment system. Figure 3 shows examples of such urinals. Urine diversion dehydration toilet units vary in price from $35 to $400 (Parkinson *et al.*, 2012).

Figure 3. Waterless Urinals for Men. Left: Centaurus model of Keramag company (Münch, Delft, 2006 from Münch and Winker, 2011). Right: Plastic Urinal from Addicom, South Africa with EcoSmellstop device (Addicom, 2013 from Münch and Winker, 2011).

Systems such as the ones in Figures 2 and 3 divert urine into a urine collection system for three purposes: urine storage, sanitization via prolonged storage, and reuse. The urine collection system of UDDTs should consider the capacity and particular needs of the user population being served. However, all UDDT systems should consist of simple pipework connecting the diverted urine to a storage tank. Urine pipework is normally made of durable plastics such as polyethylene (PE) or polyvinyl chloride (PVC). The flowrate within the urine piping system should be maximized. This can be accomplished by avoiding rough surfaces, sharp 90˚ bends, siphons, long pipes, horizontal pipes (not to exceed 200 m), and U-bends in the piping system (Münch and Winker, 2011). Ideally, piping should consist of smooth surfaces and hydrophobic materials. Additionally, wider pipes are recommended. Pipe diameters from 75 mm to 110 mm are the optimum range where the minimum recommended pipe diameter is 50 mm (Münch and Winker, 2011). Larger UDDT systems containing several toilets and or urinals should have pipe slopes of at least 1% to minimize urine precipitation. Individual systems should have a pipe slope of at least 4%, but can be built with smaller diameter pipes, down to about 15 mm (Münch and Winker, 2011).

Urine flows through the piping system into a storage tank. Storage tanks are most commonly made of glass fiber reinforced plastic, PE, polypropylene (PP), or PVC, but they can also be made of rubber bladders or high-quality reinforced concrete. Since urine is corrosive, metal components cannot be used in the storage tank or throughout the UDDT system. Stainless steel is the exception, but is an expensive material. Plastic tanks which are sold for rainwater harvesting are also suitable as urine storage tanks, and can be a good solution in developing countries (Münch and Winker, 2011). Whatever the material used, all storage tanks must be completely watertight to avoid loss of urine, prevent groundwater contamination (for systems placed directly onto ground with no liner), and prevent groundwater from entering the tank from the outside.

Storage tanks hold the collected urine for an extended period of time. Urine should be stored for at least 30 days, but depending on the urine composition, urine volume, and the specific future application of urine, storage periods vary (Kvarnström *et al.*, 2006). Storage sanitizes the urine, which can be used as a sterile nutrient-rich fertilizer. Urine is rich in nitrogen, mainly in the form of urea. When stored, a natural enzyme within the urine, urease, decomposes urea forming ammonia/ammonium and hydrocarbonate. This decomposition of urea leads to an increased pH value (pH around 9) which has a sanitizing effect, killing pathogens such as bacteria, parasitic protozoa, viruses, and intestinal helminthes that may be present in the original urine (Münch and Winker, 2011). An environment with a high temperature and low dilution with water enhances this effect (Münch and Winker, 2011). Another effect of the rise in pH is the precipitation of struvite ($MgNH_4PO_4$) and calcium phosphate ($Ca_{10}(PO_4)_6(OH)_2$) crystals. These crystals can form incrustations, also called "urine stone" within the inner walls of pipes and pipe bends (Münch and Winker, 2011). Consequently, great attention must be given to the pipe design of the system. Furthermore, methods of removing precipitates that can clog pipes and stifle urine flow should be practiced. Most blockages that occur in urine diversion dehydration systems are soft blockages caused by precipitation on hair and paper fiber. The other type, hard blockages or incrustations, caused by precipitation directly on the pipe wall, are less likely in waterless systems. Blockages can be removed either mechanically by a drain auger (being careful not to scratch smooth pipe surfaces) or chemically by use of strong solutions of caustic soda (2 parts of water to 1 part of soda) or acetic acid (>24%) (Kvarnström *et al.,* 2006; Münch and Winker, 2011). As part of the system design, pipes should be made accessible for inspection and cleaning via openings.

Proper urine sanitization requires urine to be stored without the addition of fresh urine for at least 30 days before it can be considered sterile for reuse. As a result, at least two tanks are recommended: one to receive urine and one to store urine for sanitization. Larger systems should utilize several urine storage tanks so one can be taken out of service if necessary (Münch and Winker, 2011). All tanks should have a lid and remain closed to prevent odor and loss of nitrogen via ammonia gas from the urine. The pipe and tank system should not be ventilated by any means, only pressure equalized. According to Münch and Winker (2011), this is best done by a small hole in the tank for equalization with the urine tank pressure. This allows the replacement of headspace air by urine flowing into the tank, and vice versa when emptying the tank.

Depending on user capabilities and particular circumstances, urine can either be manually siphoned from storage tanks or pumped into vehicles for transportation to locations for reuse, such as to farms. It is important to note that if urine is pumped, the systems must have sufficient flow of air into the tank. The air flow will prevent the development of a vacuum in the tank, which can cause tank implosion (Münch and Winker, 2011). Still, to avoid losses of ammonia gas to the air and odor release outside the system into homes and facilities, ventilation in the piping system should be kept minimal. Prevention of undue gas movement through the piping system can be accomplished by creating a liquid seal in the urine storage tank. This is done by bringing the opening of the incoming pipe [from the toilet or urinal receptacle] to almost the bottom of the storage tank. At the storage tank bottom, a layer of sludge containing urine precipitates and crystals forms over time, with high levels of nitrogen, phosphorous, calcium, and magnesium. Thus when emptying the storage tank it is crucial to empty the bottom sludge layer to attain the full nutrient value of the urine. Additionally, failure to remove this sludge reduces the available volume for urine storage within the tank (Münch and Winker, 2011).

Even with a good technical design and construction of a UDDT system, without alignment of the technology with user acceptance and proper use a system will not be sustainable. Common barriers to user acceptance of UDDT systems include: user unwillingness to change existing habits and behaviours, for example, from existing sanitation methods; lack of support from all involved stakeholders (users, maintenance staff, planners, farmers, politicians, etc.); cultural dynamics including superstitions regarding sanitation methods; prevailing norms regarding reuse of human excreta and related taboos; and unavailability of service providers who can offer a collection and maintenance service for the system. System users must also practice proper use. Introducing fecal matter into the urine receiving area or foreign objects such as cigarette butts, tampons, paper or other garbage into either waste depository will diminish system operability. Thus, for any system, careful planning with stakeholder participation is crucial in overcoming these social barriers and in educating about proper use prior to system implementation.

2.2.2 Urine Diversion (UD) Toilet Systems

Like UDDTs, urine diversion (UD) toilet systems consist of toilets which divert urine and feces into separate receptacles. The difference is that UD toilet systems do so with the use of water. Within these systems, feces are flushed into an existing sewer or wastewater treatment system while the urine is directed into a storage and reuse system. UD flush toilets require a reliable 24-hour water supply, a sewer system and a treatment process for the feces-water mixture (brownwater) (Münch and Winker, 2011). As a result of these additional requirements, UD toilet units cost considerably more than UDDT units ranging in price from $675 to $1500 (Parkinson *et al.*, 2012). For the same reason, UD toilets are suitable for areas with established infrastructure for wastewater treatment and disposal. Figure 4 shows two UD flush toilets used in Europe.

Figure 4. UD Flush Toilets. Left: Gustavsberg (in Meppel, the Netherlands). Right: Dubbletten (in Stockholm, Sweden) (Münch, 2007 from Münch and Winker, 2011).

Although not a dry system like UDDTs and waterless urinals, there is a significant water savings potential for UD systems versus conventional flush systems. Conventional urinals use around 4 L of water per flush, flush toilets use 8 -12 L per flush, and pour flush toilets use 2-3 L per flush. Depending on the model, UD flush toilets use between 0.5 and 2 L of water per flush. UD systems utilize “urine flush,” which uses a low volume to flush away remaining urine drops and used toilet paper. To maximize water savings, urine-soiled paper should be collected in a bin, rather than flushed away. Flushing with soft water, such as rainwater, is preferred to flushing with hard water (soft water has less calcium and magnesium which can precipitate with ammonium and phosphate present in the urine) (Münch and Winker, 2011).

In addition to water savings, UD flush systems have associated energy savings. Requiring less water than conventional systems, less energy is subsequently needed for pumping, processing and distributing water. Collecting urine lessens the nitrogen load received by wastewater treatment plants, reducing energy required for processes to remove the macro-nutrient. These savings are considerable compared to conventional sewage containing both urine and feces since 80% of the nitrogen excreted by a person is excreted with the urine (Münch and Winker, 2011). If reused as a sterile fertilizer, urine can replace artificial mineral fertilizer creating energy savings for fertilizer production and fertilizer transport. This is especially beneficial for regions with no local mineral fertilizer production facilities, as most African countries (Münch and Winker, 2011). Aside from linking the fecal compartment of the system to an existing sewer or brownwater treatment system, the system components of UD flush systems are the same as UDDT systems from urine collection to storage and reuse.

2.3 Incinerating Toilet Systems

As the name implies, incinerating toilet systems incinerate human excrement. These systems produce sterile ash from the incinerated waste. Incinerating toilet systems are self-contained, waterless, and produce no liquid or continuous effluent stream. Since the systems are self-contained, they do not require connection to an existing sewage system. Incinerating toilet systems can rely on electric power, oil, natural gas, or propane to burn human waste (NSFC, 2000). Two types of incinerating toilets are discussed in the following sections: electric-powered incinerating toilets and gas-fired incinerating toilets.

2.3.1 Electric-Powered Incinerating Toilet Systems

Electric-powered incinerating toilets require an electric source and electrical components to burn human waste within a combustion chamber. Excrement is deposited into a paper-lined upper bowl, as displayed in the leftmost schematic of the toilet system in Figure 5. The paper liner shields the stainless steel bowl from human excrement to avoid the necessity of cleaning off any residual waste that has come into contact with the bowl. Therefore, the liner must be replaced after each use. Underneath the upper toilet bowl is a covered combustion chamber where the deposited waste is burned. When the user is ready to “flush” or drop his/her waste into the combustion chamber, the user steps on the foot pedal. The foot pedal simultaneously splits the two halves of the toilet bowl and opens the combustion chamber. This action drops the waste into the combustion chamber as shown in the middle image. When the foot pedal is released, the bowl halves are rejoined and the chamber cover replaced.

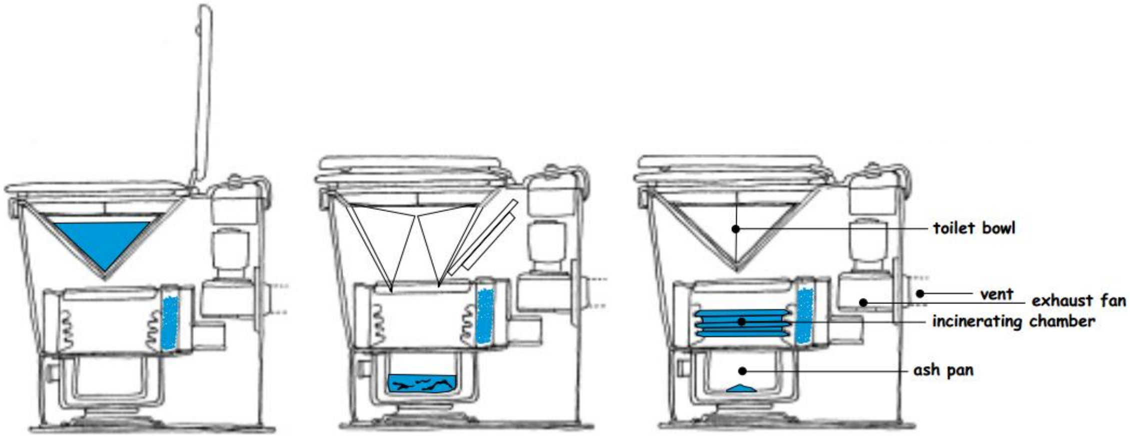


Figure 5. Diagram of a Typical Electric-powered Incinerating Toilet System (NSFC, 2000)

Once the system is full, the user begins the incineration by pressing the “start” button. A heating coil is activated expending heat into the combustion chamber at temperatures of up to 760˚C (Barnstable, 2013). The waste is burned for a preselected period, usually an hour. During this time, a blower motor draws air from the incineration chamber over a heat-activated catalyst to remove odors (NSFC, 2000). This air flow is directed by a fan through a ventilation pipe within the system and out of an exhaust into the outdoors. Once the incineration cycle is completed, the heating coil shuts off but the blower motor continues to draw heat from the chamber in order to cool it. The chamber is cooled down to about 54˚C (Barnstable, 2013). By now the incineration waste has collected in a pan located under the chamber in the form of sterile ash. After allowing the pan to cool down to room temperature, the ash, usually about a tablespoon in volume, can be removed from the pan and be discarded or reused as an agricultural fertilizer rich in potassium, nitrogen, and phosphorous. Figure 6 shows the step by step use of the system.

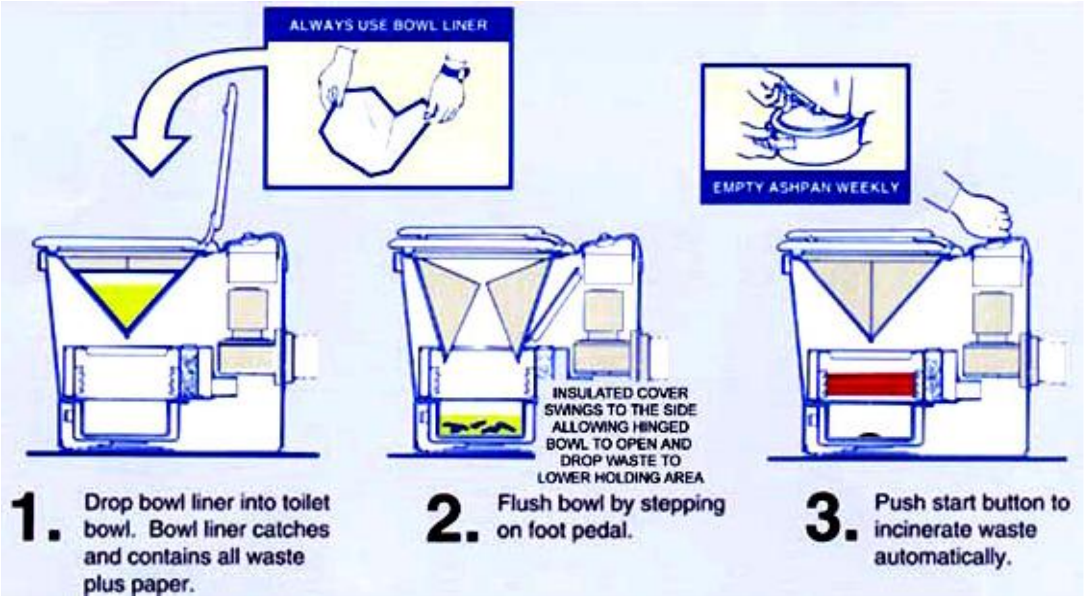


Figure 6. Step-by-step use of Electric-powered Toilet System (Barnstable, 2013)

Electric-powered incinerating toilet systems are in use in a number of locations on Cape Cod and the Islands (Bourne, Falmouth, Hyannis, Chatham and Nantucket in Massachusetts, United States). The price range of a unit is $1499-$1879, and the system cost about 28 cents per cycle to operate (Barnstable, 2013).

2.3.2 Gas-Fired Incinerating Toilet Systems

Gas-fired incinerating toilets require a propane or gas source to burn human waste within a combustion chamber. Excrement is deposited into a storage tank as opposed to a toilet bowl as with electric-powered incinerating toilets. This storage tank, located beneath the seat of the unit, can accommodate 40 to 60 uses before the need for an incinerating cycle (NSFC, 2000). There is only one manufacturer of gas-fired incinerating toilets, Storburn International Inc. (Brantford, Ontario, Canada). The STORBURN toilet (Figure 7) has a retail price of $4,000. According to the manufacturer, it can satisfy the needs of 8 to 10 workers in an average 8 to 10 hour day or about 6 to 8 persons in a cottage or residence where the daily use would be about 16 hours (Storburn, 2013).

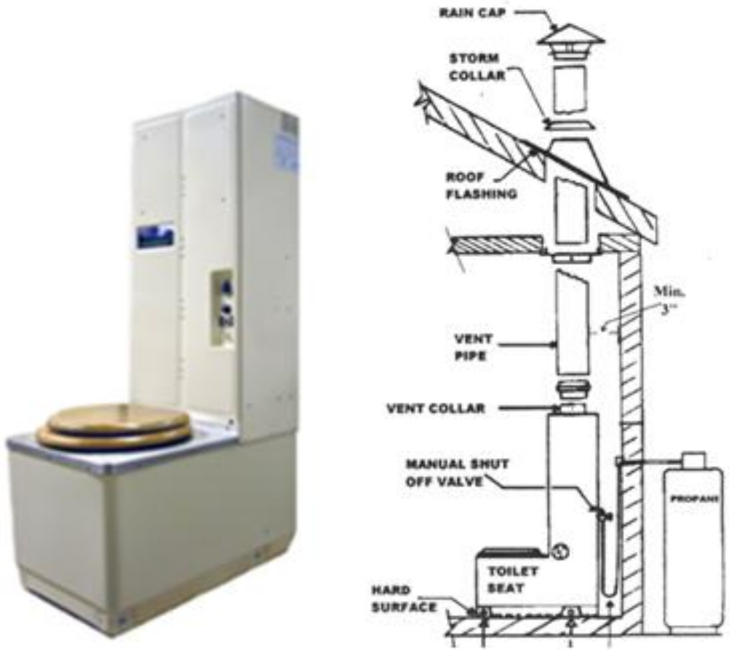


Figure 7. Left: STORBURN Unit. Right: Complete System with Propane Hookup and Ventilation System (Storburn, 2013).

Between incineration cycles, an aerosol masking foam can be used to reduce odors and cover wastes. A marker indicates when the system has reached its load capacity and incineration should be initiated. An incinerating cycle can be commenced after any number of uses even though it is more efficient to burn full loads rather than partial loads. It takes approximately the same amount of fuel to preheat the combustion chamber in either case (Storburn, 2013). Before the burning process begins, an anti-foaming agent must be added to the heating chamber to reduce the risk of liquid wastes boiling over during incineration. The seat is lifted and a cover plug is inserted over the chamber opening acting as a fire wall. The user has to set the timer for the incinerating cycle. Users are supplied with a user manual delineating recommended times for certain load sizes. Depending on the load size, incinerating cycles can take anywhere from 1.5 hours (for smaller loads) to 4.5 hours (for maximum loads) (Storburn, 2013). A user starts the cycle by pressing a button on the unit. With this action, a gas valve is turned to the pilot position and ignited. The pilot light ignites the burner (NSFC, 2000). As a precaution, the toilet system is shut and locked prior to commencement of the incinerating cycle. It remains locked until the cycle is over. The cycle produces about a half a cup of sterile ash that can either be disposed of or used on a garden as fertilizer.

During the incinerating cycle, the entire storage chamber of the unit is sterilized, destroying all odor causing bacteria. As a result, the chamber never needs washing. The self-contained gas-fired incinerating systems have no effluent discharge into soil or harmful gas emission into the atmosphere. Following the incineration cycle, all that remains is sterile mineral ash and water vapor (Storburn, 2013). Although advertised as completely safe, being a gas fixture, toilets must be routinely inspected for integrity of connections. Storburn International provides STORBURN system users with a vent kit since gas fixtures should be adequately vented to the outdoors (NSFC, 2000).

2.4 Oil Recirculating/Flush Toilet Systems

Oil recirculating or oil flush toilet systems consist of waterless toilets that use mineral oil to flush away human excreta. These systems use gravity to separate human wastes from the oil medium. As seen in Figure 8, oil flushed wastes enter a separation tank where the more dense water-based urine and feces drop to the bottom and the lighter oil floats at the top. A waste pump-out port is used to remove the waste from the tank for disposal. The waste can be incinerated, composted or removed by a licensed septage hauler (NSFC, 2000). Oil, floating at the top of the tank, is drawn up, purified, and recirculated back into the toilet where the closed-loop system begins again.

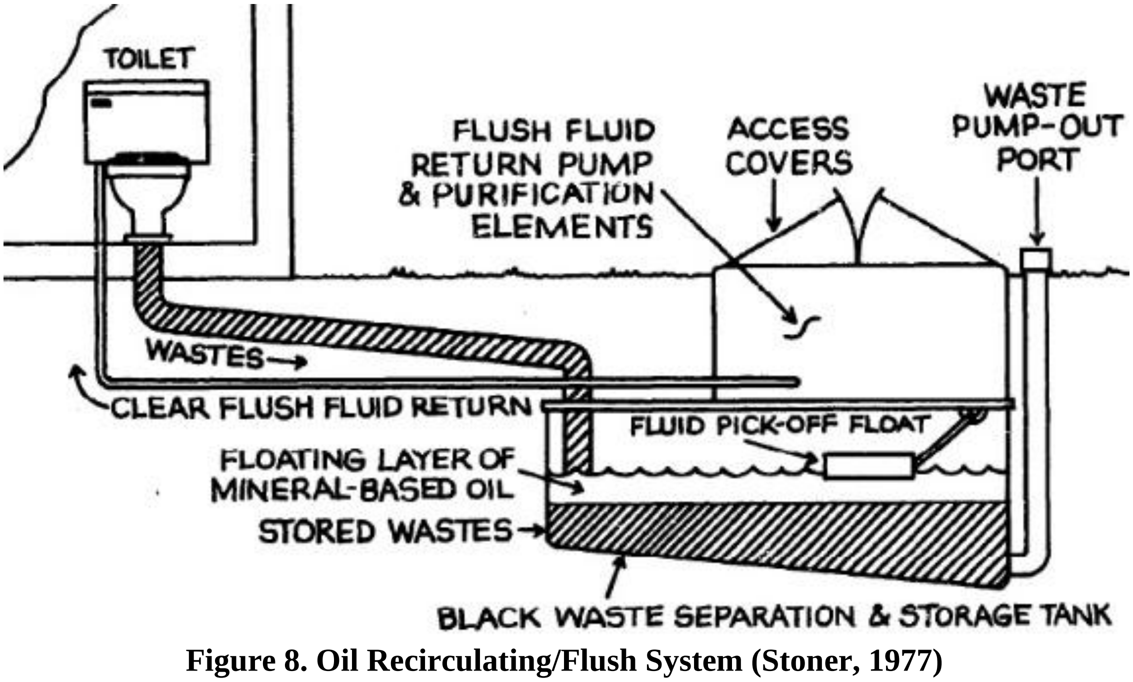


Figure 8. Oil Recirculating/Flush System (Stoner, 1977)

Oil recirculating toilet systems are an option for rural areas where no municipal sewage system exists, especially where installation of septic systems is impractical or prohibitively expensive due to shallow soils, deep slopes, high groundwater levels or extremely cold weather conditions. Systems are also a solution for remotely located roadside rest areas, where connection to a piped sanitary system is impractical and cost prohibitive. Oil recirculating systems are Coast Guard-approved for marine use. Marine vessels are usually prohibited from discharging untreated waste into bodies of water and must either hold accumulated wastes in tanks or must treat before discharge. Systems can also be utilized in areas where water is scarce. Lastly, systems are an option in areas with concerns regarding existing sewage disposal practices, especially seepage of contaminants into local water supplies from improperly functioning septic or other treatment systems, or exposure of residents to improperly dumped waste products from rudimentary collection pails, or “honey buckets” (EPA, 2000).

While oil recirculating systems have the advantages of being closed loop waterless systems with applications in several conditions, there are some disadvantages to using such systems. For one, maintenance costs and operating costs are significant and associated with fixing leaks and other system malfunctions. As of 2000, most or possibly all of the U.S. companies that once made recirculating toilets have since discontinued production of these systems. As a result, cost estimates for package systems are currently not available (EPA, 2000) In 1975, one manufacturer, Monogram Industries, Inc., (Venice, CA) had its Magic Flush oil recirculating toilet system priced between $3,020 (1 unit) and $15,680 (8 units) (approximately $13,000 and $66,000 at current worth accounting for inflation) (USDA, 1975; BLS, 2013). Another disadvantage is that complete separation of waste and oil can be disrupted by the emulsion formation between oil and urine. In addition, the oil media cannot be recirculated indefinitely. After prolonged use, the oil can become discolored and unpleasant smelling, warranting replacement of the oil media. Since the system requires a storage tank and equipment for separation and purification, a relatively large space is required for a complete system. Lastly, since oil is not completely separated from the waste, disposal of separated waste products may be problematic due to oil content (EPA, 2000).

2.5. Comparative Analysis of Toilet Sanitation System Selection

Multiple authors have attempted to formulate a standard set of criteria for selecting a sanitation system (Kalbermatten *et al.*, 1982; Franceys *et al.*, 1992; Navarro, 1994; Loetscher, 2002; Fabrega, 2007; WRC, 2007). Lists of criteria include land and water availability, proximity to groundwater table, terrain conditions, housing density, operating costs, institutional requirements, reuse potential, and more (Fabrega, 2007). One overarching criterion for selection of a sanitation system for application within informal settlement is local context, which includes social, economic, and political factors. Software developers (Kalbermatten *et al.*, 1982; Franceys *et al.*, 1992; Navarro, 1994; Loetscher, 2002; Fabrega, 2007; WRC, 2007) have created sophisticated models with algorithms capable of assessing the performance of varied sanitation system options against a list of evaluative criteria. One model developed by Fabrega (2007) uses information to serve as a tool for aiding decision-making in sanitation system selection within the informal settlements of South Africa. The aim of tools like the Fabrega model and others is to assist city officials, planners, and communities in the decision process for selecting suitable sanitation solutions for a specific area (Fabrega, 2007).

The main objective of this thesis was to select a sustainable sanitation system for application within the Zwelitsha community. Rather than utilize a specific software system, a four step approach was used to recommend a sanitation system:

1. Gather information about place of interest;
2. Research potential systems;
3. Form evaluative criteria; and
4. Select and design a system based on the criteria.

The sanitation provisions in and needs of Zwelitsha as well as other aspects important to the decision making process were presented in Chapter 1. The available toilet system options were discussed in Chapter 2. The third step in the decision making process was the formation of evaluative criteria against which each sanitation system can be assessed for local applicability (discussed here). The fourth step was the evaluation of each system and the selection of a system (see section 2.5.1).

As a reminder, Zwelitsha is an informal settlement of Cape Town where water and sanitation provision is poor. For its 604 residents, there is not a single functional toilet and only one functional tap (ISN *et al.*, 2011). Additionally, there is a need for more streets to improve access into and out of the settlement. In a settlement (Langrug) where there is only a 40% provision of electricity to all households, Zwelitsha comprises the majority of the households without electricity that resort to paraffin as an energy source (ISN *et al.*, 2011). Flooding is also a frequent experience within the settlement.

As presented in Chapter 2, urine diversion dehydration, urine diversion, composting, incinerating, and oil recirculating toilet systems were identified as potential systems for Zwelitsha. Considering the Zwelitsha context and the toilet system information jointly, the following list of criteria was formulated:

1. <u>Sewer Connection</u>: System requirement of a sewer connection for waste disposal. Zwelitsha lacks sewerage infrastructure greatly inhibiting the successful use of a system requiring a sewer connection.
2. <u>Water Connection</u>: System requirement of a water connection for operational purposes. In Zwelitsha, the provision of water is poor. Any potable water entering the settlement is better used for drinking purposes rather than used for flushing away human wastes.
3. <u>Usable Product</u>: Byproducts of system that can be reused. Commercializing valuable products can advance the local Zwelitsha economy. Product sale or reuse reduces wastes.
4. <u>Energy Dependent Components</u>: System components requiring energy to function. A majority of Zwelitsha is without electricity. Residents use paraffin to meet energy needs. Systems requiring an energy source to operate stress the existing deficit in electricity and reliance on paraffin.
5. <u>Waste Disposal Requirement</u>: Waste disposal requirement for system in addition to sewerage. Systems requiring vehicles and personnel from outside the settlement to enter Zwelitsha and collect wastes for removal face several challenges. There are limited accessible roads to service vehicles, the high density of shacks complicates the construction of disposal systems onsite, and the Stellenbosch Municipality fails to adequately provide refuse disposal services .

6. Cost per Unit: Typical cost for each toilet unit installed. The cost of different sanitation options is a very important variable for the decision whether to invest or not, and for the choice of technology (Parkinson *et al.*, 2012). Zwelitsha residents are low income earners, so high cost is a prohibitive factor for any system (ISN *et al.*, 2011).
7. Areas of Use: Areas in which system is typically used and/or most suited for use. Some areas may be more suited than others for certain sanitation systems. For Zwelitsha, systems should be appropriate for use in remote, water-scarce areas that do not have sewerage, a reliable 24 hour power supply, or a large plot of land.
8. Safety Concerns: Associated safety concerns with system use and/or operation. As it stands, Zwelitsha and its sanitation systems are unsafe. It is important that systems do not add more safety concerns to an already unsafe environment. If possible, systems should make an area safer.
9. Other: Additional salient features necessitating consideration for system evaluation. Other features beside the first seven criteria may render a system inadequate or warrant a further consideration of the system for use in Zwelitsha.

In determining this list of evaluative criteria, both fixed and variable system features were considered. Fixed features are intrinsic to systems and do not vary with system design. Variable features can differ with system design. Fixed features can often render a system infeasible whereas variable features offer flexibility in design. A major assumption of the evaluative criteria is the perpetuation of current conditions within Zwelitsha. Consequently, without intervention, these conditions are fixed features of Zwelitsha. The delineated criteria were determined with the aim of including fixed features of Zwelitsha that would rule out systems with fixed features that were not compatible with them. For example, a majority of Zwelitsha is without electricity, so electrically-dependent components are infeasible. Thus, electrical dependence is a fixed feature that will render a system inadequate for use in Zwelitsha. Thus, only systems with fixed features that do not conflict with Zwelitsha conditions and/or variable features that can accommodate Zwelitsha conditions are considered feasible options.

2.5.1 Toilet Systems Applicable to Zwelitsha

This section evaluates each system per the chosen criteria from section 2.5. Table 2 shows the evaluative criteria with a comment for each system regarding each criterion. The purpose of evaluating each system against the chosen criteria was to select technically feasible ones for further consideration. Decisions based on the characteristics of sanitation systems are limited by the suitability of a system to the specific conditions of the selected region, in this case, the settlement of Zwelitsha (Fabrega, 2007). As a result, the determination of technical feasibility should be performed according to constraining criteria inherent to each system per the particular conditions of the settlement.

Table 2. Toilet Systems and Evaluative Criteria

	Systems					
	Urine Divergent		**Composting**	**Incinerating**		**Oil Recirculating**
Criteria	**UD**	**UDDT**		**Electric-powered**	**Gas-fired**	
Sewer Connection	Required	Not required	Not required	Not required	Not required	Not required
Water Connection	Required	Not required	Not required	Not required	Not required	Not required
Usable Product	Urine fertilizer	Urine fertilizer	Nutrient-rich humus	Sterile ash	Sterile ash	Depending on oil content can get compost
Energy Dependent Components	None	None	Varies from none to electrical vent fans, water spray and waste turner	System powered by electricity	System powered by gas	Flush fluid return pump
Waste Disposal Requirement	Sewer, treatment for brownwater, and urine reuse	On-site collection, treatment, and reuse or off-site sale/use of urine	On-site collection, treatment, and reuse or off-site sale/use of compost	Ash reused in agriculture or collected and disposed of off-site		Waste must be pumped from storage tank, can be incinerated, composted or disposed of off-site
Cost per Unit	$675 - $1,500	$35 - $600	$10 - $10,000	$4,000 (Gas-fired); $1,499 -1,878 (Electric-powered)		$8,200 - $13,000
Areas of Use	Areas with established infrastructure for wastewater treatment and disposal	Water-scarce areas		Areas with reliable 24 hour electrical power or oil, gas, propane supply		Rural areas with no sewage system where septic systems are infeasible, remote areas without piped sanitary system, water-scarce areas
Safety Concerns	Improper reuse of usable product			Electrical fire or gas leak explosion		Oil-contaminated waste products
Other	Lower volumes of water (0.5 to 2 L) used per flush compared to flush toilets (8 to 12 L)	User education regarding system use and proper maintenance required		Incinerating cycles take between 1.5 - 4 hours, between a tablespoon and a cup of sterile ash is produced after each cycle		Large area requirement, incomplete oil separation from waste makes disposal problematic

It was determined that any system requiring either a sewer or water connection would be technically infeasible in Zwelitsha. As shown in Table 2, UD toilets require both connections and are considered infeasible for use in Zwelitsha. Another factor in Zwelitsha is the absence of electricity. Thus, incinerating toilet systems will not be appropriate. Both electric-powered and gas-fired incinerating toilets require energy sources to operate. Furthermore, incinerating toilets have associated safety concerns. Sanitation systems in Zwelitsha are already unsafe due to crime and waterborne diseases. Worsening the situation by the threat of electrical fire and gas explosions is undesired.

The three remaining systems (UDDT, composting, and oil recirculating) are all applicable to water-scarce areas. Each toilet system was reviewed based on technical limitations posed by Zwelitsha conditions, considering that each system has some variability in design. For instance, Zwelitsha lacks electricity provision, and energy dependent components are a variable feature of both composting and UDDTs. Either system can be designed with or without energy dependent components without affecting system functionality. Oil recirculating toilet systems, however, are designed with energy-operated flush fluid return pumps. Waste disposal requirement is another technical limitation of Zwelitsha that is a variable feature for some toilet systems (UDDT, composting, incinerating) and intrinsic to others (UD, oil recirculating). It is also a feature that renders oil recirculating toilet systems infeasible in Zwelitsha. Waste from an oil recirculating system must be pumped from a storage tank. Like in composting and UDDT systems, this waste can be composted or disposed of offsite, but, unlike in these systems, vehicles must navigate the congested settlement to pump the waste onsite prior to composting or disposal offsite. Oil-recirculating systems are also no longer manufactured in the United States and are historically expensive systems. Other negative features of oil recirculating systems are a large area requirement, no usable product if oil content is too significant, and problematic disposal due to incomplete separation of oil from wastes.

UDDT and composting toilet systems were determined to be the most technically feasible in Zwelitsha per the chosen evaluative criteria. Neither system requires a sewer or water connection. Each can be designed without necessitating energy dependent components or additional waste disposal (in the case where urine storage and fecal composting follow in each system). Both systems have the capability of generating usable products, pose no safety concerns if wastes are handled properly, and can be utilized in water-scarce areas like Zwelitsha. Lastly, UDDT and composting toilet units can be relatively inexpensive when compared to the other systems investigated.

The greatest potential for composting and UDDT toilet systems is the elimination of wastes via the reuse of human excreta. This potential is also a possible limitation of the system despite its technical feasibility in Zwelitsha. Therefore, sufficient attention must be paid to handling wastes after system use. As a result, the following chapter discusses the products attainable from human excreta through proper use of UDDT and composting toilet systems.

Chapter 3: Products from Human Excreta

Human excreta contain portions of all important nutrients and organic matter necessary for crop production. In fact, there is almost a balance between the nutrients consumed by humans in the foods they eat and the nutrients excreted by humans in urination and defecation (Richert *et al.,* 2010, Gensch *et al.,* 2011). Adults excrete the same mass of nutrients as taken up in their diets. Between the ages of 3 and 13, children retain small amounts (less than 2%) of consumed nitrogen and phosphorus for bone growth (Schönning, 2001). In toilet systems where human excreta are directed to sewer systems, the nutrients contained in the excreta are directed into surface water systems as pollutants. Human excreta contain the major proportion of the nutrients from households (Vinnerås *et al.,* 2006). In a sustainable society, human excreta have to be recycled to close the nutrient loop (Figure 1) (Vinnerås, 2007). With proper management and handling, human excreta can be converted into useful and safe agricultural products. These products can fertilize soil with the nutrients from human excreta, and the crops produced from this soil provide people with nutrient-rich food. Thus, sustainable sanitation options that recycle human excreta are integral to closing the nutrient loop. The following sections examine the nutrient value and reuse of human excreta in the form of agricultural products.

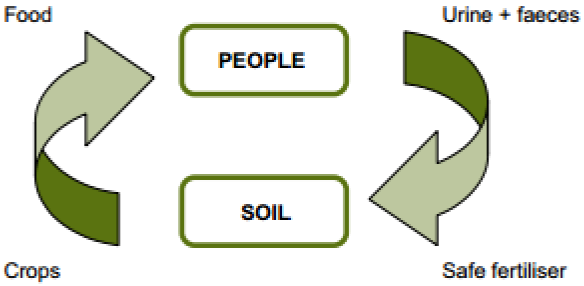


Figure 9. Closing the Nutrient Loop (Gensch *et al.*, 2011)

3.1 Sterile Urine Fertilizer

Urine is secreted by the kidneys in the human body and consists of 95% water. The remaining 5% is made up of soluble wastes and excess substances of the human body like urea, creatinine, dissolved ions (e.g., chloride, sodium, potassium), inorganic and organic compounds or salts (Richert *et al.*, 2010). Macronutrients, or larger portions of the soluble substances in urine, like nitrogen (N), phosphorous (P), potassium (K), and sulphur (S) are essential plant nutrients. In addition to these nutrients, smaller concentrations of micronutrients like sodium and chloride are available in a form that can be absorbed by plants (Münch and Winker, 2011; Gensch *et al.*, 2011). As a result, urine has been used effectively as a plant fertilizer.

Nitrogen is the most abundantly available nutrient in urine occurring mostly as urea. Phosphates and potassium occur in comparatively lower concentrations, in dissolved forms available to plants (Richert *et al.*, 2010). A person produces about 5 kg per year of nitrogen in his/her excreta. On average, approximately 80% of the total nitrogen present in human excreta is contained in urine (Jönsson *et al.*, 2004; Münch and Winker, 2011). Nitrogen is frequently the most limiting nutrient for plant growth, and the use of nitrogen is usually higher than the total use of the other macronutrients and micronutrients together (Gensch *et al.,* 2011). Consequently, urine has potential as a nitrogen-rich fertilizer. Still, the nitrogen demand for different crops may vary considerably, as shown in Table 3. Due to the high nitrogen content in urine and varying nutrient demands of different crops, urine is often applied until the specific nitrogen demand of the crop being fertilized is met. In general, urine should be applied until the first macronutrient (N, P, K, or S) reaches its optimum level for the crop. Beyond this point, over-fertilization of the other macronutrients to the crops can occur (Münch and Winker, 2011).

Table 3. Nitrogen demand of different plants (adapted from Gensch et al., 2011)

Nitrogen demand of plants	**Example Plants**	**Approximate N-demand of plants (kg/ha/year)**
Low	Herbs, Beans, Peas, Lettuce	45
Medium	Onion. Pepper, Potato. Rice,	100
High	Corn, Tomato, Spinach, Eggplant	160

Based on Swedish data, nutrients contained in urine are estimated at 4 kg N/cap/yr, 0.36 kg P/cap/yr and 1.0 kg K/cap/yr (Jönsson *et al.,* 2004). As urine composition depends on diet, the mass of nutrients in urine differs by population and therefore must be verified onsite (Münch and Winker, 2011). Table 4 presents the estimated excretion of nutrients [by mass] per capita per year from the urine produced by people of several countries. The values for Sweden are widely recognized and used (Richert *et al.,* 2010) for urine nutrients, as many measurements on excreta have come from Sweden.

Table 4. Estimated excretion of nutrients from urine per capita in different countries (Jönsson and Vinnerås, 2004; Richert *et al.*, 2010)

Country	**Nitrogen (kg/cap, year)**	**Phosphorus (kg/cap, year)**	**Potassium (kg/cap, year)**
China	3.5	0.4	1.3
Haiti	1.9	0.2	0.9
India	2.3	0.3	1.1
South Africa	3.0	0.3	1.2
Uganda	2.2	0.3	1.0
Sweden	4.0	0.4	1.0

It is important to determine the nutrients attainable from urine. In fact, comparing urine concentrations to the needs of crops is paramount to achieving urine application that is competitive with commercially-available synthetic mineral fertilizers, especially those that are ammonia and urea-based. Fertilizers are characterized by their NPK ratios, or the ratio of nitrogen to phosphorous to potassium nutrient levels. Table 5 shows the nitrogen, phosphorous, and potassium excretion per capita per annum and the NPK ratio for urine in South Africa (the area of interest for this thesis). All NPK values have been rounded to integers and; therefore, are not exact values.

Table 5. NPK ratio for urine in different countries (Jönsson and Vinnerås, 2004; Richert *et al.*, 2010)

Country	**Ratio**		
	N	**P**	**K**
China	9	1	3
Haiti	10	1	5
India	8	1	4
South Africa	10	1	4
Uganda	7	1	3
Sweden	10	1	3

Urine can mimic or supplement fertilizers to achieve desired NPK ratios for meeting plant nutrient demands. Table 5 shows that a nitrogen-rich fertilizer can be produced from urine in South Africa with an NPK ratio of 10:1:4. This NPK would be ideal for plants requiring nitrogen, phosphorus, and potassium in this exact ratio of macronutrients. The nutrient demands for crops can vary widely (FAO, 2005). Still, the fertilizing effects of nutrients in urine are the same as those of artificial mineral fertilizer if the same amount of nutrients is applied to a crop (Münch and Winker, 2011). For example, say, a crop requires a recommended rate of 60 lb N/acre and there are two fertilizer choices. The first option is the fertilizer Urea with an NPK ratio of 46:0:0 (Gensch *et al.*, 2010). The second is urine from the South African population with an NPK of 10:1:4. The rate of application for Urea (46:0:0) would be the desired rate (60 lb N/acre) divided by the percentage of the desired nutrient (N) in the urea (0.46). This gives a rate of application for Urea of approximately 130 lb Urea/acre to satisfy the recommended rate of nitrogen nutrient for the crop in this example. The rate of application of South African urine (10:1:4) would then be the desired rate (60 lb N/acre) divided by the percentage of the desired nutrient (N) in the urine (0.10). This gives a rate of application for South African (10:1:4) of approximately 600 lb South African urine/acre. As expected, a larger amount of South African urine was required than the more nitrogen-rich Urea fertilizer. Nonetheless, applying 130 lb Urea/acre or 600 lb South African urine/acre would satisfy a nitrogen application rate of 60 lb/acre.

If in-situ data are not available or cannot be easily measured, the nutrient levels and consequently NPK ratio of a urine sample can be estimated from the volume of urine produced. Design figures estimate the following concentrations of macro-nutrients in urine: 7,300 mg/L N; 670 mg/L P; and 1,800 mg/L K (Münch and Winker, 2011). The quantity of urine produced by an adult is around 0.8 to 1.5 L per adult per day (WHO, 2006), and mainly depends on the amount a person drinks and his or her perspiration (Münch and Winker, 2011). Specifically, urine production is directly proportional to liquid consumption and inversely proportional to perspiration. Children produce approximately half as much urine as adults. Based on Swedish data, 1.5 L/cap/d (or 550 L/cap/yr) is the average urine production and is a widely used design figure (Münch and Winker, 2011). Using this design figure along with the one for macro-nutrient concentrations in urine, the nutrient mass in urine of a population can be estimated. This is done by multiplying the macro-nutrient concentration by the volume of urine production with the appropriate unit conversion factors (Equation 1). This is how the Swedish values for nutrients in excreted urine, included in Table 4, were determined. The same calculations can be performed for systems where urine volume can be measured. An example calculation is shown in Equation 1.

$$\text{Annual Nitrogen Mass per Person}\left[\frac{\frac{\text{mg}}{\text{cap}}}{\text{Yr}}\right] = 7300\,\frac{\text{mg}}{\text{L}}\text{N}\times\left(\frac{10^{-6}\text{kg}}{\text{mg}}\right)\times 550\,\frac{\frac{\text{L}}{\text{cap}}}{\text{yr}} \qquad \textbf{(Equation 1)}$$

$$\text{Annual Nitrogen Mass per Person} = 4.0\ \frac{kg\ N}{\frac{cap}{yr}}$$

In addition to its high nutrient content, urine has low and manageable health risks. When excreted, urine from a healthy person is sterile and pathogen-free. Furthermore, for persons carrying diseases, most of the actual pathogen load in human excreta is associated with the feces rather than the urine (Münch and Winker, 2011; Gensch *et al.*, 2011). Nonetheless, even in source-separating systems such as UDDTs, cross-contamination with fecal material is possible (Gensch *et al.*, 2011). According to the WHO, from a risk perspective the only disease which needs to be considered prior to urine reuse in agriculture is *Schistosoma haematobium*, and only in areas where the disease is endemic (WHO, 2006). Thus, treatment of urine before application as an agricultural fertilizer is recommended for control of *Schistosoma haematobium* and of pathogens that may enter the urine due to cross-contamination with feces. Table 6 presents recommendations for the simplest, least expensive, and most common method used in treating urine for pathogen kill, extended storage (Münch and Winker, 2011).

Table 6. Recommended guideline storage times for urine mixture[a] based on estimated pathogen content[b] and recommended crop for larger systems[c] (WHO, 2006)

Storage Temp.	Storage Time	Possible pathogens in the urine mixture after storage	Recommended crops
4°C	≥ 1 month	Viruses, protozoa	Food and fodder crops that are processed
4°C	≥ 6 months	Viruses	Food crops that are processed, fodder crops[d]
20°C	≥ 1 month	Viruses	Food crops that are processed, fodder crops[d]
20°C	≥ 6 months	Probably none	All crops[e]

[a] Urine or urine and water. When diluted it is assumed that the urine mixture has at least pH 8.8 and a nitrogen concentration of at least 1 g/L.

[b] Gram-positive bacteria and spore-forming bacteria are not included in underlying risk assessments, but are not normally recognized as causing infections of concern.

[c] A larger system in this case is a system where the urine mixture is used to fertilize crops that will be consumed by individuals other than members of the household from which the urine was collected.

[d] Not grasslands for production of fodder.

[e] For food crops that are consumed raw, it is recommended that urine be applied at least one month before harvesting and that it be incorporated into the ground if edible parts grow above the soil surface.

Sources: Adapted from Jönsson *et al.*, 2000; Höglund, 2001.

For larger systems (community level) where cross-contamination with urine cannot be ruled out, it is highly recommended that urine be stored for no less than a period of 30 days if used on food or fodder crops that are to be processed. Extended storage of 6 months provides a higher safety margin where urine can be used on all crops (Münch and Winker, 2011). A study conducted by Vinnerås *et al.* (2008) suggested that if the ammonia level in urine is greater than 2 mg N/L (which it should be for undiluted urine), then shorter storage times may also be sufficient. On the household level urine storage is unnecessary. This is because disease transmission within the household via the urine-oral route is much less likely compared to transmission via day-to-day contact of household members (WHO, 2006; Münch and Winker, 2011). For systems where cross-contamination of urine with feces is definitely not occurring, urine storage is also unnecessary. Still, it may be difficult to ensure that cross-contamination is not occurring within a system so if there is any doubt urine storage should follow the recommendations in Table 6.

Table 7 shows the different characteristics of fresh urine versus stored urine. Here, "stored urine" means urine which is completely hydrolysed (Udert *et al.*, 2003), and this typically occurs within 2 -4 weeks depending on the amount of urease present (Maurer, 2007).

Table 7. Average Chemical Composition of Fresh and Stored Urine (Udert *et al.*, 2006)

Parameter	**Fresh urine**	**Stored urine**
pH	6.2	9.1
Total nitrogen, TN (mg/L)	8830	9200
Ammonium/ammonia-N, NH_4^+ and NH_3 (mg N/L)	460	8100
Nitrate/nitrate NO_3 + NO_2 (mg N/L)	0.06	0
Chemical oxygen demand, COD (mg/L)	6,000	10,000
Total phosphorus, TP (mg/L)	800-2000	540
Potassium, K (mg/L)	2740	2200
Sulphate, SO_4 ($mgSO_4/L$)	1500	1500
Sodium, Na (mg/L)	3450	2600
Magnesium, Mg (mg/L)	120	0
Chloride, Cl (mg/L)	4970	3800
Calcium, Ca (mg/L)	230	0

As exhibited by Table 7, the chemical composition of urine changes after storage. Explained in section 2.2.1, storage initiates urine sanitization where urease, a naturally present urine enzyme, decomposes or hydrolyses urea. The decomposition of urea leads to the formation of ammonia/ammonium and hydrocarbonate. Urea hydrolysis raises the urine pH to around 9 leading to pathogen kill. Table 7 displays information quantifying the chemical transformation described by this sanitizing process. Fresh urine has an average pH of 6.2; following storage, average urine pH was found to be 9.1. The average total nitrogen (TN) increased from 8,830 mg/L in fresh urine to 9,200 mg/L in stored urine (Münch and Winker, 2011). When urea hydrolyses nitrogen, it is released in the form of ammonia. Compounds and ions with low solubility like Ca^{+2} and Mg^{+2} precipitate out increasing the concentration of nitrogen in the urine (Maurer *et al.*, 2006). Fresh urine contains nitrogen mainly in the form of urea; upon urea hydrolysis from urine storage, nitrogen is found mainly in the form of ammonium/ammonia (Münch and Winker, 2011). Although stored urine has increased nitrogen levels, phosphate, magnesium and calcium concentrations are lower due to precipitation processes during storage (Münch and Winker, 2011).

3.2 Fecal Compost

Feces are discharged from the large intestine of the human body, and are normally made up of 75% water and 25% solid matter. The approximate composition of this solid matter is: 20% dead intestinal and blood cells and bacteria; 30% indigestible food matter such as fiber; 10 to 20% steroids, bile acids, and other lipids; 10 to 20% inorganic substances such as calcium phosphate and iron phosphate; and 10% proteins (Lin *et al.,* 2007). Human feces are rich in phosphorus and potassium, which as discussed before, are crucial plant nutrients (Heinonen-Tanski and van Wijk-Sijbesma, 2005). These nutrients are present within feces in ionic form making them readily available to be absorbed by soil (Kirchman and Petterson, 1995). Since most of the nitrogen in human excreta is contained in urine (only 20% in feces), feces is not a nitrogen-rich fertilizer (Jönsson *et al.,* 2004 from Münch and Winker, 2011). Within feces, nitrogen is only slowly released as it is organically bound in undigested food remains (Kirchman and Petterson, 1995). The high content of phosphorus and potassium contribute value for feces as a fertilizer for those nutrients. In addition, the high carbon content of feces makes feces a valuable soil conditioner. Higher levels of organic matter in soils correspond to better soil structure, more resistance to droughts and less erosion from heavy rains and floods (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Studies have also shown that increasing the organic matter present in soil makes plants more tolerant to salinity (Engel *et al.,* 2001; Smith *et al.,* 2001; Heinonen-Tanski and van Wijk-Sijbesma, 2005). Thus, feces have great potential for improving the fertility of impoverished soils as fertilizers and soil conditioners (Vinnerås *et al.,* 2003; Mnkeni and Austin, 2009)

Just as in urine, the composition of feces largely depends on a person's diet as well as a region's climate and the person's weight and water intake (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Thus, the composition of feces must be verified onsite in order to determine the amount of feces needed to meet the nutrient demands of certain crops and soils. Accepted average values gathered from Sweden for nutrients contained in feces include 0.55 kg N/cap/yr, 0.18 kg P/cap/yr and 0.4 kg K/cap/yr (Jönsson *et al.,* 2004*;* Münch and Winker, 2011; Jönsson *et al.,* 2005*;* Heinonen-Tanski and van Wijk-Sijbesma, 2005). Average values for South Africa (the area of interest for this thesis) are 0.42 kg N/cap/yr, 0.24 kg P/cap/yr and 0.21 kg K/cap/yr. These values translate to an NPK ratio of 1.75:1:0.88. This is a more evenly balanced fertilizer than South African urine (10:1:4). Since plants do not require nutrients in equal amounts, fertilizer in the form of fecal compost should be supplemented with other fertilizers such as urine for additional nutrients (Richert *et al.,* 2010).

Even though urine is a more valuable resource for fertilization than feces, feces can also mimic or supplement fertilizers to achieve desired NPK ratios for meeting plant nutrient demands (Heinonen-Tanski and van Wijk-Sijbesma, 2005). For one, the weighted average nutrient content of urine and feces used together yields a fertilizer with an approximate NPK ratio of 7:1:3 (Richert *et al.,* 2010). As a result, for crops requiring less nitrogen and more potassium, feces used in conjunction with urine can be an alternative to the nitrogen-rich urine fertilizer. More generally, if in-situ data are not available or cannot be easily measured, the nutrient levels and consequently NPK ratio of a feces sample can be estimated from the mass of feces produced. Based on the design figures and the nutrient distribution within human excreta, the following are estimates for concentrations of macro-nutrients in feces: 11 g/kg N; 4 g/kg P; 8 g/kg K (Jönsson *et al.,* 2004; Jönsson *et al.,* 2005; Münch and Winker, 2011).

An adult produces about 0.14 kg of feces per day or about 50 kg a year (Jönsson *et al.,* 2004; Vinnerås *et al.,* 2006). Using this figure along with the one for macro-nutrient concentrations in feces, the nutrient mass in feces of a population can be estimated. This is done by multiplying the macro-nutrient concentration by the mass of feces production with the appropriate unit conversion factors (Equation 2). The same calculations can be performed for systems where feces mass can be easily measured. Instead of using the design figures, calculations can divide macro-nutrient concentrations by the measured feces mass produced by a specific population.

$$\text{Annual Nitrogen Mass per Person}\left[\frac{\text{kg N}}{\frac{\text{cap}}{\text{yr}}}\right] = 11\,\frac{\text{g N}}{\text{kg}} \times \frac{10^{-3}\text{kg}}{\text{g}} \times 50\,\frac{\text{kg N}}{\frac{\text{cap}}{\text{yr}}} \quad (\textbf{Equation 2})$$

$$\text{Annual Nitrogen Mass per Person } = 0.55\,\frac{\text{kg N}}{\frac{\text{cap}}{\text{yr}}}$$

Feces can contain enteric bacteria, viruses, protozoa and helminth eggs (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Due to the high possible pathogenic load, feces must be sanitized to inactivate pathogens before it can be used as a fertilizer and soil conditioner. Here, “sanitized” refers to point at which pathogens have been inactivated or killed-off (Vinnerås *et al.*, 2003). Feces can be sanitized via incineration, which produces a sterile ash that can be used on gardens. Feces can also be sanitized via chemical treatment. In places where dry sanitation is used, a common method for treatment is addition of ash or lime for raising the pH and drying the surface of the fecal matter after defecation, combined with long-term storage (Vinnerås, 2007). The most common method for sanitizing feces is composting (Vinnerås, 2007). Composting is a self-heating microbial aerobic degradation of organic wastes (Niwagaba *et al.*, 2009). The resulting microbial respiration produces heat (Huag, 1993). This heat along with extended storage leads to the inactivation of pathogens in the waste.

Just as there are several methods for sanitizing feces, there are several options for composting. These include open windrows and static piles, agitated beds, rotating drums, aerated containers, in-vessel continuous flow, vermicomposting, and thermophilic composting (BioSystems, 2013a). Heat inactivation, or pasteurization, through thermophilic composting is one of the most reliable methods for sanitation (Vinnerås, 2007). Thermophilic composting is an aerobic process that produces optimal conditions in which oxygen-using bacteria can thrive within a composting mass. In order for the process to work and create a final sanitized product, many different kinds of bacteria must be maintained within the compost. This facilitates the expedient destruction and breakdown of organic materials, giving off heat as part of the biological reaction (BioSystems, 2013b). As more material is degraded and more heat is generated, different types of bacteria rapidly grow and thus thrive. Initially, pychrophilic bacteria are working within a composting mass. These bacteria give off small amounts of heat working at temperatures as low as -18°C. The optimal temperature for these bacteria to decompose is 13°C. The heat released at this point accumulates leading to the rapid growth of the next group of bacteria, the mesophilic, or middle range temperature bacteria. Mesophilic bacteria thrive from 21°C to 32°C, but just survive at temperatures above and below (4°C to 21°C, and 32°C to 43°C). In many backyard compost piles, these middle range bacteria do most of the work. However, if conditions are right they produce enough heat for thermophilic, or heat loving bacteria to thrive (BioSystems, 2013b). As implied by the process name, rapid growth of thermophilic bacteria is the goal of thermophilic composting. Thermophilic bacteria work rapidly to degrade compost. Their optimum temperature range is from 40°C to 71°C. The continual generation of heat by thermophilic bacteria leads to the rapid growth of more thermophilic bacteria until all of the original organic material is digested and broken-down into a stabilized and homogenized nutrient rich soil product (BioSystems, 2013b).

The process of thermophilic composting begins with agglomerating wastes in a holding vessel, such as a bin or container. The compiled waste will naturally generate heat [from microbial activity] within the holding vessel. Time is given for the waste to sit and decompose. Over time sustained thermophilic heat (>40°C) sanitizes the waste via pathogen kill and reduces the overall waste volume. The time-temperature combinations lethal to all pathogens excreted in faeces have been reported to be: 1 h at > 62°C; 1 day at > 50°C; and 1 week at > 46°C (Feachem *et al.*, 1983; Niwagaba *et al*., 2009). Depending on composting conditions, the degradation of the organic matter in compost can lead to the reduction of up to 90% of the original volume (Berger, 2011). The final product is a nutrient-rich humus that can safely be recycled (Vinnerås *et al.,* 2003). All types of organic material can be composted via thermophilic composting. This can be done in a homogeneous mix of one type of organic material or in a heterogeneous mix of multiple organic types. Examples include source-separated fecal matter (feces and toilet paper), and food waste and garden waste alone or in combination with each other and/or urine (Vinnerås *et al.*, 2003). Studies suggest that co-composted feces and food waste in a properly managed composting reactor achieves thermophilic temperatures more quickly than either fraction alone and than other mixes. Additionally, whereas other mixes achieve thermophilic temperatures, none sustain them for longer than the co-composted feces and food waste mix. This is significant, since sanitation requires sustained thermophilic temperatures for periods of up to a week for total pathogens kill (Vinnerås *et al.,* 2003, Niwagaba *et al.,* 2009).

Generally, a higher organic content results in a greater decomposition of wastes. This is because the microbial oxidation of carbon into carbon dioxide (CO_2) is an exothermic process that releases heat into the compost heap. Without this heat, temperatures will not be sufficient to initiate rapid growth of thermophilic bacteria. Unlike other nutrients in the compost, carbon has a dual role. As bacteria feed on organic matter, nitrogen, phosphorus, carbon, and other nutrients become a part of their component make-up. Additionally, carbon is a source of energy through its oxidization into carbon dioxide. Because of the dual role of carbon, a much larger portion of carbon is needed when compared to nitrogen to achieve thermophilic sanitation (BioSystems, 2013b). The optimum carbon-to-nitrogen (C/N) ratio is 30-40/1 (Berger, 2011).

Water-soluble carbon and nitrogen present in compost are readily available for microbial consumption (Chanyasak and Kubota, 1981). During decomposition, microbes oxidize 60% to 70% of the C as CO_2 and incorporate (immobilize) only 30–40% of the C into their body as cellular components (Henis, 1986; Barrington *et al.*, 2002). Thus, for example, in a waste mixture with a C/N ratio of 30 and with 40% of its C available, only 12 kg of C are available for each kg of N. Out of this 12 kg of available C, only 40% or 4.8 kg will be immobilized along with 0.6 kg of N. The amount of immobilized N is based on N being 100% available and a C/N ratio of 7 for the immobilized microbial mass. Thus, this compost containing 30 kg of total C for each 1 kg of total N can only fix 0.6 kg of N. The remaining 0.4 kg (40%) of N for each initial 1.0 kg of N ends up lost through volatilization (Barrington *et al.*, 2002).

Volatilization of N is the process by which N is lost to the environment via the conversion of ammonium to ammonia gas (NH_3). The nitrogen content of feces has organic and inorganic parts. The organic nitrogen content is retained throughout the composting process. However, fecal NH_4-N, which is the main component of the inorganic nitrogen (>90%) decreases rapidly under thermophilic conditions. It is eventually depleted under sustained thermophilic conditions. This is attributed to the volatilization of nitrogen through the conversion of ammonium to gaseous ammonia (Bai and Wang, 2010). By connecting an ammonia absorber to a thermophilic compost reactor, Bai and Wang (2010) found a mass balance between exhausted NH_3 and the initial fecal NH_4-N content. It was also observed that organic nitrogen content, which comprises about 80% of fecal nitrogen, remained unchanged through the composting process (Bai and Wang, 2010). This organic nitrogen content is immobilized or consumed by microbes during composting; immobilization is temporary and when the microorganisms die, the organic nitrogen contained in their cells is converted to plant available nitrate (NO_3) (Johnson *et al.,* 2005). Thus, due to its retention of organic nitrogen in compost, thermophilic composting is a valuable method for producing higher quality fertilizer. Additionally, from thermophilic composting, nitrogen volatilization represented not even 20% of total fecal nitrogen (Bai and Wang, 2010). This is beneficial since ammonia volatilization is a source of acid rain, reduces the fertilizer value of waste, and thus inhibits the sale of valuable fertilizer (Barrington *et al.,* 2002).

3.2.1 Insulation and Cover Material

Although carbon availability in waste plays a major role in N immobilization, the organic content of compost alone is not enough to reach desired thermophilic conditions (Barrington *et al.,* 2002). Insulation of the compost is essential in reaching and maintaining thermophilic temperatures. Thermophilic composting is possible even if the ambient temperature is lower than desired thermophilic temperatures. Hot ambient air is not required if heat energy produced by microbial activity within the compost is maintained (Vinnerås *et al.,* 2003). Insulation such as plastic cells or styrofoam is placed along the walls of reactors to keep in heat (Vinnerås *et al.,* 2003; Niwagaba *et al.,* 2009). Cover material placed on top of the composting heap also acts as insulation. Providing adequate insulation allows for use of thermophilic composting in varying climates, from places like Pennsylvania (U.S.) with many seasons to places like Haiti with average temperatures ranging from 24°C in the winter to 28°C in the summer (Oates *et al.,* 2003). Therefore, thermophilic composting can be utilized in Zwelitsha, South Africa, where the average minimum winter temperature is about 7°C and summer temperatures can reach 26°C (CCT, 2012b).

In addition to insulation, cover material has many purposes. Cover material should be compostable like the rest of the compost heap. Good cover material introduces more compostable organics to the compost heap, raising the C/N ratio of the compost. A rise in the C/N ratio increases microbial activity and facilitates thermophilic composting. Cover material should originate from carbon based plant cellulose material in order to promote thermophilic composting. The most popular cover material is sawdust from trees. Other materials include peat moss, rice hulls, and dry plant material [ground into the correct consistency] like coco coir, paper products, and cardboard. Agricultural byproducts like grain chaff, pine needles, coffee grounds, distillery byproducts, and cleanings from woolen mills can also be used. Cover material should not be too coarse. Coarse material, such as wood chips, wood shaving, wood ashes, and lime, inhibits thermophilic composting. The large particles present in coarse materials make the carbon content inaccessible to microbes (Jenkins, 2010). In addition, coarse materials allow bad odors to escape from the composting heap into the system and enable flies to enter the compost. Fine cover material inhibits the formation of voids small enough for odor to escape and flies to penetrate wastes. Voids are large enough for proper aeration of the system.

For systems where composting does not occur within the toilet unit, placing cover material over the collected waste within the unit is unnecessary. This is because the main purpose of cover material is to aid in composting. Still, placing cover material onto collected waste can improve the aesthetics of the system. Cover material can prevent odor and flies within the toilet unit system. When source-separated feces are not composted within the toilet unit, they are transferred to a separate reactor for composting. Within the reactor, cover material is crucial for achieving thermophilic conditions. Cover materials used on compost piles can be coarser than toilet cover materials. These include grasses, hay, straw, pine needles, weeds, leaves, and other organic plant materials that are odor free and do not attract flies (Jenkins, 2010). A fresh layer of cover material should be placed on top of the compost pile every time new waste is added.

Composting reactors allow for the sanitation of larger volumes of feces and other organic wastes than is possible within a single composting toilet unit. Additionally, they keep compost away from children, animals or other vermin, or insects. A reactor should be constructed with a "biological sponge" as its base layer. This layer consists of plant materials such as straw, hay, weeds, and grass piled at the reactor's base as an absorber of excess liquids that may collect when wastes are placed within the reactor (Jenkins, 2010). Reactors can be placed on bare soil with a slightly concave base. The concave base directs excess liquid to the center of the bin. This prevents leaching from the side of the reactor bottom beyond the soil base perimeter. The benefit of a soil base is that beneficial soil organisms, such as earthworms, can migrate into the compost (Jenkins, 2010). Earthworms accelerate composting producing a premium organic soil supplement called vermicompost (BioSystems, 2013c). Reactors can also be constructed on concrete and other hard surfaces. It is important that sufficient material is used in the biological sponge for liquid absorption. During thermophilic composting, excess liquid is rapidly evaporated by the heat produced from microbial activity. Hence, to maintain compost moisture content (optimal 45-60%), rainwater, greywater, and even urine may be used to moisten the mass (Jenkins, 2010; Berger, 2011). With regards to reactor walls, many materials can be used, including wood boards; masonry materials such as bricks, blocks or concrete; straw or hay bales (which can be reused as cover material); bamboo; poles or logs; and wood shipping pallets turned on their sides (Jenkins, 2010).

3.2.2. Proper Maintenance and Monitoring

Proper maintenance and monitoring are integral to safe and effective thermophilic composting. Most importantly, maintenance personnel and operators of a fecal composting system should remember the potentially high pathogen load that could be present in feces. As a result, direct contact with fecal material should be avoided at all times. Precautionary measures include wearing one-way rubber gloves and washing hands after handling wastes. Only mature compost, which looks and smells like rich garden soil or leaf humus should be harvested for reuse (Berger, 2011). All other material should remain in the compost reactor until it has been sanitized. A standard procedure should be implemented to best ensure wastes compost adequately.

The reactor must be prepped before wastes are transferred to the composting reactor from composting toilets, kitchens, gardens, urine divergent systems. Before starting operation, a biological sponge layer should be established at the reactor bottom. Next, on top of this layer, cover material is placed (Berger, 2011). When wastes are ready to be added to the reactor, the cover material should be wet, forming a moist bed for the added material. After the wastes are added, fresh cover material should be evenly distributed across the top completely covering the pile. This will sit until new waste needs to be introduced to the compost pile. The reactor must be prepped before every new addition of waste. New wastes should never be added on top of an existing compost pile. Instead they should be incorporated into the heap (Jenkins, 2010). Starting from the heap's epicenter, a composting tool, such as a pitch fork, can be used to pull away cover material up and against each side wall of the reactor. As this happens, a depression in the top center of the pile is formed. Into this depression is where the new material should be added. New material is introduced to the middle of the heap since the center tends to be the hotter than the areas closer to the reactor walls (Vinnerås *et al.,* 2003). Proper insulation and periodic turning of the waste material more evenly distributes the heat throughout the compost. In an active heap, steam would be seen coming from the center upon digging the depression. Once the new wastes are added, the cover material is pushed out from the walls redistributing evenly once again over the compost top. Fresh cover material must be placed on top of the compost pile after every introduction of new waste material. If properly performed, the heap should undergo thermophilic composting within hours.

Once cover material is set and the pile is left to compost, certain monitoring techniques can indicate to users if the system is functioning properly. The goal of thermophilic composting is to reach thermophilic temperatures. Thus, users can monitor the temperature of the compost using a 36 inch thermometer, which is directly placed into the compost. If temperatures are not within the thermophilic range (40°C to 71°C) or if thermophilic temperatures are not maintained for a long period of time (at least a week), then thermophilic conditions have not been met. Another indicator of poor thermophilic conditions is bad odors originating from the compost pile. Bad odors result from poor cover material selection such as coarse and/or inorganic material that allow odors to escape the piles through large voids. Inadequate cover distribution is another cause of bad odors. Flies collecting around the composting waste also demonstrate improper system maintenance since they are attracted to the odor. If the proper cover material has been selected and applied adequately, other important factors are not being met. Microbial activity can greatly diminish if the wastes are not sufficiently aerated. The weight of more massive material can cause compaction in the reactor. To ensure this is not the case, a user can take a pitchfork or an aeration stick to mechanically move the organic material (Berger, 2011). Moisture contents outside the optimum range can also inhibit decomposition. Adding greywater, rainwater, and/or urine can remedy an overly dry compost. For wet composts, more material waste or cover material should be added to soak up moisture. The pH of the compost can also inhibit activity. Lime, soda ash, and/or algae flower are additives that can serve to raise the pH value if its falls below 6.5 (Vinnerås, 2007; Berger, 2011). Still, too much ash additive decreases the organic content of feces, presenting a less attractive environment for microorganisms in the compost (Vinnerås, 2003). Therefore, regular maintenance and monitoring is crucial to achieving maximum performance in a thermophilic composting system.

Chapter 4: Sanitation System Proposal

The vision of the CTPC is to have reliable sanitation on two levels: (1) the household level and (2) the community level. The following sections propose sanitation systems on both levels. As discussed in section 2.5.1, UDDT and composting toilet systems are the most technically feasible and applicable for Zwelitsha. Neither system requires a sewer or water connection. Each can be designed without energy dependent components or additional waste disposal. Both systems have the capability of generating usable products, pose no safety concerns if wastes are handled properly, and can be utilized in water-scarce areas like Zwelitsha.

4.1 Household Level Sanitation System

Sanitation systems within Zwelitsha currently take the form of communal toilet blocks. Household systems are unprecedented (ISN *et al.*, 2011). At night, communal toilet blocks become sites for violence, rape, and overall crime (Kenney *et al.,* 2011a). As a result, persons fearing for their safety resort to alternate methods to satisfy their sanitation needs such as open defecation and defecating in buckets. Thus, for an informal settlement resident whose safety is threatened by satisfying his/her basic need of sanitation, a sanitation system within his/her own home provides security.

Although urine diversion toilets harness the nutrient value of urine, the demand for urine is less than that for fecal compost despite this nutrient advantage (Robinson, 2005). Consequently, two options are presented for the household level toilet system: one for households without a reuse application for urine and one for households with a reuse application for urine. The first option is the Loveable Loo, a composting toilet developed by Joseph Jenkins, author of "The Humanure Handbook – A Guide to Composting Human Manure" (Jenkins, 2005). The second option is a low cost UDDT designed for application in Africa by Peter Morgan, Professor at the Stockholm Environment Institute in Stockholm, Sweden (Morgan, 2007). Each system can be built using minimal, inexpensive, and local materials and unskilled labor.

4.1.1 The Loveable Loo

The Loveable Loo is a composting toilet, which collects fecal matter and urine in one receptacle. It does not require water, electricity, venting, plumbing, or chemicals. This toilet option is applicable in areas where urine reuse is unrealistic or lacking demand. The Loveable Loo is a simple, economic, and sanitary option (Figure 10). This toilet system can be purchased (retail price: $225) fully assembled and finished at the Humanure Store (Grove City, PA). It can also be constructed by individuals using wood, a 5 gallon (20 L) bucket, a toilet seat and cover.

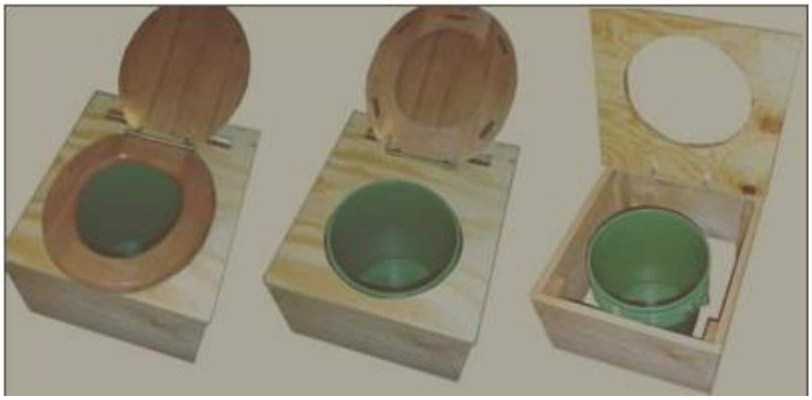


Figure 10. Loveable Loo (Humanure Store, 2013)

The humanure handbook website (Humanure Handbook, 2013) provides an 8-step visual instruction for individuals wanting to construct their own Loveable Loo toilet system (see Appendix A). The Loveable Loo toilet box is 18” wide and 21” long. Construction materials include: two 3/4"x10"x18" boards and two 3/4"x10"x19.5" boards; two door hinges; one piece of 3/4"x18"x18" plywood and one piece of 3/4"x3"x18" plywood. These two pieces of plywood are hinged together. The top of a 5 gallon bucket is used as a template to cut a hole in the larger piece of plywood (3/4"x18"x18") to fit the top of the toilet receptacle. The hole must be only 1.5” back from the front edge of the plywood. It is important that toilet receptacles (buckets) used in the system are all of identical size so they will fit properly within the toilet. The last component is the toilet seat. A standard toilet seat should be purchased for the system. Zwelitsha locals, CTPC members, or any other stakeholders of the household level sanitation system can construct Loveable Loos easily and economically.

Loveable Loo toilets can be placed anywhere in the home. In addition to the toilet, an area should be designated for holding cover material, preferably adjacent to the toilet. After each use of the toilet system, cover material, such as saw dust from cut trees, must be put on top of the human excreta within the toilet receptacle. This prevents odors and flies. If odors are coming from the toilet, additional cover material should be added until the smell disappears. There should also be multiple toilet receptacles (buckets) of identical size. A 20 L bucket fills up in about a week when one adult is using the system (Humanure Handbook, 2013). This includes fecal matter (feces and toilet paper), urine, and cover material (feminine products may also be administered into the bucket). With multiple toilet receptacles, full buckets can be sealed, set aside, and replaced by empty buckets. In this way, a household of 3 persons (around a typical Zwelitsha household size) with six 20 L buckets can wait two weeks before needing to empty out its buckets (CCT, 2012a).

For Zwelitsha, residents could either compost the waste on their property in compost bins or transport the waste in the sealed buckets to the large scale WaSH facility mentioned in section 4.2. The CTPC aims to involve the community in the upgrading of WaSH services. Often, WaSH facilities in informal settlements are not valued by residents and as a result are commonly misused and/or vandalized (Kenney *et al.*, 2011b). The CTPC has found that if spaces simultaneously address needs such as unemployment, education, and communal space, residents are more likely to value and care for them (Bell *et al.*, 2010). Zwelitsha community members have already expressed desires for foot pedal water taps, soap dispensers for water ablution basins, trash and food bins, educational signs showing proper hygienic practices, laundry wringers, and recreational space (Kenney *et al.*, 2011a). The reuse potential of human excreta can also have the potential of alleviating the financial burdens of unemployment for individuals. Users of the Loveable Loo can be economically incentivized to transport their wastes to the WaSH facility. Initially, before the sale of products returns profits to the facility, this economic incentive can be subsidized by the CTPC or the municipality within the Stellenbosch-Langrug partnership. This process can also incentivize other community members who are not currently using Loveable Loos in their homes to begin using the systems. Strategies such as these can work to involve all community members in the reuse of human excreta, which can promote the use of sustainable toilet systems.

4.1.2 UDDT for African Context

The proposed UDDT is a low cost self-built toilet in which urine is collected in a plastic container and the feces, together with soil and ash added to help the composting process, are collected in a 20 litre bucket. If there is a realistic reuse application in Zwelitsha, at the household level, the proposed low cost UDDT designed by Peter Morgan can be implemented. The design developed by Morgan incorporates a concrete base slab, a vault built of fired bricks and mortar, and a urine-diverting pedestal (Morgan, 2007). This UDDT can be constructed by individuals using a 20 L bucket, cement, reinforcing wire, brick, mortar, a plastic pipe for urine-diversion and a toilet seat and cover. Figures 11 through 14 show a constructed brick vault with concrete and a complete toilet pedestal with urine pipe.

Figure 11. Front View of Vault with Toilet Slab Placed on Top (Morgan, 2007)

Figure 12. View from Behind Vault Showing Slanted Concrete Access Slab (Morgan, 2007)

Figure 13. View from Behind Vault Showing Removed Access Slab, 20 L Collection Bucket within Vault, and Superstructure on Top Enclosing Toilet Pedestal for Privacy (Morgan, 2007)

Figure 14. Toilet Pedestal with Urine-Diversion Pipe (Morgan, 2007)

Morgan (2007) provides detailed instruction on how to construction this UDDT system (see Appendix B). The feces from the UDDT are used to make compost. Consequently, after every use, individuals are recommended to add amendment (cover material) to the collection bucket filled with deposited feces and toilet paper. Morgan (2007) recommends adding a mixture of soil and wood ash. These materials should be premixed when they are dry at a ratio of four parts soil to one part ash. About half a cup of this mix should be added following each defecation. Other cover materials may also be used including ones mentioned in section 3.2.1.2. It was observed that with the mixture of feces, toilet paper, soil, and wood ash, that the 20 L bucket took between four and six weeks to fill up for a single user. This correlates to an average daily waste production between a pound and a pound and a half.

The collection bucket containing the feces and waste mix is retrieved from behind the UDDT system, as shown in Figure 13. From here, Morgan (2007) proposes that the feces mix be to a secondary processing site. The toilet is considered the “primary processing site,” in that compost ingredients are placed together and undergo initial decomposition. Still, fresh excreta remain in the toilet system for a short period. Depending on how quickly the bucket fills up and the number of users, it may take a few days or a week or two at most before the excreta are transferred to the secondary processing site. This site can be a shallow pit composter (Figure 15) or a split cement jar (Figure 16) near the UDDT system. A series of these is recommended for a family or user groups of 5 or fewer. Once treated compost can be placed into cement basins from which plants can directly grow. Morgan (2004a) provides instructions for constructing 10 L cement basins and 30 L and 80 L split cement jars.

Figure 15. Emptying Bucket Contents into Shallow Pit Composter (Morgan, 2004b)

Figure 16. Three Cement Jars: One with an Painted Concrete Cover (left); One with Standard Cement Lid (center); One with Plants Growing from it (right) (Morgan, 2004b)

For a family or user group of greater than 5, it is recommended to build a twin pit composter (Figure 17) where the contents of the bucket are added to one shallow pit until it is nearly full, then to a second shallow pit which fills whilst the contents of the first pit are composting. Morgan (2004b) provides detailed information on the construction and use of twin pit composter. In addition to the secondary processing sites proposed by Morgan (2007), the large-scale WaSH facility containing a composting facility such as the one presented in section 4.2 can also serve as a site. Although ideal for onsite household reuse, Zwelitsha residents using this UDDT can bring their buckets to the facility as an alternative or supplemental option if their own systems are at capacity.

Figure 17. Twin Pit Composter

4.2 Sanitation System for Integration into Large-Scale Sanitation System

While a sanitation system within the home has the benefits of convenience and safety, a communal sanitation system has value. Current communal toilet blocks within Zwelitsha are unsustainable and ineffective. These communal sanitation systems are typically unclean, malodorous, and undignified (Kenney *et al.*, 2011b). Moreover, the inefficiency of the current services forces many community members to compensate with unsanitary and rudimentary means. Doing so invites poor hygiene, disease, and prevents residents from partaking in a higher standard of living (Kenney *et al.*, 2011a).

Communal toilet blocks remain unmaintained and users do not clean or value such systems (Kenney *et al.*, 2011b). The CTPC envisions a WaSH facility that will add value to sanitation systems to increase the sense of ownership residents have for them. Value is added to systems by enabling community members to express their needs and by involving them to address those needs. Zwelitsha community members have already expressed desires for foot pedal water taps, soap dispensers for water ablution basins, trash and food bins, educational signs showing proper hygienic practices, laundry wringers, and recreational space (Kenney *et al.*, 2011a). The facility can meet the particular needs of the Zwelitsha community, such as unemployment by including other features into the facility design such as salons for local businessmen (Kenney *et al.*, 2011b). Including valued amenities provides a more welcoming and dynamic communal space, an approach that has proven to increase the longevity and sense of community ownership of such facilities (Hobson, 2000).

This section proposes a sanitation system at the community level that can be incorporated into a larger WaSH facility and valued by the Zwelitsha community. UDDT and composting toilet systems were determined to be the most technically feasible and applicable for Zwelitsha. As a result, the proposed system includes UDDTs with subsequent composting and urine storage. The system is based on a facility used in the successful communal sanitation project in the informal settlement of Pook se Bos located in the City of Cape Town. Since 2009, the installed facility has provided the Pook se Bos community with clean, hygienic, and dignified sanitation facilities. It features the MobiSan toilet, a UDDT with the potential for future reuse of compost. Designed and built by a Dutch consortium, the City of Cape Town installed a MobiSan communal sanitation unit in Pook se Bos with the aim of improving sanitation in the community. Consisting of UDDTs, the facility is free to use and supervised by caretakers, with toilet paper provided at no cost to the community. The toilets have been widely accepted by the residents that recognise the improvement in the sanitation facilities and appreciate the privacy, cleanliness and dignity offered by the unit (Quayle, 2012).

The MobiSan unit comprises 13 urine diverting communal toilets, in which urine is separated from feces in individual chambers. Toilets stalls containing the toilets are raised up and accessed via steps. This allows for the collection on the feces and urine below the toilets. However, the toilets for children are only connected to the feces chamber, as it is considered too difficult for children to use the urine diversion system correctly. The unit divides the toilets by gender and age, providing seven toilets for women, three for men, and the remaining three for children (Figure 18). Additionally, 12 waterless urinals for men are located on the back of the unit (Figure 19). The facility serves 200 shacks of approximately 800 individuals (Quayle, 2012).

Figure 18. Toilet side of MobiSan: 13 UDDTs separated by gender and age (Quayle, 2012)

Figure 19. Urinal side of MobiSan: 12 waterless men's urinals (Quayle, 2012)

While not essential for operation, the municipality provided the toilet block with electricity for lighting to improve the safety for users and to power the ventilation, further reducing the incidence of bad smells. A piped water supply was also provided for hand washing. In addition, the municipality appointed local caretakers to supply cleaning materials and toilet paper for residents and to ensure the unit was not vandalized or misused. The municipality empties the feces chambers every six months and the urine tanks every 2 months. The feces and urine are collected from within the toilet stalls in an area below the toilet. Until the reuse aspect of the system is fully developed, the feces are disposed of via landfill and the urine at wastewater treatment plants (Quayle, 2012).

Although modeled after the MobiSan project in Pook se Bos, the proposed system has several keys differences. For one, the proposed system is not designed for the collection of feces and urine by the municipality for removal offsite. Instead, it is designed for onsite treatment and reuse of feces and urine. Secondly, the system is designed to serve a smaller population of 150 individuals or approximately one-fourth of the Zwelitsha population. Lastly, the proposed system was designed with anticipation that electricity will not be provisioned by the municipality to power the ventilation system. As a result, an air shaft was included in the design.

The main component of the proposed system is the UDDT unit, which will separate urine and fecal matter. The CTPC wants to bring services to approximately 50 families. According to Professor Scott Jiusto, Director of the CTPC at WPI, who has completed numerous projects in Zwelitsha, a typical family or household is three individuals. Thus, the system is designed for a user population of 150 persons. Given the Cape Town provision target of 1 toilet per 5 households, the system includes 10 toilets (CCT, 2012c). Each UDDT unit has a urine compartment and a fecal matter shute (Figure 20). The two waste receptors are separated by a dividing wall, which acts to prevent cross-contamination of urine and feces during and after toilet use. Urine collected in the urine compartment flows toward a pipe inlet. As shown in Figure 21, the inlet leads to a pipe that empties into a urine collection container. Urinals are also included in the system where urine is directed via a pipe into a connected urine collection container. The fecal matter, which includes feces, toilet paper, toilet paper center cardboard rolls and feminine hygiene products, drops down the shute into a collection bin. A ventilation shaft is located behind each toilet unit allowing air to pass through the unit, the fecal matter collection area, and the outside. Throughout the system there are access flaps, enabling maintenance personnel to retrieve the collected urine and fecal matter fractions for onsite processing. Figure 22 shows a rendered version of the whole system.

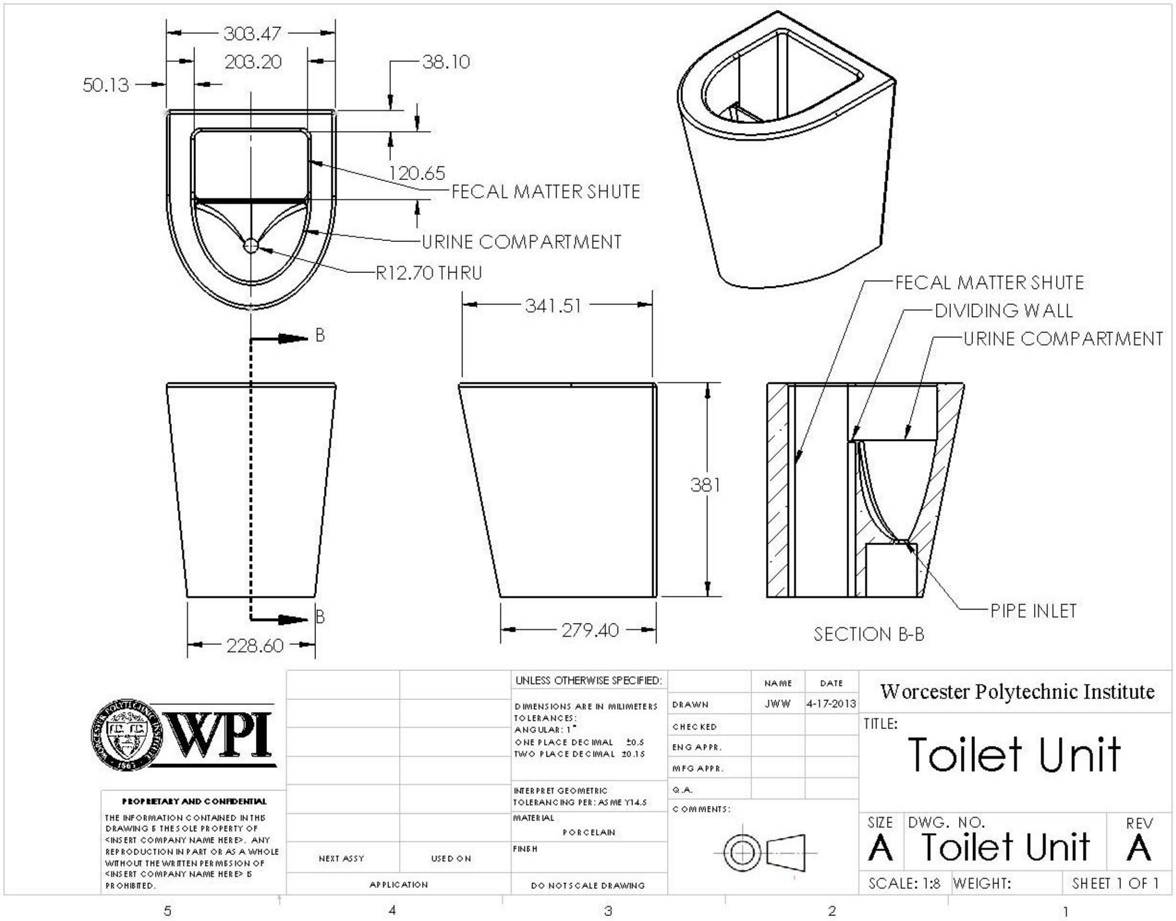


Figure 20. Schematic of UDDT Toilet Unit: Top View (Top Left); Angled Top View (Top Right); Front View (Bottom Left); Side View (Bottom Middle); Side Cross-sectioned View (Bottom Right)

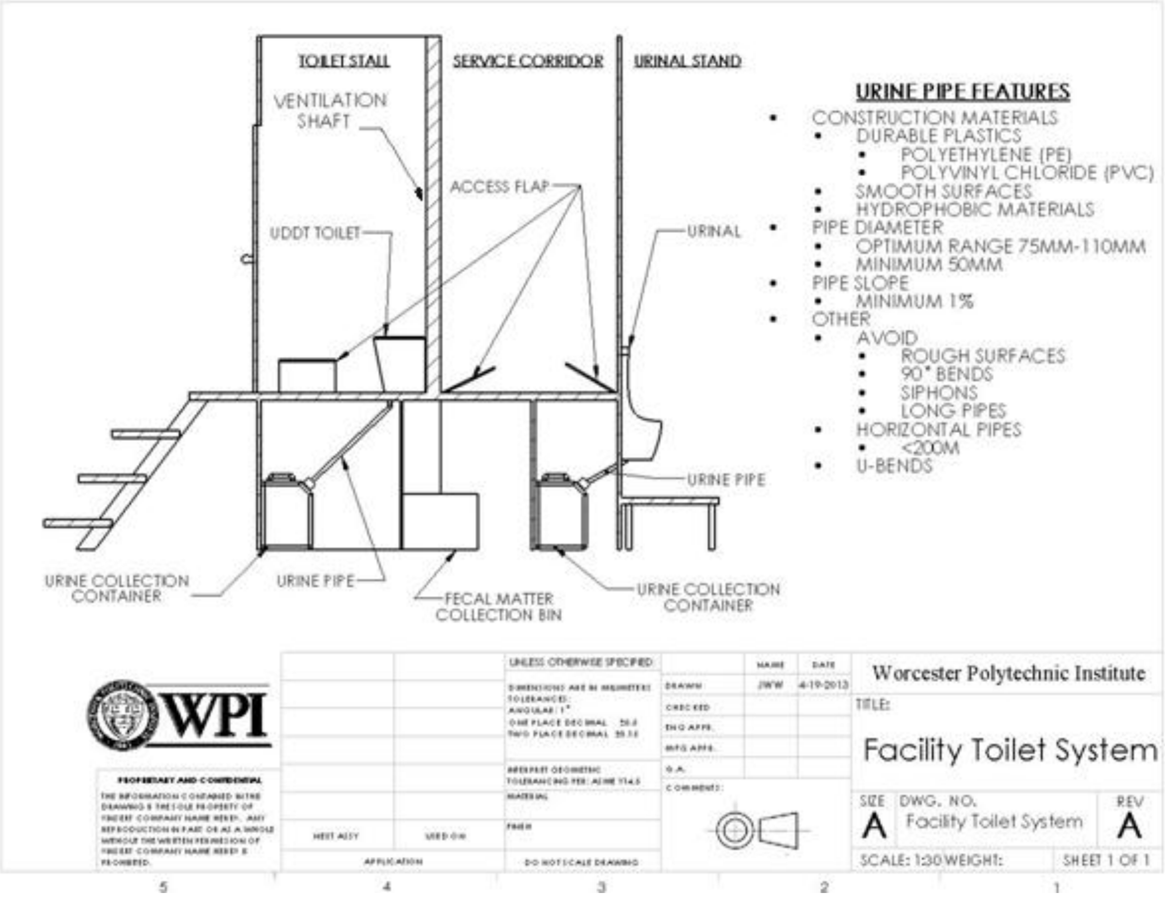


Figure 21. Schematic of Facility Toilet System with Important Design Features

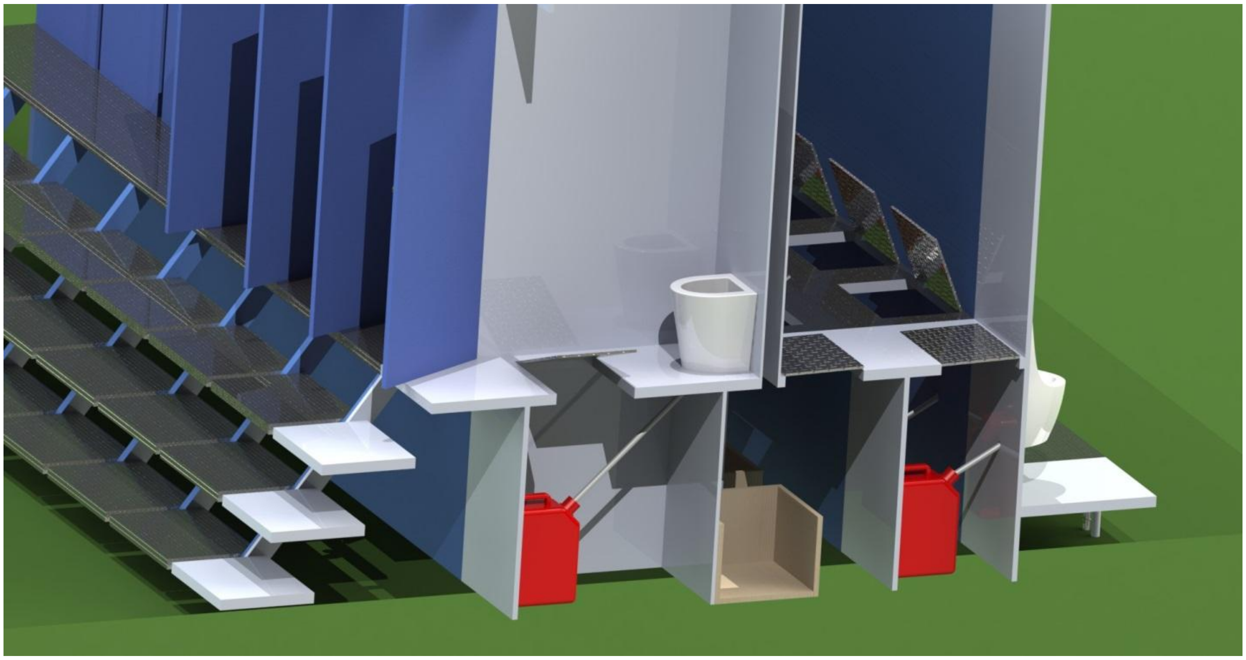


Figure 22. Rendered Version of Toilet System

Like the MobiSan project, the proposed system features a raised system in which steps and a raised platform grant access to toilets on one side and urinals on the other. A modification to the MobiSan design is a middle corridor in between the toilet units and urinals. The MobiSan unit uses a double-vault (chamber) system with a mechanical device for mixing. Fecal matter is collected in one chamber and is mixed manually via the mechanical device by the caretaker of the system. When the first vault is full, its contents are transferred to the second chamber with the help of the mixing device while the first one remains in use. In the second chamber, the fecal matter is stored for further hygienisation and improvement of the end product quality (DWS, 2013). This corridor allows the caretaker of the system to retrieve the fecal matter waste fraction from the toilet units and the urine waste fraction from the urinals for processing outside the units. Additionally, the corridor removes the possibility of cross-contamination of feces and urine. This is accomplished, specifically, because urine pipes never cross over fecal collection bins and there are separating walls and individual compartments for each collection container. As seen in Figure 22, the urine waste fraction from the toilet units are retrieved via an access flap within the toilet stall directly in front of the toilet unit.

Retrieved waste may be treated onsite or offsite. Here, it is proposed that waste is treated onsite. This eliminates the need for transport of waste offsite or for outside personnel to come onsite and collect waste for treatment elsewhere. In the Pook se Bos MobiSan installation, the municipality empties the feces chambers every six months and the urine tanks every two months. Until the feces and urine from the system can be reused as agricultural products, the feces are disposed of via landfill and the urine at wastewater treatment plants (Quayle, 2012). Within the Stellenbosch-Zwelitsha partnership through SDI, wastes can be handled in the same way. Still, here, the proposed system plans for treatment of wastes onsite.

The first element of the onsite waste treatment is the compost facility. Joseph Jenkins, a compost practitioner in the United States since 1975, designed the compost facility proposed here. With his expertise in composting, Jenkins has successfully grown food for his family from humanure (human manure) compost for the last 30 years (Jenkins, 2010).

The compost facility has two compost storage bins, a storage area for cover material, and a rainwater collection system (Figure 23). Compost storage bin volumes can vary. A typical volume for a bin is 1 m^3. Estimates of the expected fecal matter volume suggested that this volume was adequate for the system. Since feces requires 6 months of treatment, estimates were made for that period of time. The fecal matter volume was calculated considering the individual contributions of feces, toilet paper and saw dust amendment to the system. In addition, it was determined for a facility serving 150 individuals daily. Microsoft Excel was used to calculate the daily fecal matter volume. From this, a final 6-month volume of approximately 1 m^3 was computed. Calculations were based on assumptions including daily fecal, toilet paper, and saw dust mass production per person; feces, toilet paper and saw dust densities; individuals served per day; the time fraction (or time spent by user at facility); and the percent decomposition of waste over time. A chart showing the values along with associated assumptions is included in Figure 24.

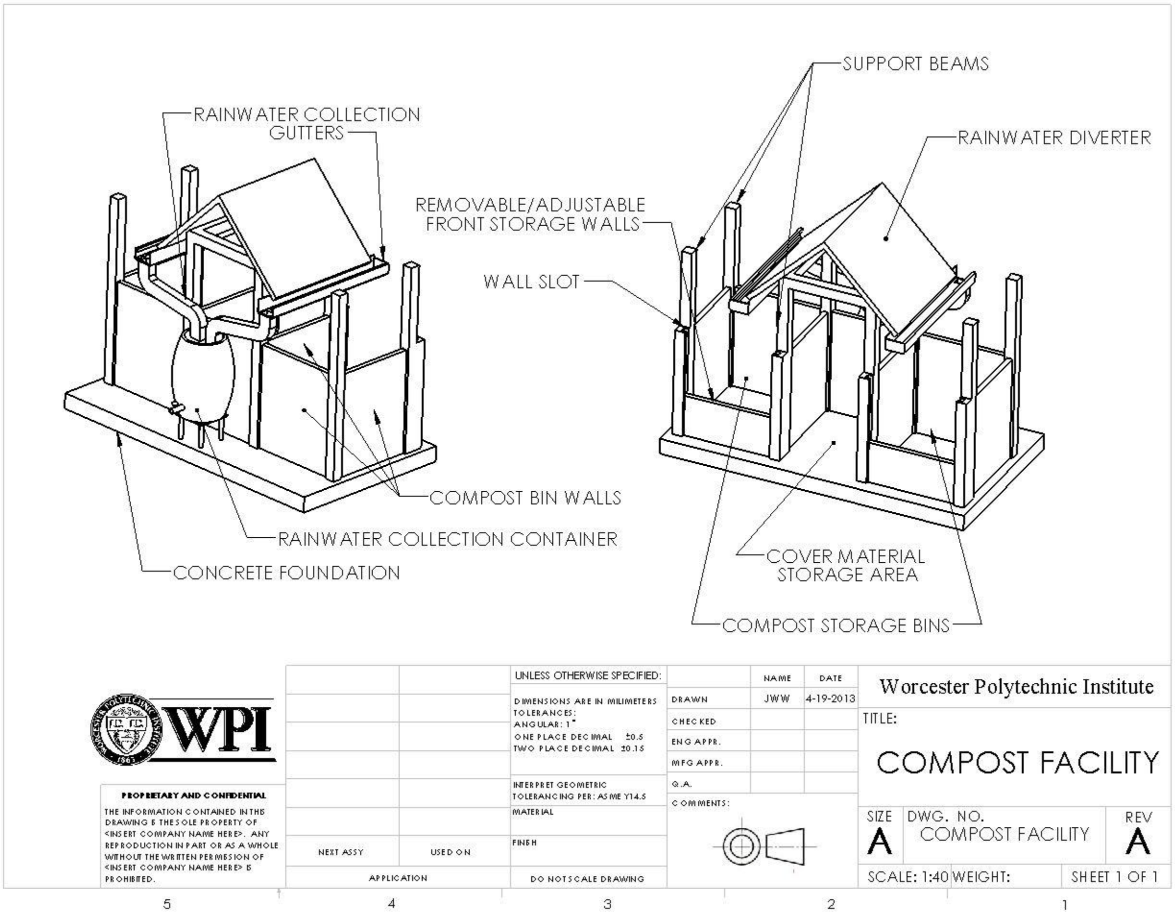
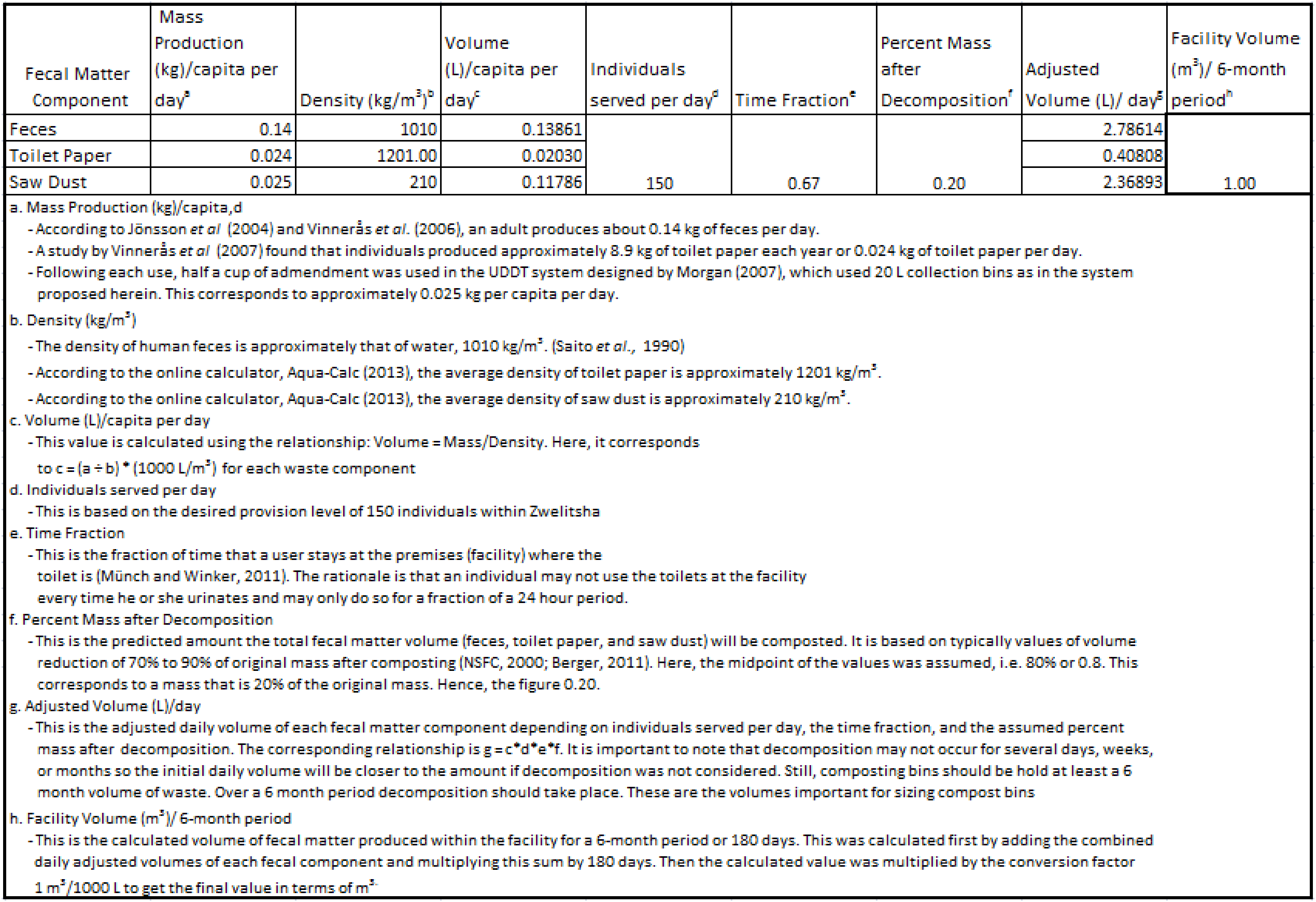


Figure 23. Schematic of Compost Facility: Rainwater Harvesting Side (left); Compost Loading Side (right)



Fecal Matter Component	Mass Production (kg)/capita per day[a]	Density (kg/m^3)[b]	Volume (L)/capita per day[c]	Individuals served per day[d]	Time Fraction[e]	Percent Mass after Decomposition[f]	Adjusted Volume (L)/ day[g]	Facility Volume (m^3)/ 6-month period[h]
Feces	0.14	1010	0.13861	150	0.67	0.20	2.78614	1.00
Toilet Paper	0.024	1201.00	0.02030				0.40808	
Saw Dust	0.025	210	0.11786				2.36893	

a. Mass Production (kg)/capita,d

- According to Jönsson *et al* (2004) and Vinnerås *et al*. (2006), an adult produces about 0.14 kg of feces per day.
- A study by Vinnerås *et al* (2007) found that individuals produced approximately 8.9 kg of toilet paper each year or 0.024 kg of toilet paper per day.
- Following each use, half a cup of admendment was used in the UDDT system designed by Morgan (2007), which used 20 L collection bins as in the system proposed herein. This corresponds to approximately 0.025 kg per capita per day.

b. Density (kg/m^3)

- The density of human feces is approximately that of water, 1010 kg/m^3. (Saito *et al*., 1990)
- According to the online calculator, Aqua-Calc (2013), the average density of toilet paper is approximately 1201 kg/m^3.
- According to the online calculator, Aqua-Calc (2013), the average density of saw dust is approximately 210 kg/m^3.

c. Volume (L)/capita per day

- This value is calculated using the relationship: Volume = Mass/Density. Here, it corresponds to c = (a ÷ b) * (1000 L/m^3) for each waste component

d. Individuals served per day

- This is based on the desired provision level of 150 individuals within Zwelitsha

e. Time Fraction

- This is the fraction of time that a user stays at the premises (facility) where the toilet is (Münch and Winker, 2011). The rationale is that an individual may not use the toilets at the facility every time he or she urinates and may only do so for a fraction of a 24 hour period.

f. Percent Mass after Decomposition

- This is the predicted amount the total fecal matter volume (feces, toilet paper, and saw dust) will be composted. It is based on typically values of volume reduction of 70% to 90% of original mass after composting (NSFC, 2000; Berger, 2011). Here, the midpoint of the values was assumed, i.e. 80% or 0.8. This corresponds to a mass that is 20% of the original mass. Hence, the figure 0.20.

g. Adjusted Volume (L)/day

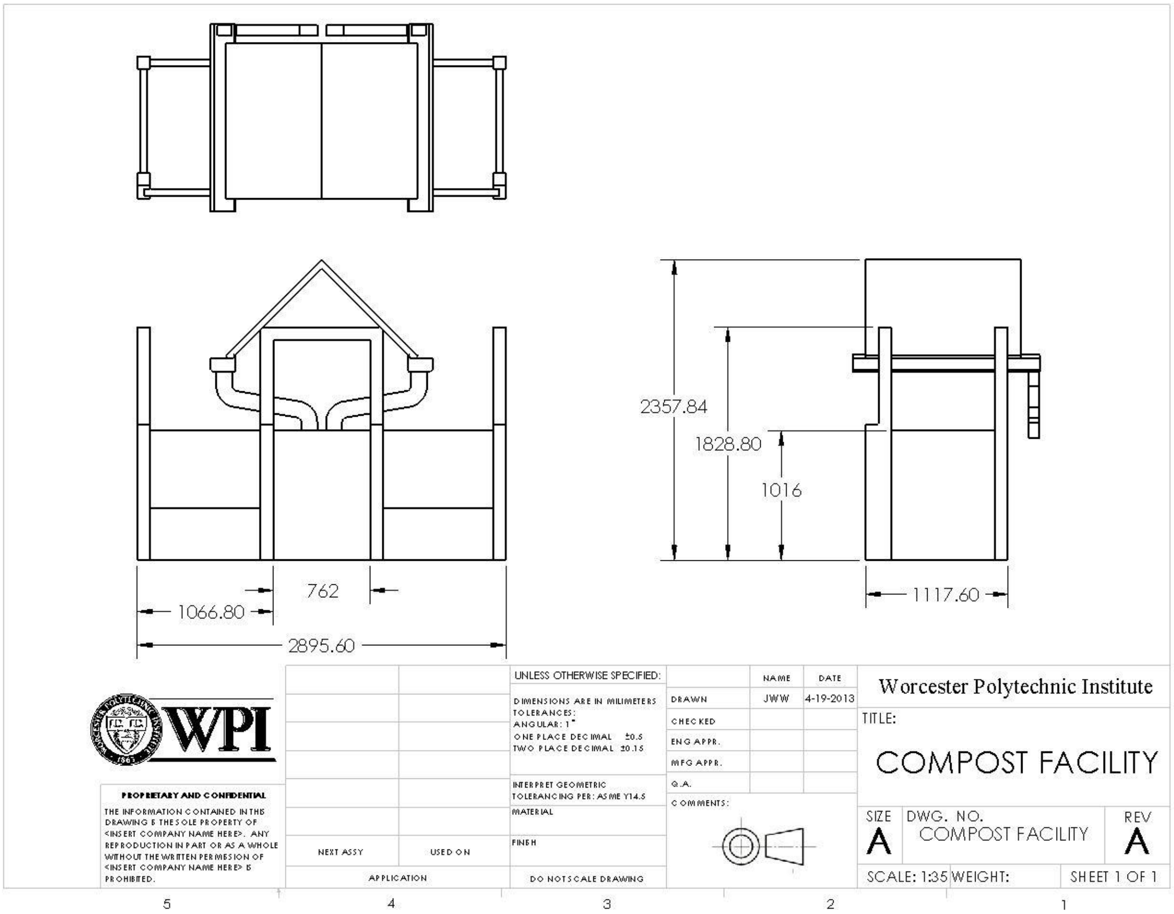
- This is the adjusted daily volume of each fecal matter component depending on individuals served per day, the time fraction, and the assumed percent mass after decomposition. The corresponding relationship is g = c*d*e*f. It is important to note that decomposition may not occur for several days, weeks, or months so the initial daily volume will be closer to the amount if decomposition was not considered. Still, composting bins should be hold at least a 6 month volume of waste. Over a 6 month period decomposition should take place. These are the volumes important for sizing compost bins

h. Facility Volume (m^3)/ 6-month period

- This is the calculated volume of fecal matter produced within the facility for a 6-month period or 180 days. This was calculated first by adding the combined daily adjusted volumes of each fecal component and multiplying this sum by 180 days. Then the calculated value was multiplied by the conversion factor 1 m^3/1000 L to get the final value in terms of m^3.

Figure 24. Fecal Matter Volume Calculation with Associated Assumptions

Thus, Figure 25 shows dimensions for one example of a storage bin. Similarly, construction materials for the bins and the compost facility can vary. Wood, bricks, blocks or concrete, straw or hay bales, bamboo, poles or logs, and wood shipping pallets are some of the materials that can be used (Jenkins, 2010). The bins are used in parallel. Retrieved wastes are placed into one compost bin at a time. When one bin is full, the bin is left to decompose without introducing any additional wastes for at least a 6 month period. During this treatment period, waste generated within the facility is emptied into the second compost bin. In between the two bins is a storage area for cover material. Hay or straw stacks, grass, leaves, or any other organic plant material can be stored here until it is placed onto the wastes within the adjacent compost bins. A roof over the cover material storage area keeps the cover material dry by diverting rainwater into gutters. Rainwater entering the gutters flows downward and collects in a collection container. Barrels or plastic containers can be repurposed to serve as a collection container for rainwater. The collected rainwater can be used to moisten the compost pile when thermophilic composting dries up the pile to unfavorable conditions (urine can also be used.) Additionally, the rainwater can be used to clean the urine and feces collection containers from the toilet system after they are emptied into the compost bins. For this, the caretaker can use a cleaning tool, such as a long-handled toilet brush, to scrub the containers with a mix of rainwater and biodegradable non-antibacterial soap (antibacterial soaps or substances should not be used at any point within the system since they can kill off bacteria necessary for thermophilic composting). About 1 gallon of water can clean two 5 gallon containers. The resulting rinse water should be added directly into the compost. This moistens the drying compost, eliminates the need for alternative disposable options, and prevents unsustainable introduction of wastewater into the environment. Figures 26 and 27 show rendered versions of the compost facility.



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILIMETERS
TOLERANCES:
ANGULAR: 1°
ONE PLACE DECIMAL ±0.5
TWO PLACE DECIMAL ±0.15
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN	JWW	4-19-2013
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Worcester Polytechnic Institute
TITLE:
COMPOST FACILITY
SIZE A
DWG. NO. COMPOST FACILITY
REV A
SCALE: 1:35
WEIGHT:
SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

Figure 25. Aerial View (top), Front View (bottom left), and Side View (bottom right) for Compost Facility

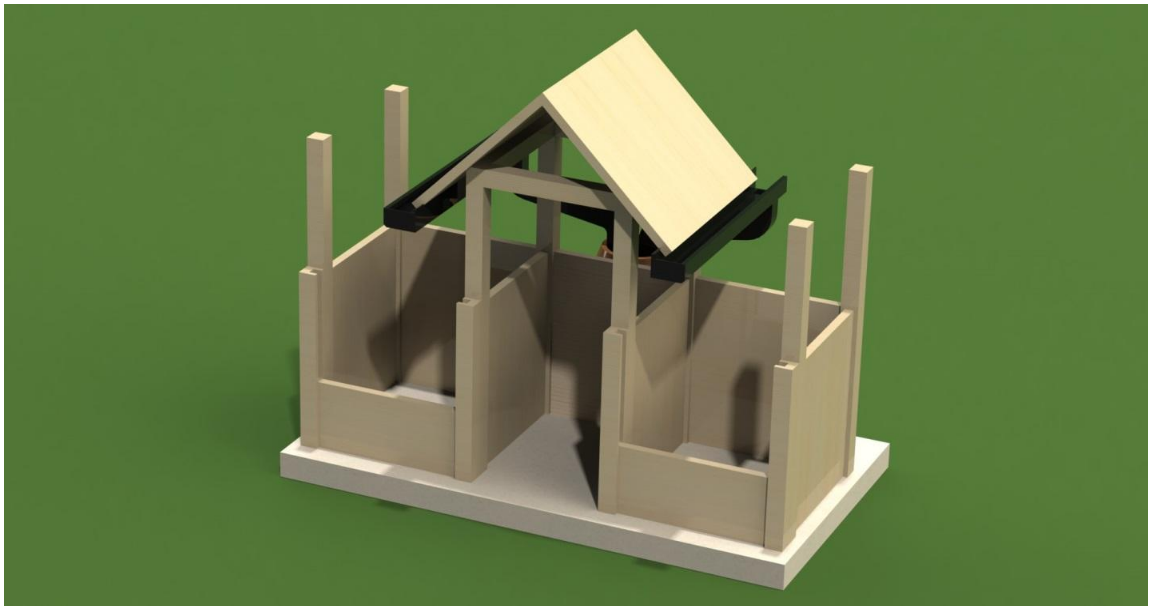


Figure 26. Composting Facility on Concrete Slab (Compost Loading Side)

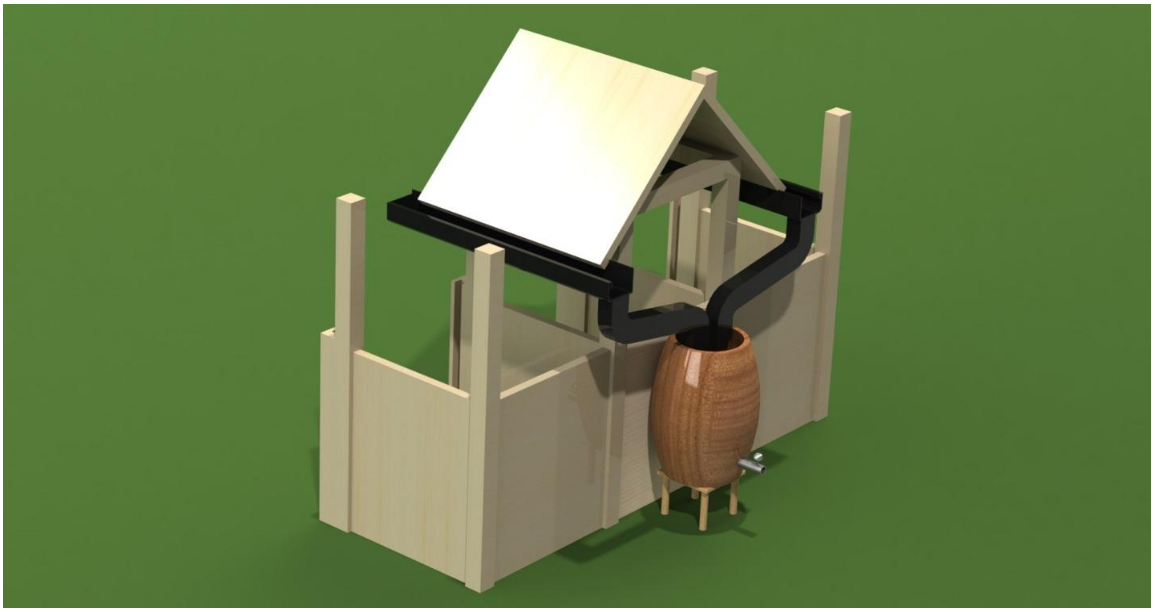


Figure 27. Compost Facility on Soil (Rainwater Harvesting Side)

The second element of the onsite waste treatment is the urine storage tanks. Storage tanks can be constructed of glass fiber reinforced plastic, PE, polypropylene (PP), PVC, rubber bladders, high-quality reinforced concrete, or stainless steel. Plastic tanks which are sold for rainwater harvesting are also suitable as urine storage tanks, and can be a good low-cost solution in developing places like Zwelitsha (Münch and Winker, 2011). Storage tanks should be completely watertight to avoid loss of urine, prevent groundwater contamination (for systems placed directly onto ground with no liner), and prevent groundwater from entering the tank from the outside. As shown in Figure 28, a concrete foundation can be placed below the tanks to serve as a barrier to any urine leakage. Plastics liners are also an option. Like the compost bins, storage tanks are used in parallel. Retrieved wastes are place into one storage tank at a time. When one tank is full, the tank is left without introducing any additional urine for at least a 30 day period. During this treatment period, urine generated within the facility is emptied into the second storage tank.

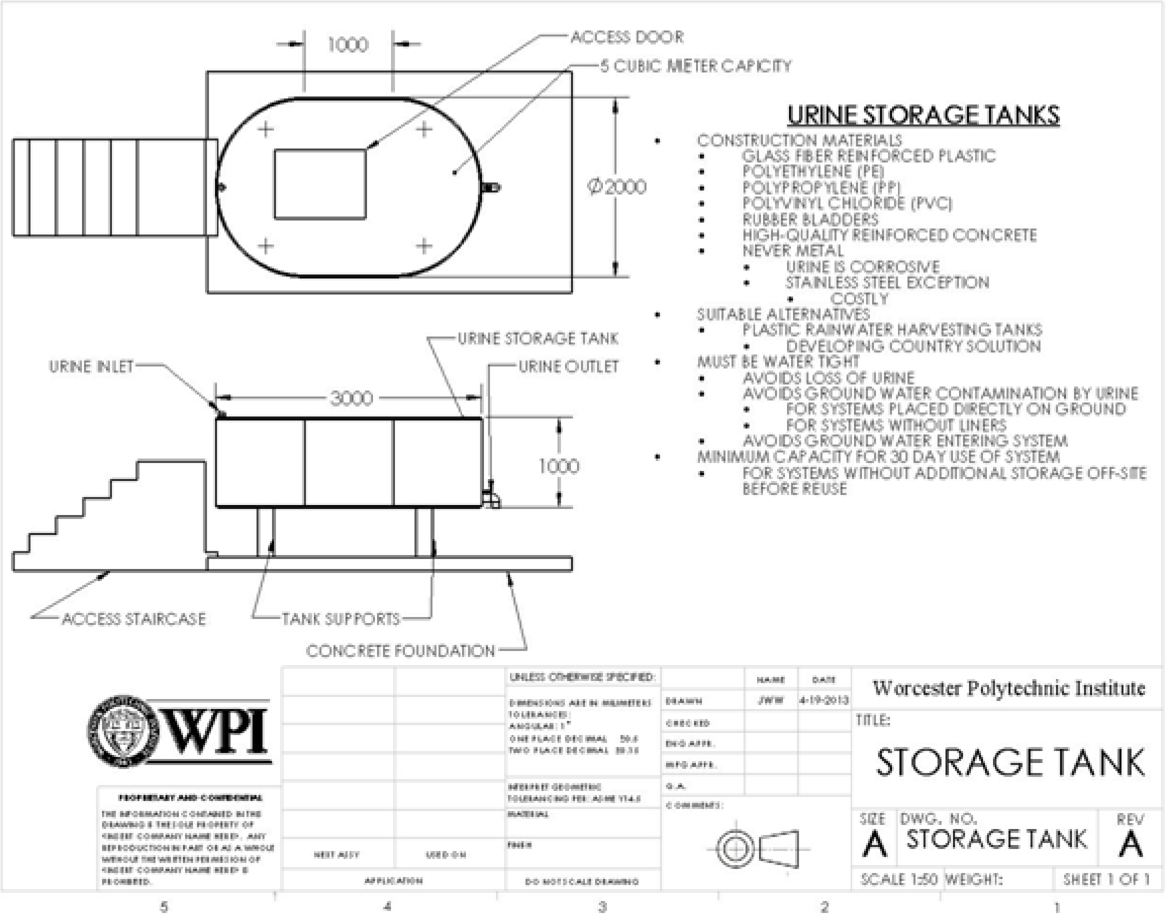


Figure 28. Schematic of Urine Storage Tank with Important Design Features: Aerial View (top); Side View (bottom)

The caretaker can add collected urine to the tank by climbing the access staircase and opening the access door located on top of the tank. Once urine is ready for reuse it can be retrieved via the urine outlet located on the end of the tank. Since the tank sits raised up on top of supports, gravity directs urine to the outlet for removal. The proposed storage tank volume is 5 m^3. Figures 29 and 30 show rendered versions of the urine storage tanks.

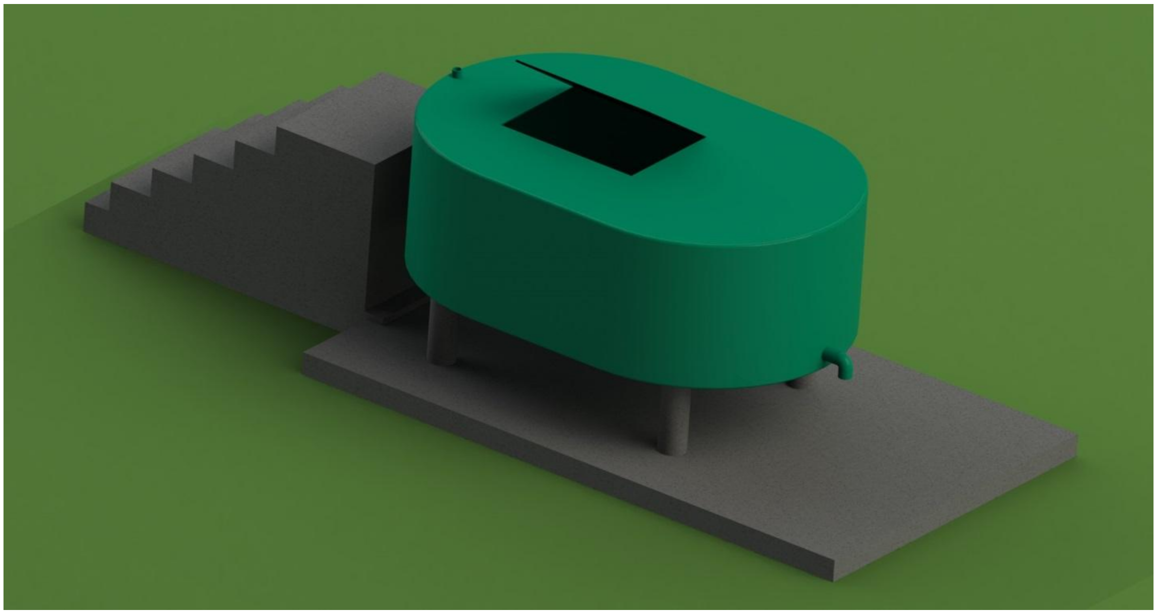


Figure 29. Urine Storage Tank with Access Lid Open

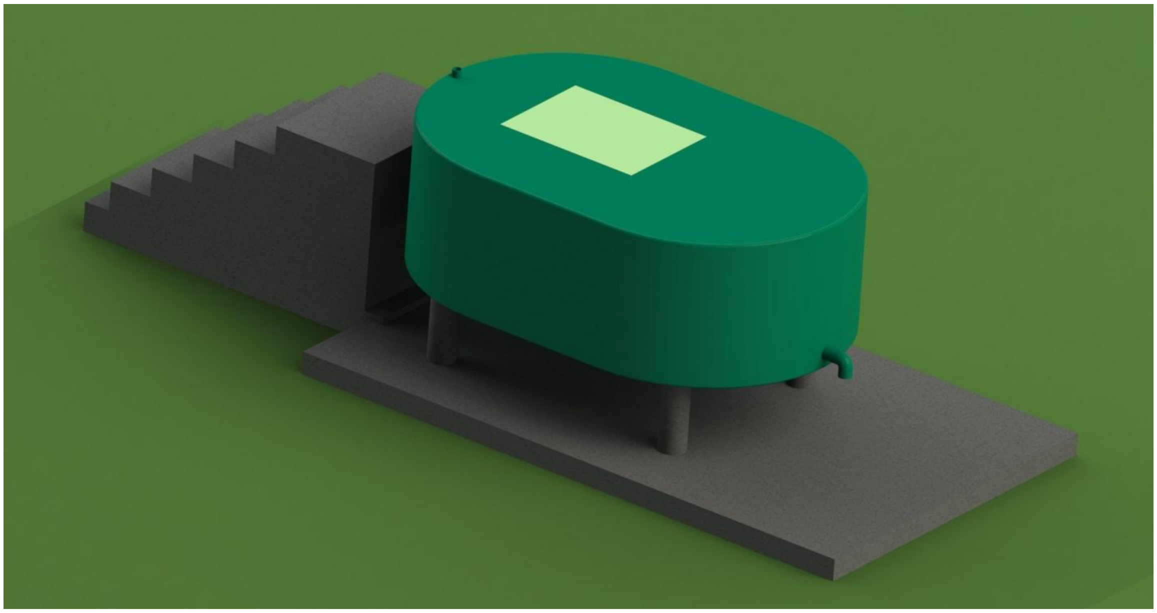
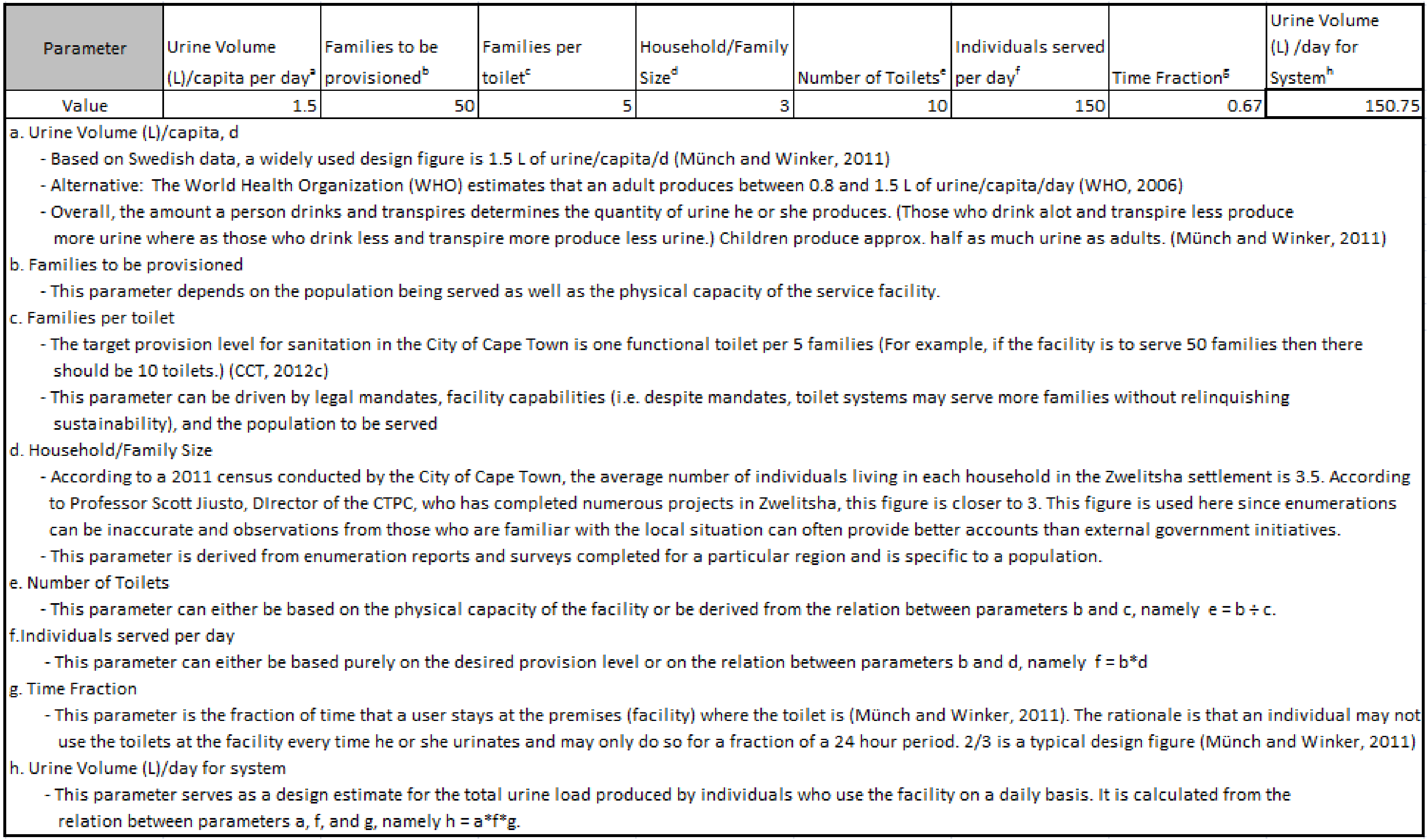


Figure 30. Urine Storage Tank with Closed Access Lid

The proposed urine storage tank volume (5 m^3) is based on the estimated 30-day storage capacity for a facility with toilets serving 150 individuals daily. This volume was calculated using Microsoft Excel. Calculations were based on assumptions including daily urine volume, families to be provisioned, families per toilet, household size, number of toilets needed, individuals served per day, and the time fraction (or time spent by user at facility). A chart showing the values along with associated assumptions is included in Figure 31.



Parameter	Urine Volume (L)/capita per day[a]	Families to be provisioned[b]	Families per toilet[c]	Household/Family Size[d]	Number of Toilets[e]	Individuals served per day[f]	Time Fraction[g]	Urine Volume (L) /day for System[h]
Value	1.5	50	5	3	10	150	0.67	150.75

a. Urine Volume (L)/capita, d

- Based on Swedish data, a widely used design figure is 1.5 L of urine/capita/d (Münch and Winker, 2011)
- Alternative: The World Health Organization (WHO) estimates that an adult produces between 0.8 and 1.5 L of urine/capita/day (WHO, 2006)
- Overall, the amount a person drinks and transpires determines the quantity of urine he or she produces. (Those who drink alot and transpire less produce more urine where as those who drink less and transpire more produce less urine.) Children produce approx. half as much urine as adults. (Münch and Winker, 2011)

b. Families to be provisioned

- This parameter depends on the population being served as well as the physical capacity of the service facility.

c. Families per toilet

- The target provision level for sanitation in the City of Cape Town is one functional toilet per 5 families (For example, if the facility is to serve 50 families then there should be 10 toilets.) (CCT, 2012c)
- This parameter can be driven by legal mandates, facility capabilities (i.e. despite mandates, toilet systems may serve more families without relinquishing sustainability), and the population to be served

d. Household/Family Size

- According to a 2011 census conducted by the City of Cape Town, the average number of individuals living in each household in the Zwelitsha settlement is 3.5. According to Professor Scott Jiusto, DIrector of the CTPC, who has completed numerous projects in Zwelitsha, this figure is closer to 3. This figure is used here since enumerations can be inaccurate and observations from those who are familiar with the local situation can often provide better accounts than external government initiatives.
- This parameter is derived from enumeration reports and surveys completed for a particular region and is specific to a population.

e. Number of Toilets

- This parameter can either be based on the physical capacity of the facility or be derived from the relation between parameters b and c, namely $e = b \div c$.

f.Individuals served per day

- This parameter can either be based purely on the desired provision level or on the relation between parameters b and d, namely $f = b*d$

g. Time Fraction

- This parameter is the fraction of time that a user stays at the premises (facility) where the toilet is (Münch and Winker, 2011). The rationale is that an individual may not use the toilets at the facility every time he or she urinates and may only do so for a fraction of a 24 hour period. 2/3 is a typical design figure (Münch and Winker, 2011)

h. Urine Volume (L)/day for system

- This parameter serves as a design estimate for the total urine load produced by individuals who use the facility on a daily basis. It is calculated from the relation between parameters a, f, and g, namely $h = a*f*g$.

Figure 31. Urine Volume Calculations with Associated Assumptions

Altogether, the large-scale community level facility has toilets and urinals for Zwelitsha resident use and onsite treatment of human excreta with a compost facility and urine storage tanks. Rendered versions of the facility are displayed in Figures 32 and 33. Depending on available materials and user demand, the design of this facility can vary. Still, the proposal herein is for a facility containing three main components: (1) a sanitation system (toilets and urinals), (2) onsite composting, and (3) onsite urine storage. The combination of these three features eliminates the need for waste collection for disposal offsite by outside personnel. Additionally, it presents the opportunity for immediate reuse applications onsite if agriculture is practiced at the WaSH facility incorporating the proposed system.

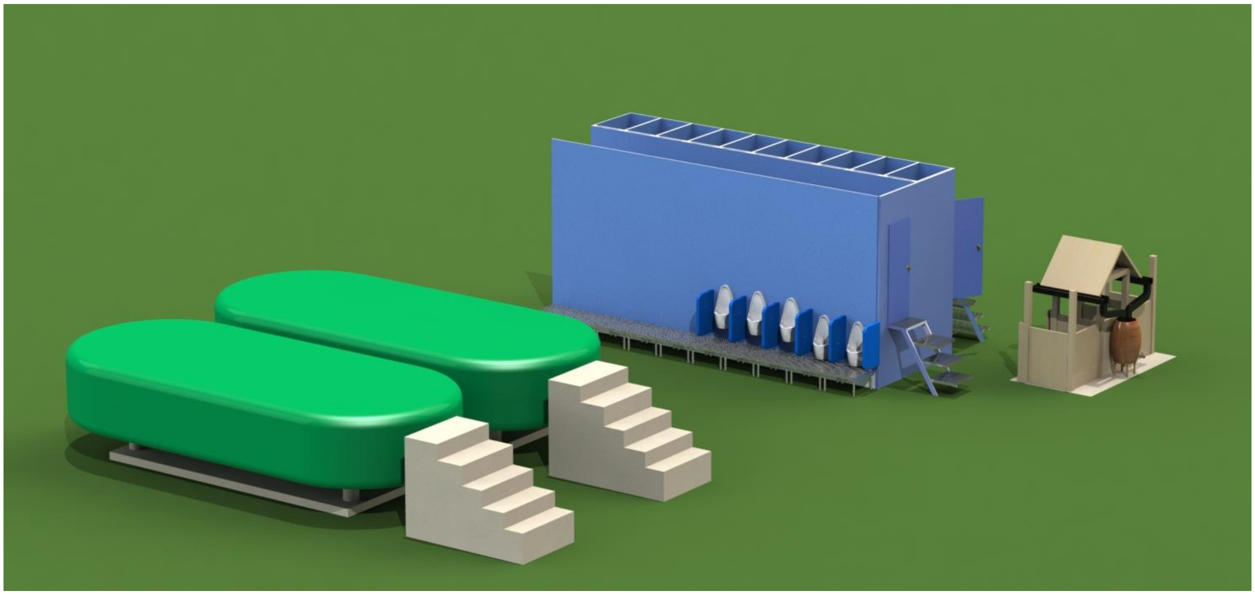


Figure 32. Toilet Facility (middle) with Parallel Urine Storage Tanks (left) and Composting Station (right)

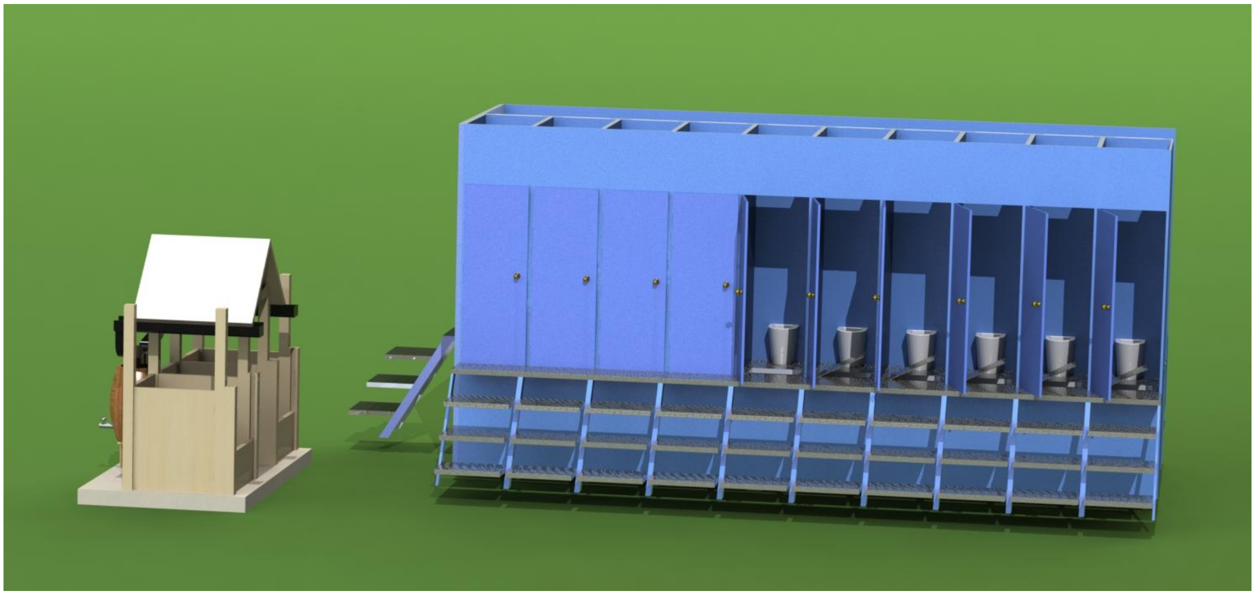


Figure 33. View of Composting Station and Toilet Facility looking into Toilet Stalls

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

Globally, water, sanitation, and hygiene (WaSH) issues affect over 3 billion people. Currently, 605 million people lack access to safe drinking water and 2.5 billion people lack access to basic sanitation. Often, this lack of access is a daily realty for persons residing in informal settlements throughout the developing world. The focus of this thesis was the area called Zwelitsha in the informal settlement of Langrug. Located in Stellenbosch Municipality near Cape Town, South Africa, Zwelitsha currently has one working drinking water tap and few functional toilets for its 604 residents. The aim of this thesis was to address the shortcomings in the provision of sanitation services within Zwelitsha. Thus, the major objectives of this thesis were: (1) to evaluate possible sanitation systems and (2) to select a sustainable and technically feasible toilet system to meet the sanitation needs of Zwelitsha as part of a WaSH facility.

Of the systems reviewed, urine diversion dehydration toilet and composting toilet systems were determined to be the most technically feasible and sustainable sanitation options for the informal settlement. Neither of the proposed systems require a water or sewage connection or electricity. Additionally, these systems can eliminate wastes through their potential reuse applications: urine as a sterile fertilizer and feces as a soil conditioner and fertilizer.

At the household level, two alternatives are the Loveable Loo and the Morgan UDDT. The Loveable Loo consists of a 5 gallon (20 L) bucket system in a constructed toilet housing to which cover amendment is added after use. Using the Loveable Loo, a family of 3 would need 3 buckets per week to meet their sanitation needs. The Morgan UDDT incorporates a concrete base slab, a brick vault, and a urine-diverting pedestal. It can be constructed using a 5 gallon (20 L) bucket, cement, reinforcing wire, brick, mortar, a plastic pipe for urine-diversion and a toilet seat and cover. Using the Morgan UDDT, a single user may take between four and six weeks to fill the bucket.

On the communal level, a UDDT system with subsequent onsite urine storage and thermophilic composting was proposed for the settlement. The proposed system was designed to serve 150 Zwelitsha residents daily with 10 toilets and 5 urinals. The composting stations for onsite fecal compost treatment were designed with a volume of 1 m^3 to accommodate fecal matter over a 6 month treatment period. The urine storage tank for onsite urine treatment was designed with a volume of 5 m^3 to allow for a 30-day treatment period. Once treated, it was proposed that the fecal compost and urine be reused as agricultural products onsite.

5.2 Recommendations for Future Work

The implementation of sanitation systems will take great consideration and other factors will contribute to project success or failure. With respect to the proposed systems, the following sections offer recommendations for future work toward a successful project.

5.2.1 Integrate Sanitation into a Full-Service WaSH Facility

The primary ways to reduce the transmission of enteric pathogens are through safe stool disposal and adequate handwashing. Therefore, it is recommended that toilet systems be integrated into a multi-service WaSH facility with handwashing stations and a supply of clean water and soap. Among WaSH issues, providing adequate facilities to dispose of bodily excretions and promoting the hygienic practice of washing hands with soap may be almost three times as effective as improving water quality, reducing the risk of diarrhea by 47% (Curtis and Cairncross, 2003). Consequently, the facility should promote the hygienic practice of washing hands with soap and associated education programs should be implemented in the community.

5.2.2 Cultivate User Awareness

Cultivating user awareness of proper system use is recommended to maximize the effectiveness and success of UDDT and composting toilet systems. The recommendations include:

- Employ a Caretaker: A WaSH caretaker can supervise individuals using the system, clean toilet units, distribute soap and toilet paper, handle wastes, and discourage vandalism of the system. The presence of a caretaker can help raise awareness on proper use of sanitation systems.
- Stress Importance of Cleaning System Regularly: Regular cleaning of the toilet and toilet areas is an important method of maintaining the sanitation systems. Biological disinfectants such as a vinegar or citric acid are recommended for cleaning the toilets as these will not inhibit proper treatment. Chemical disinfectants should be used on surfaces that are touched by users within communal toilet systems since hands are vectors for disease transmission.
- Involve Users in Reuse Activities: User awareness can be increased by involving users in the reuse of excreta, for example, via farming on an onsite garden. Users can see first-hand the value of excreta separation through the local production of food and/or growing food for their families on the household level. Furthermore, an external demand for agricultural products generated from human excreta can enable individuals to earn profit from product sale.

5.2.3 Enlist Local Farmers in Excreta Reuse

Local farmers are crucial stakeholders for any system that generates agricultural products from human excreta. Engaging farmers early can provide valuable agricultural expertise about desired fertilizer for the specific crops of the local region. Furthermore, they represent the potential demand for the products since they comprise the target market. Several concerns surrounding sustainable sanitation systems with excreta reuse are generating products above agricultural demand, quality control and safety, and product acceptability by farmers and by persons consuming the crops of farmers who use the products (Kvarnström *et al.*, 2006; Richert *et al.*, 2010). A few recommendations for further research into these concerns are:

- Research Options for Handling Excreta Surplus: One potential option is contracting farmers who can regularly pickup treated excreta for immediate use or untreated excreta for treatment on their own land. Contracting farmers who have knowledge of excreta reuse is recommended. Regardless of farmer knowledge, proper contracts regulating storage length, quality control, application methods, and so on should be arranged (Kvarnström *et al.*, 2006).

- Assess Compliance with EHS: In general, system managers should be able to assess compliance with environmental health and safety (EHS) standards at all phases of system operation and reuse.
- Assess Local Acceptance of Human Excreta Reuse in Agriculture: Due to varied levels of acceptance and differing attitudes towards the reuse of human excreta in agriculture, local reception should be investigated.

5.2.4 Perform a Financial and Economic Analysis of System

Prior to system investment, it is recommended to perform a financial and economic analysis. A full financial analysis includes all expenditures and revenue streams associated with a system. To ensure system sustainability, the recurring costs for operation and maintenance and not just initial investment costs should be considered. As a potential revenue stream for resource-separating systems, excreta reuse should be included in a long-term financial cost-benefit analysis. An economic analysis including financial costing as its core and the assignment of monetary values to social and environmental costs and benefits should also be conducted (Parkinson *et al.*, 2012).

References

Aqua-Calc (Aqua-Calc). 2013. Densities for common substances and materials, foods and gravels: Average density at standard atmospheric conditions. http://www.aqua-calc.com/page/density-table/substance/ (accessed May 2013)

Bai and Wang (Bai, F. and Wang, X.). 2010. Nitrogen-retaining property of compost in an aerobic thermophilic composting reactor for the sanitary disposal of human feces. Front. Environ. Sci. Engin. China. [Online] 2010, 4 (2), 228-234.

Barnstable (Barnstable County Department of Health). 2013. Incinerating Toilets. http://www.barnstablecountyhealth.org/ia-systems/information-center/compendium-of-information-on-alternative-onsite-septic-system-technology/incinerating-toilets (accessed May 2013)

Barrington *et al.* (Barrington, S., Choinière, D., Trigui, M., & Knight, W.). 2002. Effect of carbon source on compost nitrogen and carbon losses. Biores. Tech. 2002, 83 (3), 189-194.

Bell, H., Barbour, I., Gottshall, A., & Sparrell, C. (2010). Supporting early childhood development in Monwabisi Park. Worcester Polytechnic Institute: Worcester, MA, 2010; 1-5.

Berger (Berger, Wolfgang). 2011. Technology review of composting toilets: Basic overview of composting toilets (with or without urine diversion). GIZ. Eschborn, Germany, [Online] 2011; 1-21.

BioSystems (BioSystems Solutions). 2013a. Composting Methods. http://www.biosystemsolutions.com/learn/composting_methods.html (accessed May 2013)

BioSystems (BioSystems Solutions). 2013b. Thermophilic Composting. http://www.biosystemsolutions.com/learn/thermophilic_composting.html (accessed May 2013)

BioSystems (BioSystems Solutions). 2013c. Vermi-Composting. http://www.biosystemsolutions.com/learn/vermi_composting.html (accessed May 2013)

BLS (United States Bureau of Labor Statistics). 2013. Consumer Price Index Inflation Calculator. http://www.bls.gov/data/inflation_calculator.htm (accessed May 2013)

Brooks *et al.* (Brooks, S., Dempsey, M., Erlandson, T., MacDonald, C., Nichols, B., Reif M., Rookey, R., Venegas, J.). 2012. Laying the Foundation for a Resilient Partnership: Innovative Upgrading in the Informal Settlement of Langrug. Worcester Polytechnic Institute: Worcester, MA, 2011; 1-8.

Carr-Hill (Carr-Hill, R.). 2013. Missing millions and measuring development progress. World Dev. Institute of Education, London, United Kingdom, [Online] 2013, 46(0), 30-44.

CCT (City of Cape Town). 2012a. 2011 Census. City of Cape Town, Strategic Development Information and GIS Department. Cape Town, South Africa, [Online] 2012; 1-5.

CCT (City of Cape Town). 2012b. Water Services Development Plan 2012/2013: Demographics. City of Cape Town, Water and Sanitation Department. Cape Town, South Africa, [Online] 2012; 15-37.

CCT (City of Cape Town). 2012c. Water Services Development Plan 2012/2013: Service Levels. City of Cape Town, Water and Sanitation Department. Cape Town, South Africa, [Online] 2012; 38-48.

Chanyasak and Kubota (Chanyasak, V. and Kubota, H.). 1981. Carbon/organic nitrogen ratio in water extract as measure of composting degradation. J. Ferment. Technol. 1981, 59 (3); 215–219.

Curtis and Cairncross (Curtis, V., & Cairncross, S.). 2003. Effect of washing hands with soap on diarrhoea risk in the community: A systematic review. The Lancet Infect. Dis. [Online] 2003, 3 (5), 275-281.

DWS (Dutch Water Sector). 2013. Landustries places second generation MobiSan dry sanitation unit in Cape Town. http://www.dutchwatersector.com/news-events/news/631-landustries-places-second-generation-mobisan-dry-sanitation-unit-in-cape-town.html (accessed May 2013)

ECSECC (Eastern Cape Socio Economic Consultative Council). 2012. Census 2011- Key Results for the Eastern Cape. Vincent, East London, [Online] 2012; 1-6.

Engel *et al.* (Engel, A., Kunz, A., and Blanke, M.). 2001. Effects of compost and wood chippings on soil nutrients and on vegetative and reproductive growth and fruit quality of apple to overcome the replant problem. Erwerbsobstbau 2001, 43 (6), 153–160.

EPA (U.S. Environmental Protection Agency, Office of Water). 2000. Water Efficiency Technology Fact Sheet: Oil Recirculating Toilets. NSCEP: Washington, D.C., [Online] 2000; 1-4.

Fabrega (Fabrega, D.C.). 2007. Decision Support Tool for the Appropriate Selection of Sanitation Systems. Wageningen University, Department of Environmental Sciences, The Netherlands, [Online] 2007; 1-94.

FAO (Food and Agriculture Organization of the United Nations, Land and Plant Nutrition Management Service Land and Water Development Division). 2005. Fertilizer use by crop in South Africa. Rome, Italy, [Online] 2005; 1-38.

Feachem *et al.* (Feachem, R.D., Bradley, D.J., Garelick, H., and Mara, D.D.). 1983. Sanitation and Disease: Health Aspects of Excreta and Wastewater Management. World Bank Studies in Water Supply and Sanitation 3. John Wiley & Sons: Washington, D.C., 1983; 1-68.

Franceys *et al.* (Franceys R., Pickford J., and Reed R.). 1992. A guide to the development of on-site sanitation. World Health Organization, Geneva, Switzerland, 2002.

Gensch *et al.* (Gensch, Robert, Miso, Analiza, and Itchon, Gina). 2011. Urine as Liquid Fertilizer in Agricultural Production in the Phillippines: A Practical Field Guide. Xavier University Press: Cagayan de Oro, Philippines, [Online] 2011; 1-42.

HDA (The Housing Development Agency). 2012. Western Cape: Informal Settlements Status. Johannesburg, South Africa, [Online] 2012; 1-38.

Heinonen-Tanski and van Wiik-Sijbesma (Heinonen-Tanski, H. and van Wijk-Sijbesma, C.). 2005. Human excreta for plant production. Bioresource Technology, 2005, 96 (4), 403-411.

Henis, 1986 (Henis, Y.). 1986. Soil microorganism, soil organic matter and soil fertility Chen, Y., Avnimelech, Y., Eds.; Developments in Plant and Soil Sciences: The Role of Organic Matter in Modern Agriculture; Springer Netherlands: The Netherlands, 1986; 25, 159-168.

Hobson (Hobson, J.). 2000. Sustainable sanitation: experiences in Pune with a municipal-NGO community partnership. Environ. and Urbaniz. 2000, 12 (2); 53-62.

Hoffmann *et al.* (Hoffmann, Heike, Platzer, Christoph, Winker, Martina, and Münch, E.v.). 2011. Technology review of constructed wetlands: Subsurface flow constructed wetlands for greywater and domestic wastewater treatment. SuSanA. Esborn, Germany, [Online] 2011; 1-36.

Höglund (Höglund C.). 2001. Evaluation of microbial health risks associated with the reuse of source-separated human urine. Bioteknologi: Royal Institute of Technology, Department of Biotechnology, Stockholm, Sweden, 2001; 1-78.

Huag (Haug, R.T.) 1993. The Practical Handbook of Compost Engineering. LEWIS: Boca Raton, FL, USA 1993; 1-699.

Humanure Handbook (Humanure Handbook). 2013. Make your own Humanure Toilet. http://humanurehandbook.com/humanure_toilet.html (accessed May 2013)

IIUD (Institute for International Urban Development). 2013. Re-Blocking: In-situ Upgrading of Informal Settlements in South Africa.
http://i2ud.org/2013/02/
re-blocking-in-situ-upgrading-of-informal-settlements-in-south-africa/

(accessed May 2013).

ISN *et al.* (Informal Settlement Network, Stellenbosch Municipality, Langrug Community Leadership, and Community Organisation Resource Centre). 2011. Langrug Settlement Enumeration Report. Franschhoek; Stellenbosch Municipality, South Africa, [Online] 2011; 1-21.

Jenkins (Jenkins, J.). 2005. The Humanure Handbook: A Guide to Composting Human Manure, 3; Joseph Pub.: Grove City, PA, USA, 2010; 1-255.

Jenkins (Jenkins, J.). 2010. Humanure Sanitation: The "no waste, no pollution, nothing to dispose of" toilet system. Joseph Pub.: Grove City, PA, USA, [Online] 2010; 1-18.

Johnson *et al.* (Johnson, C., Albrecht, G., Ketterings, Q., Beckman, J., and Stockin, K.). 2005. Nitrogen Basics – The Nitrogen Cycle. Agronomy Fact Sheet Series. Cornell University Cooperative Extension: Department of Crop and Soil Sciences, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, [Online] 2005; 1-2.

Jönsson *et al.* (Jönsson, H., Vinnerås, B., Höglund, C., Stenström, T. A., Dalhammar, G., and Kirchmann, H.). 2000. Recycling source separated human urine. VA-forsk report, 1., 2000.

Jönsson and Vinnerås (Jönsson, H. and Vinnerås, B.). 2004. Adapting the nutrient content of urine and faeces in different countries using FAO and Swedish data. In: Ecosan –Closing the loop. Proceedings of the 2nd international symposium on ecological sanitation, incorporating the 1st IWA specialist group conference on sustainable sanitation. Lübeck, Germany, 7th-11th April 2003; GTZ: Eschborn, Germany, 2004; 623-626.

Jönsson *et al.* (Jönsson, H., Richert Stintzing, A., Vinnerås, B. and Salomon, E.). 2004. Guidelines on the use of urine and faeces in crop production. Report 2004-2. EcoSanRes Publications Series; EcosSanRes Programme and Stockholm Environment Institute: Stockholm, Sweden, [Online] 2004; 1-36.

Kalbermatten *et al.* (Kalbermatten, J.M., Julius, D.S., and Gunnerson, C.G.). 1982. Appropriate sanitation alternatives: a technical and economic appraisal; John Hopkins University Press: Baltimore, MD, USA, 1982; 1-115.

Kenney *et al.* (Kenney, M., Sheppard, P., Shooshan, R., and Siemian, J.). 2011a. WaSHUp: Innovating water sanitation and hygiene upgrading in Langrug – Process Guide. Worcester Polytechnic Institute: Worcester, MA, 2011; 1-42.

Kenney *et al.* (Kenney, M., Sheppard, P., Shooshan, R., and Siemian, J.). 2011b. Innovating water sanitation and hygiene upgrading in Langrug – Executive Summary. Worcester Polytechnic Institute: Worcester, MA, 2011; 1-5.

Kirchmann and Pettersson (Kirchmann, H. and Pettersson, S.). 1995. Human urine Chemical composition and fertiliser use efficiency. Fert. Res. 1995, 40, 149-154.

Kvarnström *et al.* (Kvarnström, Elisabeth, Emilsson, Karin, Stintzing, A. R., Johansson, Mats, Jönsson, Håkan, Petersens, E. a., Schönning, Caroline, Christensen, Jonas, Hellström, Daniel, Qvarnström, Lennart, Ridderstolpe, Peter, and Drangert, Jan-Olof). 2006. Urine Diversion: One Step Towards Sustainable Sanitation. EcoSanRes. SEI. Stockholm, Sweden, [Online] 2006; 1-66.

Lin *et al.* (Lin, S., Shih, S., Wu, D., Lee, Y., Wu, C., Lo, L., and Shiea, J.). 2007. Matrix-assisted laser desorption/ionization time-of-flight mass spectrometry for the detection of hemoglobins as the protein biomarkers for fecal occult blood. Rapid Comm. Mass Spectrom. [Online] 2007, 21 (20); 3311-3316.

Loetscher (Loetscher T., Keller J). 2002. A decision support system for selecting sanitation systems in developing countries. Advanced Wastewater Management Centre, The University of Queensland, Brisbane, Australia, Socio-Economic Planning Sciences. 2002, 36, 267–290.

Maurer *et al*. (Maurer, M., Pronk, W. and Larsen, T. A.). 2006. Treatment processes for source-separated urine. Water Research 2006, 40 (17), 3151-3166.

Maurer (Maurer, M.). 2007. Urine treatment – absolute flexibility, Eawag News, results from Novaquatis research project, Dübendorf, Switzerland, [Online] 2007.

Mnkeni and Austin (Mnkeni, P.N.S and Austin, L.M.). 2009. Water S.A. 2009, 35 (1), 133

Morgan (Morgan, Peter). 2004a. Some Special Constructional Techniques. In An Ecological Approach to Sanitation in Africa: A Compilation of Experiences. EcoSanRes, Stockholm: Stockholm, Sweden, 2004; 1-23.

Morgan (Morgan, Peter). 2004b. Urine Diversion-how to build and manage a single vault composting toilet system. In An Ecological Approach to Sanitation in Africa: A Compilation of Experiences. EcoSanRes, Stockholm: Stockholm, Sweden, 2004; 11-12.

Morgan (Morgan, Peter). 2007. Toilets That Make Compost: Low-cost, sanitary toilets that produce valuable compost for crops in an African context. EcoSanRes: Stockholm Environment Institute, Stockholm, Sweden, 2007; 1-100.

Münch and Winker (Münch, E.v. and Winker, Martina). 2011. Technology review of urine diversion components: Overview of urine diversion components such as waterless urinals, urine diversion toilets, urine storage and reuse systems. SuSanA. Esborn, Germany, [Online] 2011; 1-32.

Navarro (Navarro R.G.). 1994. Improving Sanitation in Coastal Communities with Special Reference to Puerto Princesa, Palawan Province, Philippines. School of Architecture, McGill University: Montreal, Canada, [Online] 1994; 1-123.

Niwagaba *et al.* (Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C., & Jönsson, H.). 2009. Bench-scale composting of source-separated human faeces for sanitation. Waste Management 2009, 29 (2), 585-589.

NSFC. (National Small Flows Clearinghouse). 2000. Alternative Toilets: Options for Conservation and Specific Site Conditions. Pipeline. [Online] 2000, 11 (3), 1-10

Oates *et al.* (Oates, P. M., Shanahan, P., & Polz, M. F.). 2003. Solar disinfection (SODIS): Simulation of solar radiation for global assessment and application for point-of-use water treatment in Haiti. Water Res. [Online] 2003, 37(1), 47-54.

Parkinson *et al.* (Parkinson, Jonathan, Hutton, Guy, Pfeiffer, Verena, Blume, Steffen, and Feiereisen, Philipp). 2012. Sustainable Sanitation Alliance Factsheet: Financial and economic analysis. SuSanA. [Online] 2012; 1-8.

Quayle (Quayle, T.). 2012. MobiSan: Communal urine diversion toilets in Pook se Bos, Cape Town. ACCESSanitation, [Online] 2012; 1-6.

Richert *et al.* (Richert, A., Gensch, R., Joensson, H., Stenstroem, T., and Dagerskog, L.). 2010. Practical Guidance on the Use of Urine in Crop Production: EcoSanRes Programme Stockholm Environment Institute Kräftriket 2B, Stockholm, Sweden, [Online] 2010; 1-55.

Robinson, Brian, E. (2005). Household Adoption of Ecological Sanitation: An Assessment of Agricultural Value and User Perspectives in Nyanza Province, Kenya. Massachusetts Institute of Technology: Massachusetts, USA, [Online] 2005; 1-154.

Rodriques *et al.* (Rodriques, Elvira, Gie, Janet, and Craig Haskins). 2006. Informal Dwelling Count for Cape Town (1993-2005). City of Cape Town, Information and Knowledge Management Department, Strategic Information Brach. Cape Town, South Africa, [Online] 2006; 1-15.

Saito *et al.* (Saito, T., Hayakawa, T., Nakamura, K., Takita, T., Suzuki, K., and Innami, S.). 1990. Fecal Output, Gastrointestinal Transit Time, Frequency of Evacuation and Apparent Excretion Rate of Dietary Fiber in Young Men Given Diets Containing Different Levels of Dietary Fiber. J. Nutr. Sci. Vitaminol. 1990, 37, 493-508.

Schönning (Schönning, Caroline). 2001. Urine Diversion-hygienic risks and microbial guidelines for reuse. Department of Parasitology, Mycology and Environmental Microbiology Swedish Institute for Infectious Disease Control (SMI). Stockholm, Sweden, [Online] 2001; 1-41.

SDI (South African SDI Alliance). 2013. Informal Settlement Upgrading: Langrug. http://sasdialliance.org.za/projects/langrug/ (accessed May 2013)

Smith *et al.* (Smith, D.C., Beharee, V., Hughes, J.C.). 2001. The effects of composts produced by a simple composting procedure on the yields of Swiss chard (*Beta vulgaris* L. var. *flavescens*) and common bean (*Phaseolis vulgaris* L. var. *nanus*). Scientia Horticulture 2001, 91 (3-4), 393-406.

StatsSA (Statistics South Africa). 2011. Census 2011: Census in brief. Pretoria, South Africa, [Online] 2011; 1-102.

Stoner (Stoner, C. H.). 1977. Goodbye to the Flush Toilet: Water-Saving Alternatives to Cesspools, Septic Tanks, and Sewers. Rodale Press: Emmaus, Pennsylvania, [Online] 1977; 1-286.

Storburn (Storburn International Inc.). 2013. Info-Specifications-Operation: Storburn 60K Series Pollution-Free Toilets. http://www.storburn.ca/storburn.html (accessed May 2013)

Udert *et al.* (Udert, K., Larsen, T., Biebow, M., and Gujer, W.). 2003. Urea hydrolysis and precipitation dynamics in a urine-collecting system. Water Research [Online] 2003, 37 (11) 2571-2582.

Udert *et al.* (Udert, K., Larsen, T., Biebow, M., and Gujer, W.). 2006. Fate of major compounds in source-separated urine. Water Science and Technology 2006, 54 (11-12), 413-420.

UN (United Nations). 2012. The Millennium Development Goals Report. New York, USA, [Online] 2012; 1-68.

UN (United Nations). 2013. United Nations Millennium Development Goals. http://www.un.org/millenniumgoals/ (accessed May 2013)

UNICEF (United Nations Children’s Emergency Fund). 2013. Water, Sanitation and Hygiene. UN. http://www.unicef.org/wash/ (accessed May 2013)

USDA (United States Department of Agriculture, Forest Service Equipment Development Center). 1975. Oil-Recirculating Waterless Toilet. San Dimas, California. [Online] 1975; 1-6.

Vandenberg (Vandenberg, Samantha). 2013. "SDI Agreement 'first in the world'" Eikestad Nuus. http://eikestadnuus.mobi/news/read/1193/sdi-agreement-first-in-the-world (accessed May 2013)

Vinnerås (Vinnerås, B., Björklund, A., and Jönsson, H.). 2003. Thermal composting of faecal matter as treatment and possible disinfection method—laboratory-scale and pilot-scale studies. Bioresource Technology 2003, 88 (1), 47-54.

Vinnerås *et al.* (Vinnerås, B., Palmquist, H., Balmer, P. and Jönsson, H.). 2006. The characteristics of household wastewater and biodegradable solid waste – A proposal for new Swedish design values. Urban Water [Online] 2006, 3 (1), 3-11.

Vinnerås (Vinnerås, B.). 2007. Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. Bioresource Technology, [Online] 2007, 98 (17), 3317-3321

Vinnerås *et al*. (Vinnerås, B., Nordin, A., Niwagaba, C., and Nyberg, K.). 2008. Inactivation of bacteria and viruses in human urine depending on temperature and dilution rate. Water Research, [Online] 2008, 42 (15), 4067-4074.

WHO (World Health Organization). 1999. Environmental Health Indicators: Framework and Methodologies- Protection of the Human Environment, Occupational and Environmental Health Series. Geneva, Switzerland, [Online] 1999; 1-119.

WHO (World Health Organization). 2006. WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater: Excreta and greywater use in agriculture. Geneva, Switzerland. 2006; Vol. 4.

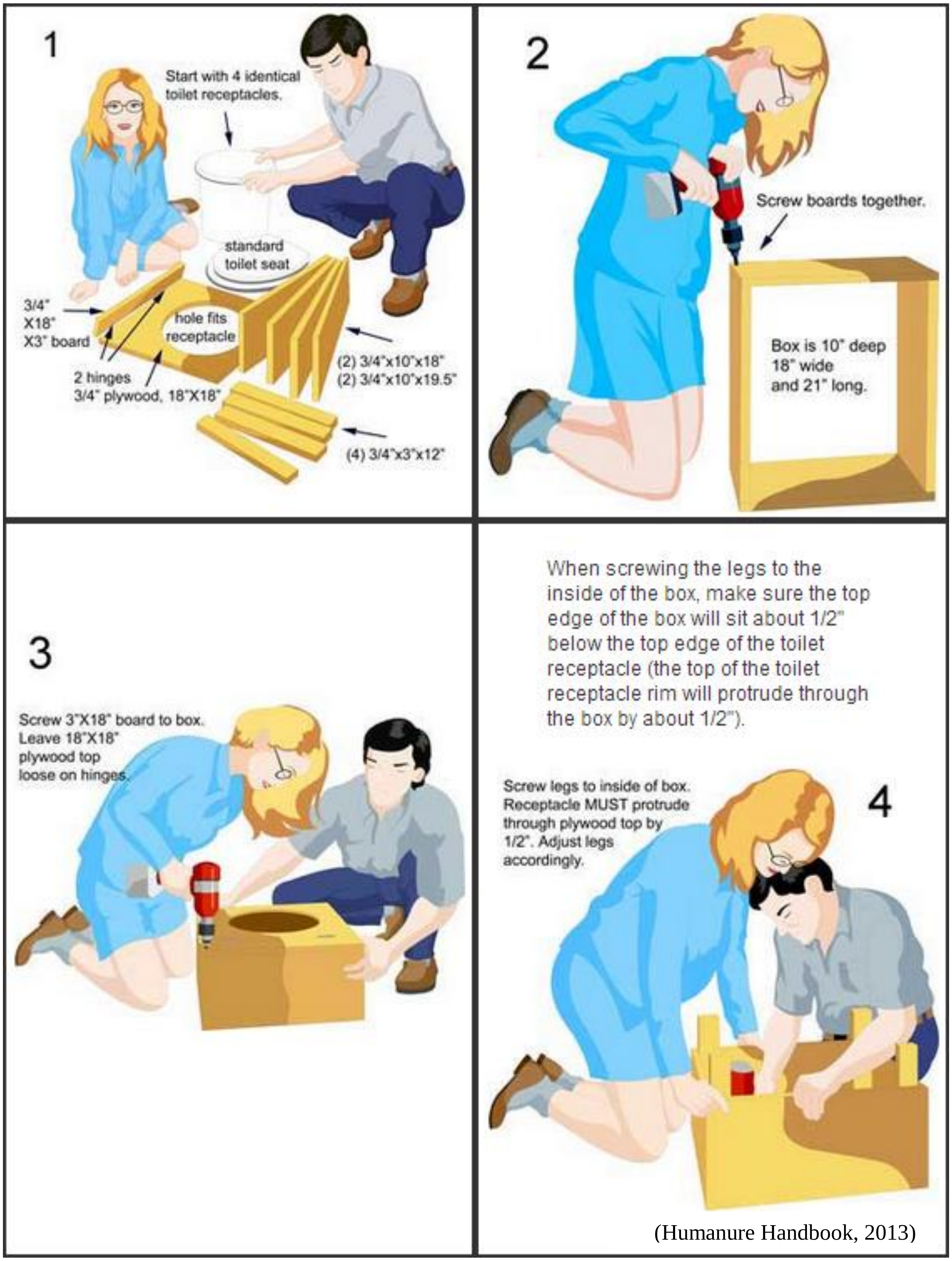
WHO (World Health Organization). 2013a. Water Sanitation and Health (WSH): Health through safe drinking and basic sanitation. http://www.who.int/water_sanitation_health/mdg1/en/ (accessed May 2013)

WHO (World Health Organization). 2013b. Water Supply, Sanitation and Hygiene Development. http://www.who.int/water_sanitation_health/hygiene/en/ (accessed May 2013)

WRC (Water Research Commission). 2007. Sanitation Decision Support Model. Pretoria. South Africa

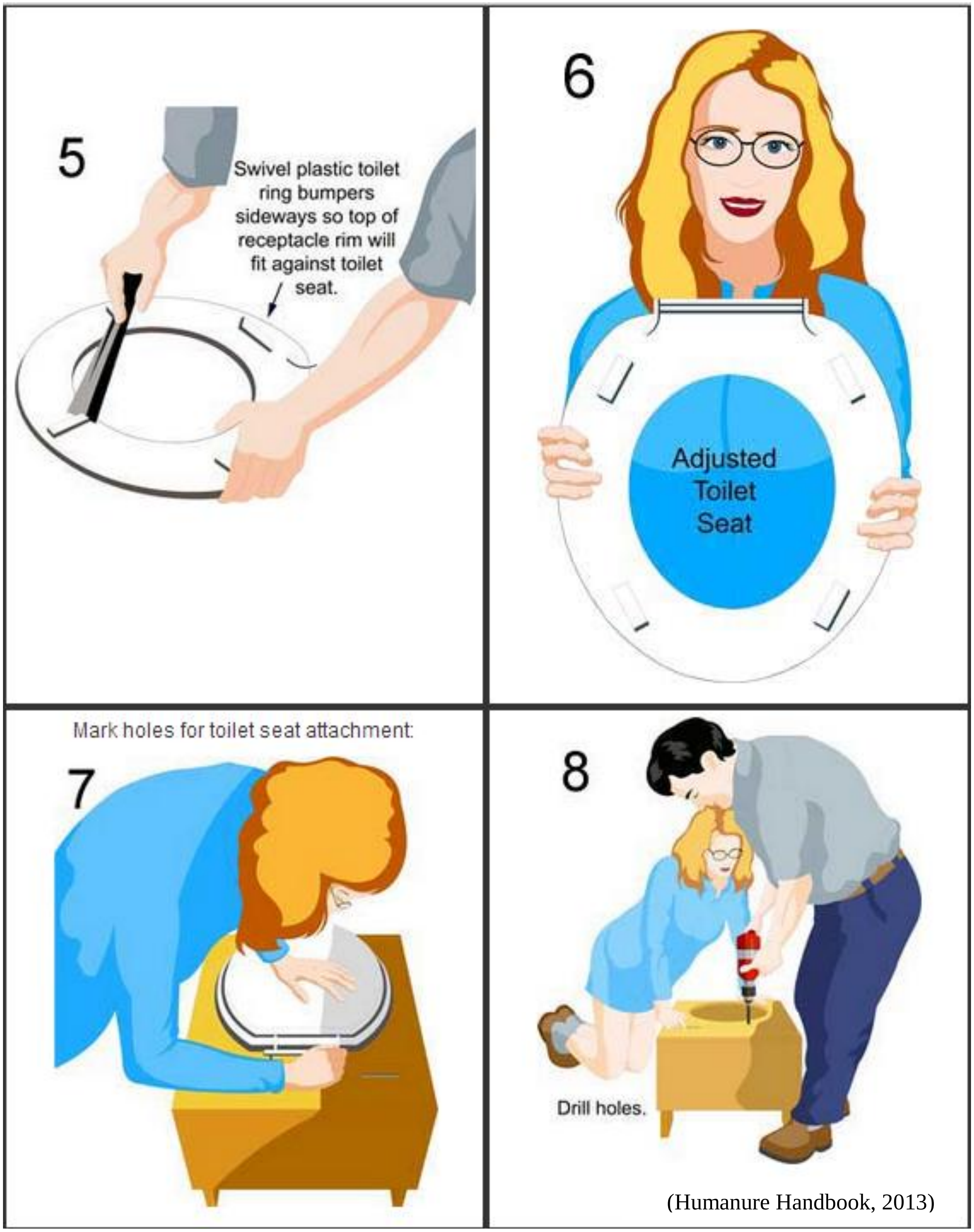
WSCC (Water Supply & Sanitation: Collaborative Council). 2013. Global WaSH Campaign. http://www.wsscc.org/wash-advocacy/campaigns-events/global-wash-campaign (accessed May 2013)

Appendix A: Constructing a Loveable Loo



When screwing the legs to the inside of the box, make sure the top edge of the box will sit about 1/2" below the top edge of the toilet receptacle (the top of the toilet receptacle rim will protrude through the box by about 1/2").

(Humanure Handbook, 2013)



Swivel plastic toilet ring bumpers sideways so top of receptacle rim will fit against toilet seat.

Mark holes for toilet seat attachment:

Drill holes.

(Humanure Handbook, 2013)

Figure 34. Visual Instruction for Constructing a Loveable Loo

Appendix B: Constructing a UDDT Locally

A concrete mix is made using five parts clean river sand (50 litres) and one part cement (10 litres). Alternately 3 parts river sand, 2 parts small stones and 1 part cement can be used. A brick mould with dimensions 1.35 m long by 0.9 m wide by 75 mm deep (Figure 35) is used to cast the concrete slab. An area, 450 mm long and 335 mm deep, is made for the step. Steel wires are place in the concrete slab for reinforcement. The slab is left to cure for at least 2 days. It should be kept wet for several days to cure properly (Morgan, 2007).

Figure 35. Brick Mould for Concrete Slab (Morgan, 2007)

A second slab with dimensions 1.2 m long and 0.9 m wide and about 40 mm deep (Figure 36) should be cast offsite using the same method as for the base slab (Morgan, 2007). When placed directly on top of the vault, this slab will serve as the base for the toilet. Holes for the pedestal and vent pipe can be cast in the slab by placing a bucket and metal cylinder in the mould, respectively. The concrete mix should be added to the mould to half the slab height. Reinforcing wires are to set in the mix. More mix is added for the remainder of the slab height. The concrete should be smoothed down with a wooden float followed by a steel float (Morgan, 2007).

Figure 36. Brick Mould for Toilet Slab with Bucket and Metal Cylinder for Pedestal and Vent Pipe Space (Morgan, 2007)

Using bricks on their edge and mortar, a vault is built on top on the concrete slab base (Figure 37). If a 20 litre bucket is used the vault should be about 40 cm high. This will require about 4 layers of bricks built on edge or about 6 layers built normally. The walls are built so that the outer measurements of the top are 1.2 m x 0.9 m and the base 1.35 m x 0.9 m. This allows for the slope at the back of the vault over which the vault access slab at the rear will be fitted (Figure 37). To support the rear end of the toilet slab placed on top the brick vault, a reinforced concrete lintel spanning the rear end of the vault should be used. A lintel, with dimensions 0.9 m long and 225 mm x 75 mm wide, can be made with 3 parts river sand and one part cement and 3 or 4 mm wires for reinforcement. It takes about a week for the lintel to cure after which it can be mounted on the rear wall of the brick vault (Figure 38) (Morgan, 2007).

Figure 37. Vault Using Bricks on Their Edge (Morgan, 2007)

Figure 38. Vault with Concrete Lintel above 20 Litre Bucket (Morgan, 2007)

The dimensions for the vault access slab are about 90 cm x 45 cm - the exact dimensions must match the vault. A thin high strength concrete slab can be cast using 2 parts river sand and one part cement with 15mm chicken wire as reinforcing and two wire handles inserted for lifting. The slab should cure for 7 – 10 days. It rests against the sloping rear side of the vault (Figure 39). A neat, almost airtight fit is required. This is made by applying strong cement plaster to the vault brickwork and grease to the adjacent cement panel side and bringing the two together. After curing the panel can be withdrawn leaving an exact impression on the vault. The concrete toilet slab is then fitted and bonded on top of the vault in cement mortar (Figure 40) (Morgan, 2007).

Figure 39. Fitting Vault Access Slab (Morgan, 2007)

Figure 40. Front View of Vault with Toilet Slab Placed on Top (Morgan, 2007)

The UDDT pedestal is constructed using a 20 L bucket, a 20 mm polyethylene bend, a plastic toilet seat and cement, sand and wire. First the base of the bucket is sawn off squarely (Figure 41). The base is then cut in half (Figure 42 and 43). One half is fitted within the bucket about halfway up the walls at an angle (Figure 44). This serves as the urine diverter. The diverter is secured by drilling small holes through the cut base halve and bucket walls and passing wire through and tightening (Figure 45). For fitting the 20 mm polyethylene bend, a hole is drilled through the bucket wall just above the base of the diverter. The bend is turned at an angle on the outside (Figure 46 and 47) (Morgan, 2007).

Figure 41. Cutting off the Bucket Base (Morgan, 2007)

Figure 42. Marking base for Cutting (Morgan, 2007)

Figure 43. Cut Base Halves (Morgan, 2007)

Figure 44. Placing Urine Diverter (Cut Base Half) Half-way up Bucket at an Angle (Morgan, 2007)

Figure 45. Attached Diverter with Wire (Morgan, 2007)

Figure 46. Fitting Pipe Bend to Bucket (Morgan, 2007)

Figure 47. Inside View of the Fitted Pipe Bend (Morgan, 2007)

A hot wire is used to drill holes through the plastic ribs which support the toilet seat (Figure 48). Through these holes a wire is threaded in a loop under the seat (Figure 49). Concrete from a mix of 3 parts river sand and 1 part cement is added to the underside of the toilet seat (Figure 50). The concrete and wire will create a higher strength toilet seat that will form a bond with the side walls of the pedestal (Morgan, 2007).

Figure 48. Using Hot Wire to Make a Hole through the Plastic Toilet Seat Ribs (Morgan, 2007)

Figure 49. Toilet Seat with a Threaded Loop of Wire (Morgan, 2007)

Figure 50. Concrete Added to the Toilet Seat (Morgan, 2007)

The bucket is fitted centrally over the toilet seat, with the urine-diverting hold facing the front of the toilet seat (Figure 51). Eight pieces of bent wire are introduced into the cement supporting the seat (Figure 52). This is allowed to cure overnight. A mix of 3:1 sand and cement is made and plastered half way up the walls of the bucket (Figure 53). This is left overnight to cure (Morgan, 2007).

Figure 51. Bucket Fitted to Toilet Seat (Morgan, 2007)

Figure 52. Bent Wire around Toilet Seat (Morgan, 2007)

Figure 53. Concrete Added Half-way up Bucket (Morgan, 2007)

The rest of the bucket is cemented with the 3:1 mix after the bottom half cures (Figure 54). It is left to cure overnight. A mould to form the base of toilet pedestal can be made with wood, about 60 cm x 60 cm and 40 mm deep (Figure 55). The bucket and seat are overturned into a base mould, which is laid on top of a plastic sheet. The same 3:1 river sand and cement mix is placed within the mould to create the base. Wire is added to both the base and coiled around the pedestal (Figure 56). A final layer of the 3:1 mix is plastered up the side walls of the pedestal over the wire. The final layer can be made with cement watered down to make a thick paint and applied with a brush. The completely cemented pedestal should cure for several days kept wet at all times (Figure 57). A plastic sheet and sacking can be used to cover the curing toilet pedestal (Morgan, 2007).

Figure 54. Concrete Added to the Second Half of Bucket (Morgan, 2007)

Figure 55. Bucket and Seat within Base Mould (Morgan, 2007)

Figure 56. Wire Added for Reinforcement (Morgan, 2007)

Figure 57. Completely Cemented Pedestal Curing (Morgan, 2007)

A pliable putty should be applied to the space between the bucket side wall and urine diverter. The putty is pressed into the gap from underneath (Figure 58). It is also be pressed into the gap from the upper side (Figure 59). This seals the apparatus enabling urine to enter the urine diverter and flow into the plastic bend. A plastic pipe is connected to the bend (Figure 60). The pipe is led back over the concrete base of the urine-diverting pedestal to the rear of the toilet (Figure 61). Once the concrete is completely cured and dry, a coat of enamel paint can be applied to the pedestal to improve the aesthetics of the toilet system (Figure 62). The completely dry pedestal is placed into the toilet slab and enclosed by a superstructure for privacy (Figure 63). Superstructures can be made from bricks or timber, metal sheeting, asbestos sheeting, reeds, grass or of any material that offers privacy. The urine pipe can be led into a soakaway or into a vegetable garden, preferably beneath ground level. The urine can also be led to a plastic container placed in a hole dug in the ground. The pipe can also be led to a tree, such as a banana tree (Figure 64) (Morgan, 2007). Within the vault, feces is collected, such as in a 20 litre bucket. Buckets are retrieved via the access slab located at the rear of the vault (Figure 65).

Figure 58. Urine Diverter Sealed from Bottom (Morgan, 2007)

Figure 59. Urine Diverter Sealed from Top (Morgan, 2007)

Figure 60. Attached Urine Pipe (Morgan, 2007)

Figure 61. Urine Pipe Led to Rear of Toilet (Morgan, 2007)

Figure 62. Painted Pedestal (Morgan, 2007)

Figure 63. Installed UDDT on Slab within Straw Superstructure (Morgan, 2007)

Figure 64. Urine Pipe Led to Banana Tree (Morgan, 2007)

Figure 65. View of Collection Bucket for Feces within Vault after Removing Access Slab (Morgan, 2007)