Sanitation Strategy for Waste Management in a Low Income Region of Ghana

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Executive Summary

As many African nations are struggling with serious health, economic and political issues, sanitation must find its place among national and municipal priorities. The vast amount of disease and, ultimately, death related to sanitation problems is disproportionate to other causes and amounts to about eighty percent of world's sicknesses (WaterAid 2007). In Ghana there is a picture of relative economic prosperity with Accra and Kumasi leading the way. These cities have begun sophisticated waste treatment with the implementation of Fecal Sludge Treatment Plants before many other African cities (Doku 2003). However, these cities continue to be overrun with waste, both organic and inorganic, and are also burdening surrounding areas by dumping and open-pit landfill practices (Boadi and Kuitunen 2003). How did a city of 1,970,400 (Accra, 2005) become a place where only two fecal-waste treatment plants are operating and both at reduced capacity (Doku 2003)?

Lack of appropriate treatment methods, collection vehicles, labor, capital, management; the reasons are countless and extremely complex. In an attempt to understand a waste treatment system in Ghana and its feasibility technically, socially and economically, this project was initiated. The study village, a modest population of 750 spread over 1.1 km^2 is seen in this report as a future Kumasi, or Accra. What can the village do to prepare for fast population growth? What kind of waste treatment system could be the roots for a smooth transition into an urban environment? The objective of the project is to design a waste treatment system for the village of 750, but it could be said that the motive is the need for a new waste-culture of beliefs and practices that can be a foundation for the building of a healthy community, no matter the size.

This report explores the literature on Ghana and the relevant social and technical aspects of waste treatment and sets up three design scenarios for the overall waste treatment system from toilet to landfill. In order to analyze the feasibility of the scenarios and provide a basis for future physical designs a mathematical model was made to simulate each major process in the scenario. In addition to the three scenario models, a social engineering design is included as it is essential that the local people are involved in financing, design, construction and management of whatever technology they are to own. While economic comparisons were calculated, the social and technical complications would most likely outweigh the ability to pay. Without education of the people and tools, such as the model created for this report, it is likely that a small village would not prioritize waste treatment, setting up for a lack of infrastructure and organization in the future.

The production of this design project has been very rewarding to the authors as literature searches have led the way to more and more insight about a new people and culture from their perspectives. The report will, hopefully, only reflect the respect and admiration the authors have for the people of Ghana and enlighten the reader as well.

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Introduction

Designing for Ghana: a change in Ideology

This design project involves a different perspective on design due to the remote nature of the area in study and the consequent large number of uncertainties.

Participatory development is a change in the ideology behind product design (Narayan 1998). Rather than detailed components being designed for a community based on waste generation data, the tools with which to learn and make decisions are designed for a community and the decisions are made with the participation of community members considering many more aspects than data. For example, the available materials, location of system, desirable end products, laborer skills and potential operational staff are all crucial factors the community can educate the engineer on.

Participatory development is an appropriate way to tackle waste treatment projects in developing countries because it removes the blind aspect of designing for a remote location. Since each community is different on so many levels it is a better strategy to aid the locals in designing an appropriate waste treatment system than to design and then present the options to the community(Narayan 1998).

While all stakeholders should be involved, women are most important in the design process because, as the primary managers of water and waste in the household, it is the women who know the community water and waste situation the best (Narayan 1998). They not only have the highest to gain from sanitation improvements, but have the most knowledge about what the community has for resources and needs in terms of health and safety of their families.

In any project in a developing country there are two objectives (Narayan 1998):

1. Completing the designed facilities or processes
2. Achieving sustainability and capacity building for the community and the implementing agency

In order to properly reflect the duality of this project an atypical design ideology will be used throughout the report. Rather than the conventional engineering project process, this report will design a project utilizing participatory approaches. The tools to begin a community-specific design will be laid in place. A model to determine the feasibility of waste system components and basic values for future design will be included as well as a strategy for capacity building among the community. With such tools, the engineer may begin the design using input from the community with participatory approach.

Problem identification

It is estimated that 80% of the world sickness toll can be traced back to poor sanitation and related hygiene (Talbot 2005). The improper handling and disposal of waste frequently causes disease and contamination but especially in locations where there isn't infrastructure to handle waste sanitarily, such as the focus of this study: Northern Ghana. To further complicate the problem in this area there is little financial capacity for infrastructure and a dry climate, making water a valuable resource. A lack of education on the importance of sanitation and simple precautionary measures only exacerbates the problem. More detailed analysis of these issues can be read in the Design Proposal submitted in March 2008 (Ebner and Leroux 2008).

The safe stabilization of waste without the use of water for transport is a challenge facing many areas of the world. Although this is the main problem being addressed in this report, attention will be given to solid waste from households as well as the root cause of much of these problems: lack of education. It is necessary to view these problems together and examine the community waste system as a whole to judge the feasibility and potential success of a waste system.

Objective

The objective of the project is to study this specific area in Sub-Saharan Africa and create a multi-faceted waste transport, treatment and redistribution strategy following the use of a mathematical model of some of the key waste treatment processes. The design will focus on three scenarios for treatment of organic waste but also include strategies for sanitary transport of waste and a breakdown of the mass of waste for recycling versus a landfill. With respect to the participatory approach, it would be inappropriate for the authors to design specific waste treatment facilities without consulting the community. Therefore, a mathematical model will be designed to aid in learning about and understanding how the mechanisms of waste treatment can work together. The model will yield the key values needed to design the specific components based on waste characteristics, participation ratio and even climate. With these parameters community leaders and engineers could work together to design appropriate waste treatment facilities. Economic benefit to the community and long term effects of improved health and individual productivity will be considered. The design will include a detailed strategy for education as social engineering and is expected to mesh well with the culture.

Literature Review

Context

As described in detail in the proposal by the same title (Ebner and Leroux 2008), an area in Northern Ghana was chosen for the study based on information available on the area, climate and poverty profile. The climate is hot and dry with a transition from semi-arid conditions to more wet conditions. The average temperature is 31°C and annual rainfall of about 1000 mm (Ghana 2002). The area is about 1.1 km^2 and there are approximately 750 residents. It is estimated that the average household has 6.8 people (Whitehead 2006). The waste generation data used for the area (Appendix A Table A1) is from a study in Nigeria and typical urine and feces generation data was used (Appendix A Table A1). The people in the area have a mostly carbohydrate diet where corn, millet and yams form the base of it (Armar-Klemesu, T.Rikimaru et al. 1995).

The area of study is approximately 20 km southeast of Bawku town. This area was identified on satellite images. The image below shows many home compounds and an agricultural area bordering the local water source.

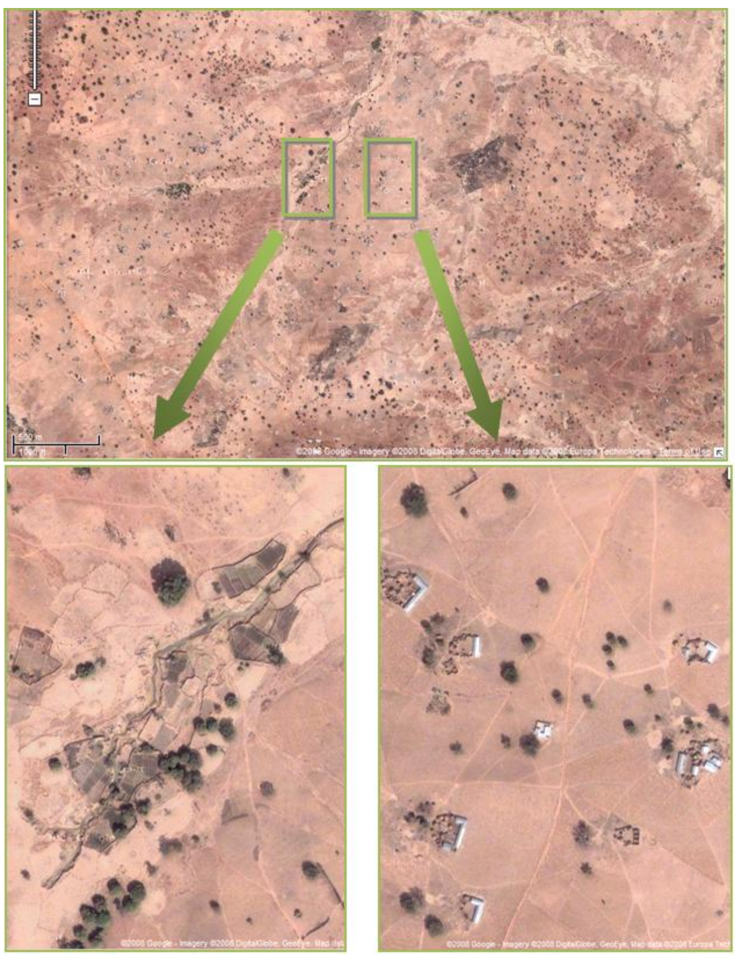

Figure 1. Satellite image of the area of study. Agriculture along a water source (left) and examples of home arrangements (right).(Google 2008)

Definitions

"Solid Waste" refers to household waste, not feces or urine, for the purpose of this document.

"Night Soil" is a combination of human feces and urine, often collected in bucket latrines in homes or at public toilet locations. Night soil will be considered to consist of the proportions of urine and feces described by Doku (2003). Night soil is a high-strength waste due to the minimal dilution factor.

"Toilet Sludge" refers to the large volume of night soil that has collected and sat in public pit latrines. Sludge, as defined by *Metcalf and Eddy* (1991) is a concentration of solids and semisolids in human waste. Toilet sludge, a high-strength waste, is partially digested night soil resulting from a long collection period characteristic of public bathroom facilities. Toilet Sludge is usually removed by a vacuum truck to be transported to a treatment facility and is the main cause for the failure of the Fecal Sludge Treatment Plants in Ghana(Doku 2003).

"Septage" refers to the mixture of human waste and added water used for flushing and transporting the waste to a septic tank or to a centralized treatment center. Septage, a low-strength waste, is more common in Accra, Kumasi and other urbanized areas. In Northern Ghana, the driest region, septage is rare (Johnson 2008).

"Fecal Sludge" is a term used to describe a mixture of urine, feces and water or any combination of these. Night soil, toilet sludge and septage are all considered fecal sludge as well as combinations of them. In most literature (Doku 2003) the term is determined based on context.

"Stabilized Waste" is used in much of the literature without a clear definition. For the purpose of this report waste will be considered to be a substance can be handled without putting human health at risk. The pathogenic and parasitic organisms must be inactive.

Solid Waste in Ghana

Ghana, similar to many developing countries, is overwhelmed by solid waste. Proper disposal sites are not common and there are serious health risks associated with open dumping and the resulting scavenging activities. As reviewed in *Solid Waste Landfills in Middle- and Lower-Income Countries* (1999), the human health risks lie in four main categories:

1. Direct Physical Harm from slope collapse, explosion, or transport activities
2. Bacteriological and protozoan pathogens or other infective agents
3. Chemical contaminants affecting organs and regulatory functions in the body and inducing cancer.
4. Impact of chemical and microbiological contaminants, organic compounds and radioactive material on reproduction. Stillbirth, low birth weighs and specific birth defects are common.

The uncontrolled dumping of wastes also has great affect on the environment. Landfills in Ghana do not have provision for leachate or gas collection (Boadi and Kuitunen 2003). Since the percentage of organic matter being dumped is high, leachate is a serious issue because as decomposition takes place, the resulting moisture travels towards the water table carrying contaminants such as heavy metals. In general, a lack of knowledge about waste technology is evident. For example, in Accra, compactor trucks are used in the low income areas. They squeeze leachate from the organic waste causing more risk of contamination and disease spreading (Boadi and Kuitunen 2003).

Solid waste in low income areas has a high share of inert (sand and dust) and organic matter. Also, it is usually stored in open containers, promoting decay and attracting pests. Waste generation as reported in Accra by Boadi and Kuitunen (2003) in a low income area was 0.4 kg/cap/day. Similar values were found by Cointreau-Levine (1992). Pearce and Turner (1994) suggested a breakdown of waste type by percentage, which was adapted for this report.

Table 1: Waste Composition for Low Income Area

Component	Percent by Weight	Production per Capita per Day (kg)	Production per Day, Village (kg)
Putrescible	76	0.416	312.33
Paper	6.6	0.036	27.12
Metal	2.5	0.014	10.27
Glass	0.6	0.003	2.47
Plastic, Rubber, Leather	4	0.022	16.44
Textile	1.4	0.008	5.75
Ceramics, ect.	8.9	0.049	36.58
		TOTAL	**410.96**

Source: Authors' calculations based on Pearce and Turner, 1994

Economically, solid waste disposal is overlooked because the majority of the municipal budget for waste is spent on collection and transport. Pearce and Turner report gross efficiencies as "commonplace" in solid waste management where 20% to 50% of an operational municipal budget might be spent on solid waste to reach collection efficiencies between 60% and 70% (1994).

As pointed out by Rushbrook and Pugh (1999) the disposal of waste to land is inevitable. In any waste management system, it is necessary to have an endpoint for wastes. The authors suggest, however, that landfills should be set up and operated properly according to the local populations and waste. The future costs of health and environmental problems and loss of natural resources are high compared to the cost of an organized landfill effort. It is possible to improve landfills step-by-step and in many studies landfill situations have been improved greatly just by reorganizing the funds available into better practices (Philip Rushbrook and Pugh 1999). It has been estimated that the cost of an upgraded landfill in lower-income countries is between US$3 and 10 per tonne of waste. Not counting the mass of the putriscible waste, this equals US$108 to 360 per year for the small village being studied.

Fecal Sludge in Ghana

In Northern Ghana night soil and toilet sludge are the most common forms of fecal sludge. These high-strength wastes are often disposed of inappropriately into streams, bushes or farmlands. Below is an image of the current waste transport and treatment system in Ghana as seen by Doku (2003).

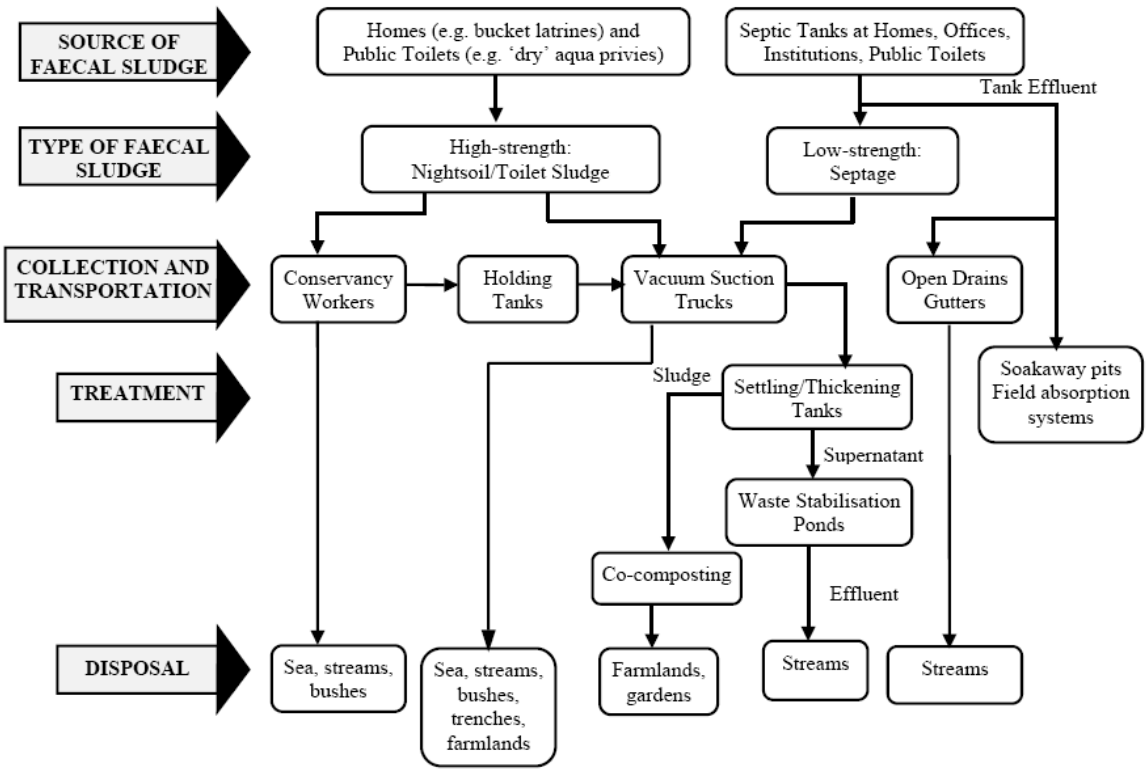

Figure 2.Diagram of source, type, collection, transport, treatment and disposal of fecal sludge in Ghana. Source: (Doku 2003)

In more populated and developed areas of Ghana there are several treatment facilities know as Fecal Sludge Treatment Plants (FSTP) that are intended to treat human waste while satisfying the basic criteria of waste treatment for a developing country. As described below treatment facilities should (Doku 2003):

"a. be technologically appropriate, i.e. low-cost both in capital and operating costs, simple to construct, operate and maintain (compatible with available expertise);
b. need little or no imported equipment;
c. not be energy-intensive; and
d. be able to treat the wastes to at least secondary level, with emphasis on the removal of pathogens and helminth eggs."

These FSTP systems begin with solid-liquid separation and include anaerobic sludge ponds, an evapotranspiration bed and composting of solids. A treatment schematic is seen below:

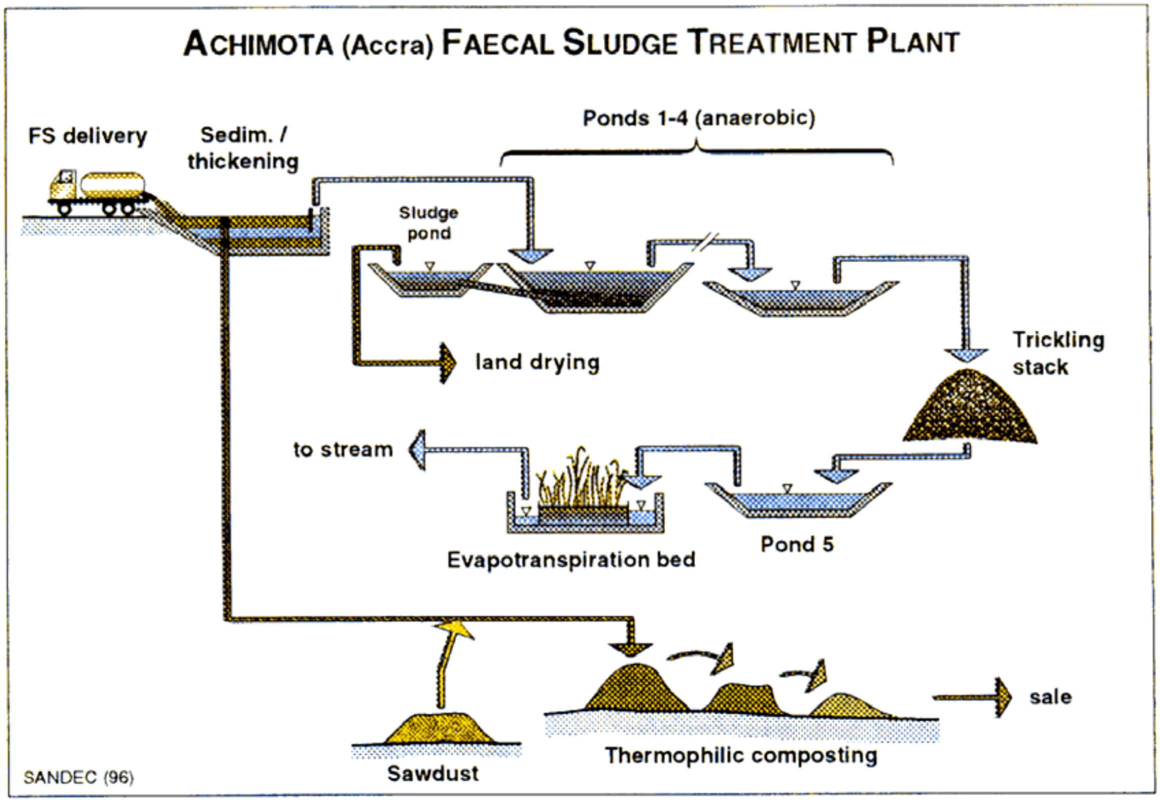

Figure 3. Schematic diagram of the Achimota Faecal Sludge Treatment Plant
Source: Heinss et al. (1998)

The systems have been shown to work properly with septage, but not with public toilet sludge or night soil. The difference is due to the separation properties of the mixtures. Septage has good settling characteristics so that liquids and solids can be treated separately. However, when public toilet sludge or night soil is introduced, poor settling characteristics cause a higher concentration of solids directed into the liquid treatment system, which subsequently fails (Doku 2003). Ghanaian conservancy workers responsible for collecting and delivering the fecal sludge are turned away from the struggling FSTP and often release the vacuum trucks full of waste into the environment. It has been noted that a different process is in need of development.

Since several FSTP systems implemented in Ghana have sustained success under the proper low-strength waste loading, there are workers with knowledge of some waste treatment technology and experience with plant operation which is a huge asset and should be considered when examining the feasibility of new processes. Composting solids and treatment of liquids through anaerobic and facultative ponds are also common processes in Ghana. For that reason, they will not be modeled in detail for feasibility. The local knowledge of materials, construction and operation of these processes could be a huge asset to new fecal sludge treatment designs (Doku 2003).

The data for the composition of toilet sludge and night soil vary greatly over the literature and from city to city. The variation is cited as being the result of different amounts of water used in the facilities, seasons, collection methods and efficiency, emptying frequency and user habits (Doku 2003). Most data is given per capita, yet there is no record of how many people are using each facility and or how often. A review of available waste characteristics from Ghana can be observed in Appendix B (Table B1). Several authors suggest more thorough examination of local waste characteristics are necessary for treatment design success (A. Mensah, O. Cofie et al. 2003).

Since the FSTP is not efficient at handling high strength wastes, as described previously, and the main type of waste in the area of study is high-strength, this design will use some concepts and technology from the FSTP and the lessons learned from the failed FSTP systems to examine high-strength waste treatment options for Northern Ghana.

Treatment Scenarios

There are three main scenarios to accomplish stabilization of human wastes without dilution:

i. Anaerobic digestion for biogas, with further processing of remaining waste
ii. Co-composting after dewatering fecal sludge
iii. Solar drying and composting

The second option is prefaced by "co" to indicate the inclusion of organic food waste to aid the process. Since food waste is high in sugar, it is a good additive to the nitrogen strong fecal sludge in the composting process (A. Mensah, O. Cofie et al. 2003). All three processes result in usable end products as described in detail below.

i. Anaerobic digestion

A study by Doku (2003) suggests that anaerobic digestion before the initial solid-liquid separation would be an advisable addition to the FSTP process to adapt it to high-strength waste. The digestion process would reduce the strength of the waste (Doku 2003) and due to long residence time has the capacity to kill some pathogens including E.coli, bacilli and spirochetes (McGarry and Stainforth 1978). The effluent mixture would also have improved settling characteristics since, as noted by Younge and McCarty in 1969, the anaerobic sludge forms readily settle-able aggregates and the organic matter concentration is greatly reduced (Lettinga 1995; Reynolds 1996). Due to the complimenting nature of food waste and night soil, it would be beneficial to co-digest the two (A. Mensah, O. Cofie et al. 2003) and the process would likely yield more biogas.

The anaerobic digestion process is generalized as follows:
(Organic Matter) + (Combined Oxygen) → (New Cells) +CO_2 + CH_4 + (other end products)

The generalization is quite deceiving as digestion is a complicated process including three major biological processes: hydrolysis of proteins carbohydrates and lipids, acetogenesis to form volatile fatty acids, and finally methanogenesis to form methane gas. The rate and efficiencies of conversion depend greatly on environmental factors as well as the waste type and bacterial sludge types (Reynolds 1996). A good diagram to help understand the sequence of methane formation from organic matter is in Appendix F.

The major concern with anaerobic digestion is the incomplete stabilization of the waste. A low cost digester can expect to achieve fifty to eighty percent organic matter removal. As noted by Koné and Strauss (2004), the remaining organic matter along with the microbial sludge produced will need to undergo further treatment since human health is at stake and anaerobic digestion cannot be relied upon to kill a high percentage of pathogens and parasite eggs. It is necessary to raise the temperature of the waste over sixty degrees Celsius for 5 hours to be sure the waste is safe for handling and crop application (Golueke 1977). Therefore, it is advisable to compost after anaerobic digestion or to solar-dry the waste material. Since both these processes can also stabilize the waste without anaerobic digestion, one can conclude that anaerobic digestion should only be used if the resulting bio-gas is a large enough quantity to be useful for the community.

In the case that the fundamental design equations produce results indicating favorable waste characteristics for digestion, the environmental conditions must be considered. Anaerobic digestion is optimized in thermophilic or mesophilic temperature ranges. The area of study is normally in the mesophilic range, with regular temperatures around thirty-one degrees Celsius (Verle 1994). The first factor to be considered is the pH, which is optimal between 6.5 and 7.6 (McCarty 1964). The bacteria also require certain nutrient levels in the digester. McCarty suggests that the nitrogen requirement is 0.11A, while the phosphorous requirement is 0.02A.

Toxicity is also a concern for the anaerobic digestion process. McCarty describes the major types of toxicity in the third part of his four article series on anaerobic digestion (1964). Alkali and alkaline-earth salt, sulfide and ammonia toxicity are three major threats to the anaerobic digestion process. In general night soil has an ammonia content considered to be too high for the anaerobic digestion process, but recently there has been much literature citing success of anaerobic digestion of night soil. For example, Park et al. reported that under optimal conditions methanogens can acclimate to 10,000 mg/l of ammonia nitrogen (2001). It has also been suggested that some ammonia volatilization should be encouraged by aerating the night soil prior to digestion as an added precaution to ammonia toxicity(Barrington 2008).

Modern anaerobic digester designs are high-rate processes which usually recycle the sludge. However, most anaerobic digesters are also designed for a relatively low strength sludge resulting from aerobic treatment of municipal sewage. Complete reviews of the process and design guidelines can be found in both Reynold's and Richard's Unit Processes in Environmental Engineering (1996) and Wastewater Engineering (Tchobanoglous, Burton et al. 2003) along with many other reputable sources. However, design guidelines for the process adapted to a high strength waste such as that in Ghana are illusive at best. More research is certainly needed regarding anaerobic digestion of fecal sludge.

A digester should be chosen for implementation in the study area after a thorough review of the waste characteristics and the calculation of the basic design parameters to be discussed in the process modeling section of this report. Currently in Ghana there is a upflow anaerobic sludge blanket (UASB) digester beginning operation in Accra (Doku 2003). A diagram of this continuous flow digester can be found in Appendix F. Since there are Ghanaian people familiar with the technology and operations, this type of digester would be a good first choice for the village. However, for simplicity, a simpler plug-flow digester such as the Taiwanese type may be more appropriate. Financial and management constraints are as big of a factor in choosing a digester type as the waste characteristics.

ii. Co-composting

Alternatively, separation of the concentrated public toilet sludge and night soil prior to the FSTP process is explored in much literature. Lessons from an experience with co-composting in Kumasi are detailed by Mensah, Cofie and Montangero (2003). In this application, collection would have to be conducted with care to keep septage apart from the high strength wastes. This strategy could be easily dismissed because of collection complications in an urban setting. However, in a setting where high strength waste quantities are much greater than septage a co-composting plant would be an efficient way to begin waste treatment and there would be capacity for expanding to the full FSTP process in the future.

Co-composting is a well-established process in Ghana and therefore, there is no need to explore the science underlying it in great detail in this research. The basic composting process is depicted in Figure 4.

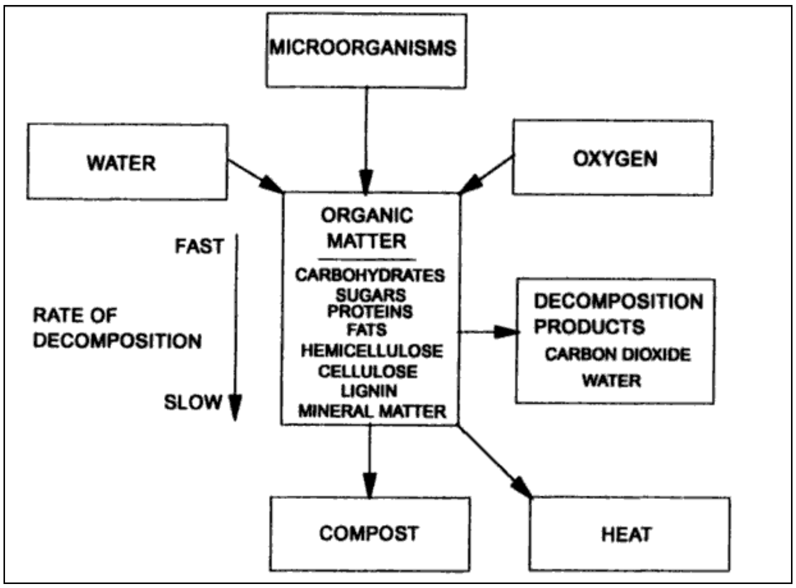

Figure 4: the composting process, pg. 20 (Epstin 1997)

The major factors affecting the decomposition of organic matter by microorganisms are oxygen and moisture. Aerobic conditions are essential to composting. Therefore, to increase the chances of successful composting the fecal sludge should be previously dewatered to a moisture content more conducive to aeration (Heinonen-Tanski and van Wijk-Sijbesma 2005). Once the process has begun proper aeration could be achieved through passive airflow from pipes or through mechanical turnover of the piles. When a mechanical turnover of the composting pile is considered, it is suggested that once every seven to fourteen days is usually sufficient to keep the system under aerobic conditions. Since most biochemical reactions occur in a moist medium, it is recommended to keep the composting pile under moisture content of about 50-60%. At lower values, the microbial activity has been shown to slow down due to water scarcity, whereas anaerobic conditions may develop at higher values creating potential odor problems.

Other important factors that could limit the composting process are nutrients, pH, and temperature. Nutrients, especially carbon and nitrogen, play an important role in the process as they are essential for microbial growth. Carbon is the principal source of energy, and nitrogen is needed for cell synthesis. It has been suggested that a C:N ratio lower than thirty is desired, where in-between fifteen and twentyfive is considered ideal (Haug 1993). Table 3 gives typical values of C:N ratio and moisture content for compostable waste. As for pH, a neutral pH of around 6 and up to 8 is usually recommended to maintain a high thermophilic microbial population (Epstin 1997).

Table 2: C/N Ratio and Moisture Content of Various Wastes

Material	C/N ratio	Moisture %	Reference
Night soil	6-10	80	Golueke1977
Urine	0.8	100	Golueke1977
Cow manure	18		Golueke1977
Food waste	20	85	(Barrington 2007)
Poultry manure	15		Golueke1977
Raw sewage sludge	11		Golueke1977
Grass clipping	12-15		Golueke1977
Corn residue	55-70	60-85	(Mannereng and Griffith)
Wood chips	240	10	BREE-518

Source: Adapted from Golueke (1977)and (Barrington 2007)

Temperature is an important factor in the composting process and since temperature is partially the result of microbial activity, it is a good indication of the stage and health of the composting pile. For example, during the first stage, the active stage, temperature usually ranges between 45°C to 70°C due to peaking microbial activity. During the maturation stage, lower temperatures are frequently recorded. As mentioned previously, researches have indicated that temperatures of 60°C for at least five to six hours are ideal for pathogen control (Epstin 1997; A. Mensah, O. Cofie et al. 2003; Barrington 2007)

When the moisture content of the inputs is over the optimum range, bulking agents including, but not limited to, wood chips, ash and dried plant residues can be used. It is advisable to use a combination of bulking agents whenever this option is available (Haug 1993). For example, wood chips are a good moisture buffering agent and promote aeration, but often require some nitrogen amendment in order to reestablish the C:N ratio of the composting pile. On the other hand, since ash is mostly depleted of carbon and nitrogen it does not alter the C:N ratio, but it is rich in potassium and other micronutrients (Epstin 1997). Also, since ash tends to increase the pH and is not considered as a good aerating agent, it should not be used alone. As for plant residue, it is usually a more labor intensive bulking agent because of the harvesting and quality control required.

In times when the bulking agent requirements exceed the practical viability in terms of volume and availability, a primary dewatering treatment could be used effectively. Specific requirements and characteristics for large scale drying beds can be found in Appendix D, Figure D1, whereas table D1 shows their removal efficiencies from a pilot plan in Kumasi, Ghana (Cofie, Agbottah et al. 2006). It is worth mentioning that though drying beds are very effective in reducing the BOD, COD and helminth eggs in the percolate water, the effluent needs further processing before being discharge directly into waterbodies. The Effluent can be sent to stabilization ponds, such as those in the current FSTP process, that foster anaerobic or facultative conditions in order to reduce the strength of the waste biologically.

iii. Solar drying

Solar drying the fecal sludge is a method that uses the sun's energy to stabilize the waste material. If evaporation and radiative heating are enough to kill pathogens and parasites, the waste can be considered stable and used for agriculture. Waste moisture content must be below 10% for extermination of parasites (Florian Klingel, Agnes Montangero et al. 2002). Also, as mentioned above, the waste should be heated to 60^{o}C for about five hours. Common pathogens and parasites are listed with their corresponding time and temperature requirements for death in Appendix D, Table D2.

Solar drying is possible because of the gradient in moisture content between a substance, in this case fecal sludge, and the surrounding air. Since the fecal sludge has a higher moisture content, water will tend to transfer into the air by evaporation towards an equilibrium. The evaporation process, a phase change from liquid to vapor, requires heat to take place. The heat absorbed by the water/vapor during the process is called the latent heat of evaporation. Solar energy can be used to provide this heat, which is stored in the air mass until condensation can take place.

Solar dryers can generally be classified into two broad categories: active and passive. Active solar dryers are designed with fans or pumps in order to move solar energy in the form of heated air to the drying beds. Passive dryers use only the natural movement of heated air. They can be easily constructed with inexpensive, locally available materials such as seen in Figure 5, below, which make them appropriate for small farms (Chua and Chou 2003). Since passive drying does not require any type of equipment or much management to complete the process, it is logical to incorporate drying as a decentralized process, implying that each home has a drying bed for the waste. Chua and Chou also note that other advantages besides keeping the rain away from the sludge, include rainfall and evaporated N-rich water (2003).

This type of dryer is composed of a drying chamber that is covered by a transparent plastic. Solar radiation passes through the transparent cover and is converted to low-grade heat when it strikes the concrete slab. This low-grade heat is then trapped inside the box by what is known as the greenhouse effect (Perumal 2007).

For pathogen control, it is recommended to bring the moisture content as low as 10%, whereas for ease of transportation, a moisture content of 40% is considered sufficient (Choi, Grabau et al. 2005). For a more thorough description of the kinematic equations of solar drying, the reader is welcomed to read Solar Drying in Africa (IDRC 1986).

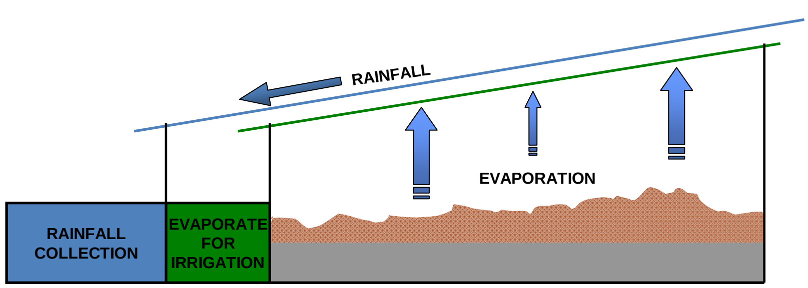

Figure 5. Sludge Drying Bed

Transport

Some mention must be made of the conditions of waste transport. Currently, the waste is hauled in bucket latrines to a ditch or nearby bushes (Johnson 2008). Ghislaine Johnson, while traveling in Northern Ghana, experienced a rare household where there was a gravity flush toilet. However, the waste was discharged in a ditch directly behind the facility (2008). In the cities there are large vehicles and regulated pick-ups, but due to inefficient processes, poor management and lack of sufficient treatment facilities, there is still large amount of illegal dumping of human waste(Obirih-Opareh and Post 2002). In Northern Ghana there is very little waste transported at all. The relative lack of technology established leaves room for the development of a new waste transport culture.

There are two different types of waste system: centralized, utilizing community waste collecting, and decentralized, meaning treatment-on-location. In either case toilets at the household level are necessary since, as recorded in a survey by Obika, Boateng et al. Ghanaian people desire a household toilet for reasons such as health, safety, privacy, and cleanliness (2003).

i. Centralized:

A centralized system implies the use of a container and vehicle to transport the waste from the household to the community treatment center. In the area of study, a bucket is currently the container and humans are the vehicles, only they don't have a proper destination. The implementation of a waste treatment system in the community would give the households a destination for waste relief, but the container for transport still needs improvement. The bucket latrine is not considered "improved sanitation" by the WHO and there are many cases of community bucket latrines gone foul by lack of care (Rosemarin 2003). However, other centralized systems require deep pits and vacuum trucks which are costly.

Since the container for transport is closely tied to the type of toilet in a household, some literature review was performed on the topic. According to an in-depth survey, households desire the following characteristics in a toilet facility (Obika, Boateng et al. 2003):

- Easy to flush away feces (feces not visible)
- No smell and good ventilation
- Low construction cost
- Little or not dependent on water
- Easy access for emptying
- Easily used by children
- Possibility of seating
- Easy to clean

Examples of successful household toilets with regular small container transport do exist. In one case in Vietnam, workers were able to collect household night soil barrels each week to haul them on a cart to the waste treatment location (Florian Klingel, Agnes Montangero et al. 2002). This system involves the locals by creating jobs and utilizes the strength of the community for treatment. If the containers and handling systems could be further improved the workers and household members would be less exposed to the fecal matter ensuring the beneficial implications of the system. The photo to the left was taken in China to show the traditional waste collection which is done by farmers or intermediates who sell the waste to farmers for use as fertilizer(Florian Klingel, Agnes Montangero et al. 2002). These are both examples of human-run waste collection working successfully.

ii. Decentralized:

There is extensive research on different types of toilets to achieve solid-liquid separation or composting while protecting people from odors and pathogens. Most relevantly, Anne Peasey reviewed a variety of dehydration and decomposition facilities including the common ECOSAN toilet, and the Mexican-developed SIRDO system (2000). In Ghana, one type of separation toilet was tested on a large scale with the installation of 210 “enviroloos.” Unfortunately, there was a high failure rate due to two different factors. The people were not properly educated on the technology and didn’t understand that there was a specific lever to pull to separate the feces. Also, the proper collection vehicles did not exist so the waste was mixed for transport defeating the purpose of the separation technology (Tsiagbey 2003). In one study where 2500 households were sampled, 94% were interested in waste separation technology, but only 17% wanted to be responsible for selling the waste to farmers(Tsiagbey 2003). These findings indicate that the less waste responsibility at the household level the better. It can be observed that a key to success for a decentralized system is simplicity in design and understanding of the technology. Also, for health reasons, it is necessary for a decentralized system to have the capacity to fully stabilize the waste.

Decentralized systems may have more of a place in rural settings than urban due to the low density of households and benefits of drying or composting. As a community is growing, however, it is better to remove the waste from populated areas to avoid pests and consequent epidemics, with such events as the Plague in mind(Philip Rushbrook and Pugh 1999).

Design Details

Since there are two levels to be considered in the design, the design portion of this report will first overview the three proposed scenarios for an overall waste management system in Northern Ghana. Each scenario will be represented schematically and attention will be called to the aspect of each that is unique. Following the scenarios will be a detailed design of each process in the mathematical decision-making and learning model.

Scenario Schematics

Anaerobic digestion: The most technological and operationally demanding scenario, anaerobic digestion yields biogas which has a high potential for quality of life improvement in the community. However, the sludge resulting from anaerobic digestion must continue stabilizing by another means, in this case composting is being considered. In order to proceed to composting, it is highly beneficial to separate the supernatant into a stabilization pond, causing the need for another structure. The stabilization pond is commonly used in Ghana and detailed design will not be included in the model since the focus is on anaerobic digestion. Depending on community size, this intensive process could be the best option for high strength waste treatment.

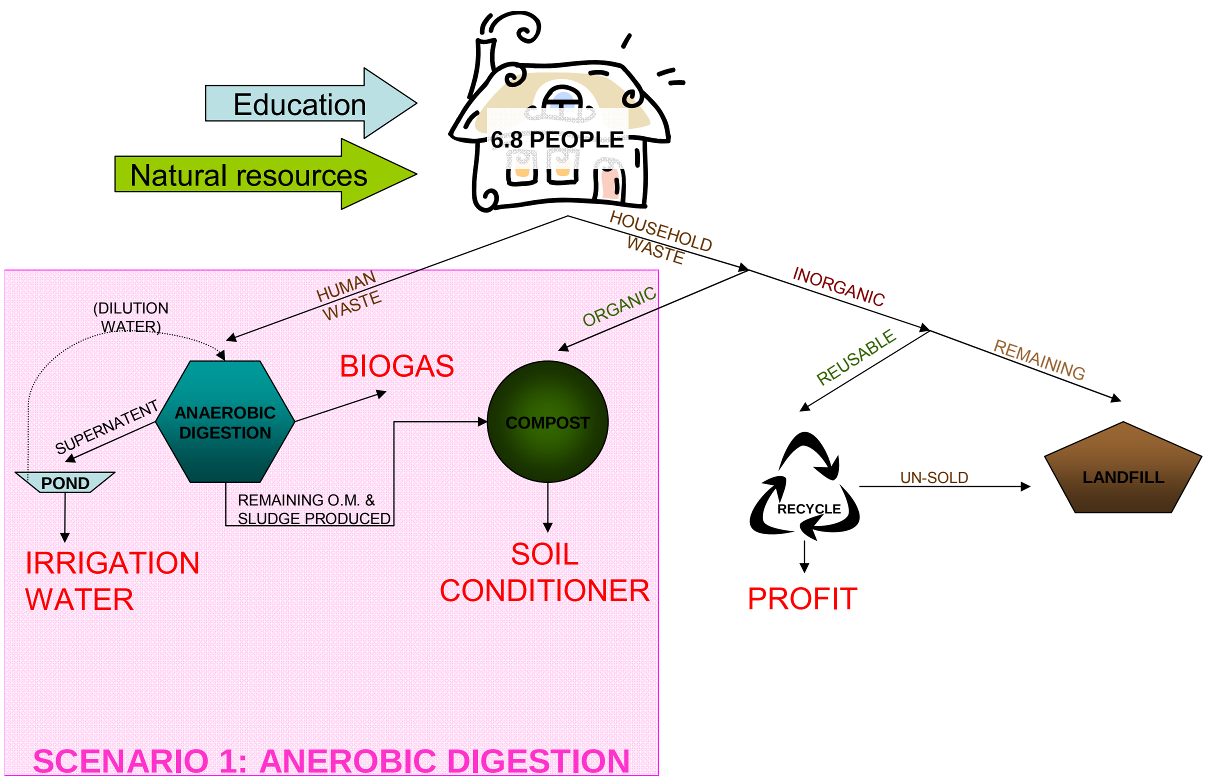

Figure 6. Schematic of Scenario 1: Waste treatment strategy utilizing anaerobic digestion for the production of biogas.

Co-composting: If it is not economically beneficial (because of biogas production) to operate scenario 1 in a community, co-composting might be considered. In this scenario human waste is dewatered and added to household organic waste in the composting process. Although a dewatering bed is required for this process, it will only be included in the model in the simplest terms. Detailed design of watering beds in Ghana is readily available from such sources as Heinss, Larmie & Strauss (1998). Notice the simplification of the human waste portion of the diagram and process due to the replacement of anaerobic digestion with a dewatering bed. Simplicity comes at the cost of biogas production.

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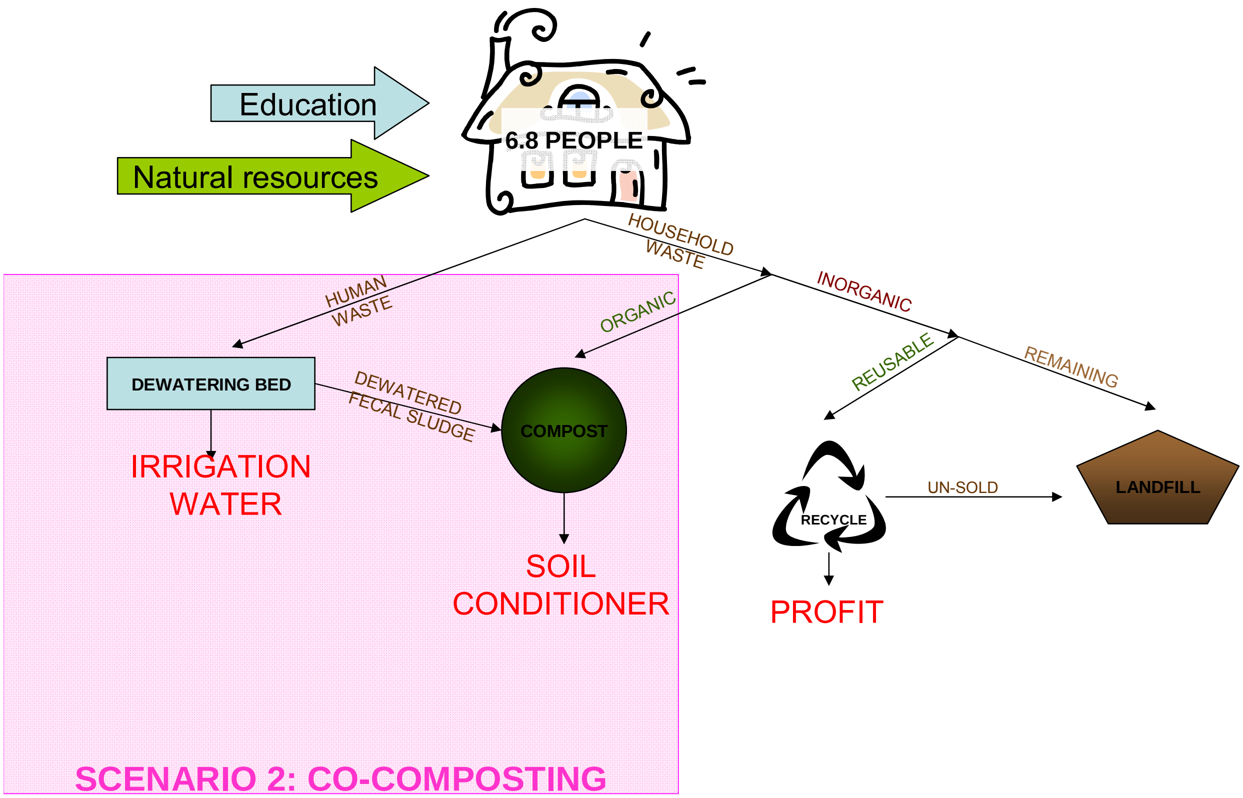


Figure 7. Schematic of Scenario 2: Waste treatment strategy utilizing co-composting for organic waste treatment.

Drying: In the case that scenario 2 is too labor intensive for a community beginning to implement waste treatment technology due to the transfer required from waste receptacles to the dewatering bed and then to the compost, scenario 3 is suggested. The simplest of all scenarios, there is less benefit for the community and households must be responsible for the drying of their waste. Notice the lack of interaction between waste streams, minimizing the benefit of the complimenting food and human waste types.

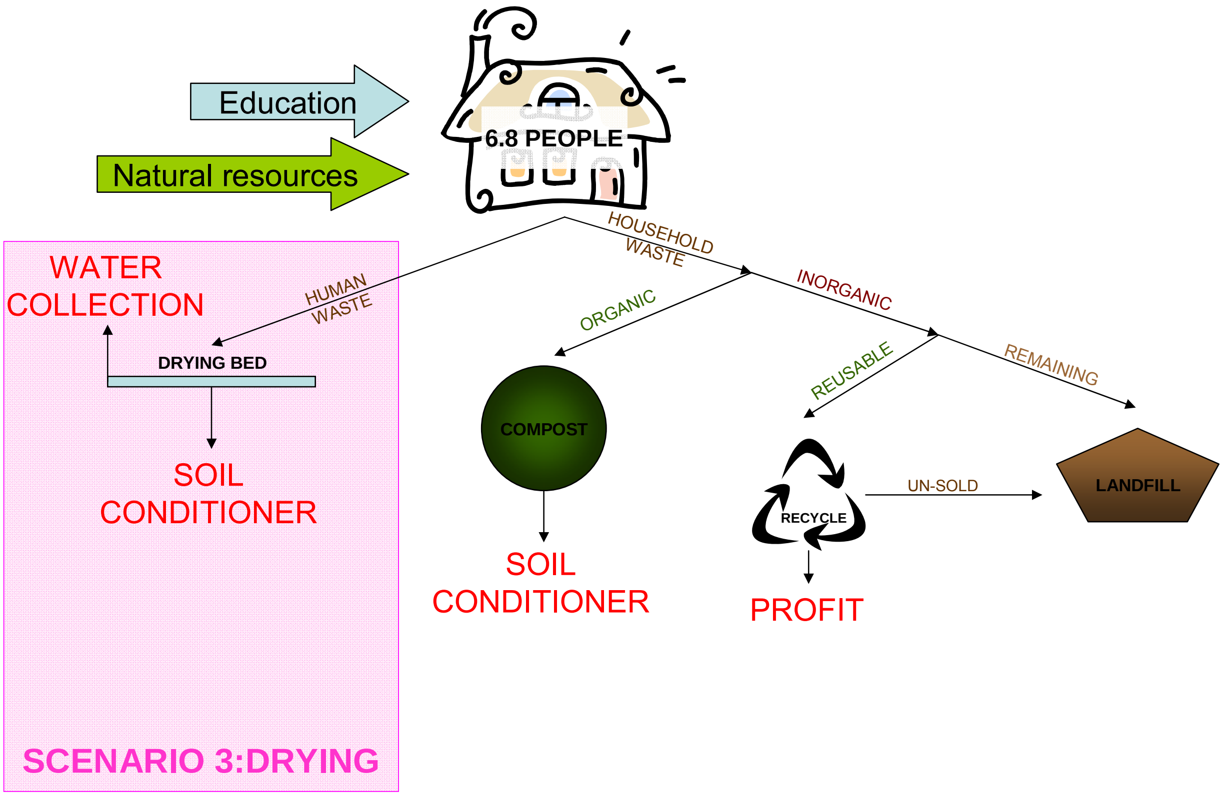


Figure 8. Schematic of Scenario 3: Waste treatment strategy utilizing decentralized drying bed treatment of human waste.

Process Modeling

To understand the feasibility of each scenario in Northern Ghana a mathematical model was created to calculate scenario outputs based on basic inputs such as waste type and quantity, village size and participation rates. With this tool local planning teams could assess the possibility of improving the community waste treatment in each of the above three ways as well as have parameters to begin a preliminary physical design. There is also much flexibility in the model for changes in the scenarios. While each complete scenario is modeled, the emphasis will be placed on the organic waste stabilization method.

Since the study is focused on the feasibility of the processes, not the performance, the model is based on mass balances of waste alone. Each stage of the three scenarios will be represented by waste input and product output, not considering the performance change over time and assuming proper operation.

Each scenario combines anaerobic digestion, composting and drying differently, so each of these processes were modeled and subsequently combined and adjusted for a particular scenario. Once the most realistic situation was modeled for each scenario (see appendix A for results) the input parameters were varied one at a time to get an idea of the sensitivity of the model to changes. Also, each scenario was modeled as a function of a participation ratio. The effect of the participation ratio was recorded over many values and is found in Appendices B-D. The mathematical basis for each process is detailed below:

i. Inorganic Waste

The inorganic waste handling strategy is designed according to the generally accepted basic requirements for solid waste handling. As noted by Pearce and Turner, any waste management plan must include a way to balance recycling, landfill and composting to accurately represent the solid waste situation (1994). Using the solid waste data calculated from the Pearce and Turner study, a mass balance approach was used to determine the amount of waste entering the landfill (see equation 1a) below).

Percent recycled must be determined by the model user based on the village of application and the waste reuse culture. Percent recycled indicates the amount of waste that an active participant in the waste management system is likely to be able to recycle. So, under ideal participation, the village would have the following amount of waste in the landfill:

$$Mass_{Landfilled} = W - (\% Re)*W, \qquad 1a)$$

W = Total Mass of Solid Waste (village)
%Re = Percent Recycled

However, as it is not likely that the entire village will participate, especially during the beginning of implementation, a participation ratio is introduced throughout the model. The participation ratio represents the percent of villagers participating in the waste management system as a decimal. The equation for the mass landfilled becomes:

$$Mass_{Landfilled} = \{\text{Mass from Non-Participants}\} + \{\text{Mass from Participants}\} \qquad 1b)$$
$$= \{(1-PR)*W\} + \{PR*(1-\%Re)*W\},$$

PR = Participation Ratio

The inorganic waste design is the same throughout the adaptations of the model to different organic waste handling systems.

The default percent recycle was 75% for all types of waste. There was no data in the literature about this parameter. Local leaders would have a better idea of the value of such a parameter from life experience, indicating that the participatory approach is necessary yet again.

ii. Anaerobic Digestion

To understand the feasibility of scenario 1 in Northern Ghana some basic parameters need to be determined including the input and output from the system. In order to find the products of the anaerobic digestion process, design parameters were obtained by using equations proposed by Perry L. McCarty (1964). The following equations utilize basic information about the waste characteristics and bacteriological kinetics to estimate the methane production, volatile biological solids production and percentage removal of Biological Oxygen Demand (BOD), which indicates organic matter.

$$A = \frac{aF}{1+b(SRT)}, \tag{2a}$$

A = Volatile Biological Solids Produced (lbs/d)
a = biological growth constant (observed in similar waste types)
F = BOD added (lbs/d)
b = endogenous respiration rate (observed in similar waste types)
SRT = Solids Retention Time (d)
= Hydraulic Retention Time (no sludge recycling)

$$C = 5.62(eF - 1.42A) \tag{2b}$$

C = CH^4 produced (ft^3/d)
e = Process efficiency (usually 0.80 – 0.95)

$$S = \frac{100C}{5.62F} = \frac{100(eF - 1.42A)}{F} \tag{2c}$$

S = BOD Stabilized (%)

Source: (McCarty 1964)

The BOD added, F is computed in the model by equation 2d from the BOD-concentration and waste inflow, Q, which accounts for the participation ratio.

$$F = BOD\left({}^{mg}/_{l}\right) * Q\left(\frac{m^3}{d}\right) * \left(\frac{2.2\ {}^{lbs}/_{kg} * 10^3\ {}^{l}/_{m^3}}{10^6\ {}^{mg}/_{kg}}\right) \tag{2d}$$

Similar to the final factor in the above equation, unit conversion equations are programmed into the model in order to enable metric waste-input data.

These three design parameters are essential to obtaining a basic idea of the feasibility of anaerobic digestion of a waste. Parameter A, calculated by equation 2a, is the amount of volatile biological solids produced per day. The majority of the volatile biological solids in the waste are bacteria, therefore daily sludge production from the process is known. The growth and decay coefficients for the bacteriological kinetics can be found in the literature for different waste types (McCarty 1964). They differ based on whether the waste is primarily proteins, carbohydrates or fats and oil.

The second design parameter, C, is an indication of the amount of methane that could be produced and the process efficiency, e, is suggested based on field experience.

The final parameter, S, indicates the percent of BOD that will be stabilized and is calculated from C and F in equation 2c. This is a measurement of how much organic matter is converted to biogas and sludge and how much remains in the waste.

To check the validity of the equations given by McCarty, an alternative method was also used to calculate the amount of methane produced. The Buswell Equation, seen below, utilizes the stochiometry of anaerobic digestion to calculate the amount of methane produced.

Buswell Equation: 2e)

$$C_nH_aO_bN_d + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3d}{4}\right)H_2O \Rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3d}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3d}{8}\right)CO_2 + (d)NH_3$$

Source: (T.Z.D. de Mes, A.J.M. Stams et al. 2003)

To calculate the methane produced from equation 2e, the ratio of molecular weights and the molecular coefficients must be used as shown below in equation 2f:

Ideal Methane Produced = $X * (MW_{CH_4}) * \left(\frac{LoadingRate}{MW_{LOADING}}\right)$, 2f)

X = Coefficient of CH_4 from Buswell Equation
MW_{CH4} = Molecular Weight, CH_4
Loading rate = CHON added per time
$MW_{LOADING}$ = Molecular Weight, CHON

Since the Buswell equation assumes complete stabilization, an "efficiency factor" must be multiplied in order to gain an appropriate estimate of methane production for comparison to the McCarty equations. The efficiency factor used in the design is the percent BOD stabilized, S, as calculated above.

Actual Methane Produced = (Ideal Methane Produced)*S

To fully know what we are dealing with after digestion it is logical to do a final total mass balance. In the simplest case, with no sludge recycling, the only thing leaving the digester is the biogas. Therefore,

[Total Mass of Effluent = (Influent Mass) – (Biogas Mass)]kg

The input parameters for the most realistic situation based on the literature search and waste data are briefly described in Table 3 and Table 4.

McCarty:

Table 3: Input parameters

INPUT:		**Source / Justification**
growth constant, a	0.24	Table B2, Appendix B, (McCarty 1964), Carbohydrate Diet
endogenous decay rate, b	0.033	Table B2, Appendix B, (McCarty 1964), Carbohydrate Diet
SRT (days)	20	Table B2, Appendix B (McCarty 1964), Temp ~ 75˚F
Efficiency, e	0.85	Min. of Suggested range (worst case), (McCarty 1964)
BOD (mg/l)	13500	Common value in Literature, see Table B1 in Appendix B

Buswell:

Table 4: Input parameters

INPUT		Source / Justification
C	5	Common molecular makeup of anaerobic bacteria, used since accurate waste molecular makeup could not be found. (Elefsiniotis 2007)
H	9	
O	3	
N	1	
Waste Inflow (m^3/d)	1.014	From urine and feces production, population, and participation ratio.

iii. Composting

Modeling compost requires mass balance equations in order to create a recipe where all the major factors affecting the composting process are set to their optimum ranges. As a result, the tedious part of the modeling process is to get the initial input characteristics of the biomaterials to be composted such as their moisture content, C:N ratio and pH. The major equations used are depicted below (Barrington 2007):

The dry mass of all the inputs were calculated using:

$$Mass_{dry} = Mass_{wet} * \text{dry matter ratio} \quad \text{3a)}$$

Whereas the mass of carbon and nitrogen were found using:

$$Mass_{Carbon} = Mass_{dry} * VS/1.83 \quad \text{3b)}$$

where

VS = Volatile Solid fraction

$$Mass_{Nitrogen} = Mass_{Carbon} / (C/N) \quad \text{3c)}$$

And the final mixture masses were found by simply adding all their respective components together. For example, the final wet mass equation scenario 1 was:

$$Mass_{wet/final} = Mass_{wet/A/D} + Mass_{wet/Put.} + Mass_{wet/wood} + Mass_{wet/ash} + Mass_{wet/CR} \quad \text{3d)}$$

And final dry matter content and C/N ratio equations were:

$$\text{Dry matter} = Mass_{dry/final} / Mass_{wet/final} * 100 \quad \text{3e)}$$

$$C/N_{final} = Mass_{Carbon/final} / Mass_{nitrogen/final} \quad \text{3f)}$$

Volumes were calculated using a density, ρ, of 450 kg/m^3 and so, one obtains the following equation on a daily basis:

$$V_{day} = Mass_{wet/final} / \rho \quad \text{3g)}$$

In terms of final volume requirements, they were split into two phases, mainly the active and the maturation phase.

$$V_{active} = V_{day} * RT_{active} \qquad 3h)$$

where

RT_{active} = Retention time (days)

And

$$V_{maturation} = V_{day} * RT_{maturation} * (1-VRR) \qquad 3i)$$

Where

$RT_{maturation}$ = Retention time (days)

VRR = Volume Reduction Ratio

And

$$V_{final} = V_{active} + V_{maturation} \qquad 3j)$$

Using the input parameters mentioned in table 5, a recipe is obtained via the previous mass balance equations where the masses of the bulking agents are manually changed in order to get the dry matter content, C:N ratio as close as possible to the optimum ranges previously described. Since the model needs to account for a participatory ratio, all inputs parameter such as the effluent from anaerobic digestion, the dry sludge, the putriscible (food waste) and the bulking agents masses are multiplied by the participatory ratio such that the recipe remains balance during the simulation and sensitivity analysis. A row system composting design could be considered for the current situation since it is well suited for future expansion expected from higher participation rate of the villagers. A complete description of different types of composting facilities is explore by Drechsel and Kunze (2001) and it is up to the village leaders to select which one is the most appropriate for their village.

Table 5: Composting Input Characteristics

Waste Characteristics	Input Parameters					
	Organic Wastes			Bulking Agent		
	After A/D+d/w[2]	d/w slugde[2]	putriscible[1]	wood chips[1]	ash	corn residue[3]
dry matter ratio	0.4	0.4	0.15	0.9	0.9	0.8
VS	0.9	0.9	0.9	0.99	0	0.85
C/N	10	10	20	240	0	70
C, fraction VS	0.492	0.492	0.49	0.541	0	0.464
N, fraction VS	0.049	0.049	0.0245	0.0023	0	0.007

[1] data obtained from (Barrington 2007)

[2] data obtained from (M. Strauss, S.A. Larmie et al. 1997)

[3] data from (Mannereng and Griffith)

iv. Drying

The drying model design is based on the principal of latent heat of evaporation. The amount of radiative energy from the sun reaching Ghana is estimated from average monthly data from Mali over a five years period found in Table D3 Appendix D. Knowing that the latent heat of evaporation of water is 2,270 kJ/kg, one can find the amount of water loss on a daily basis using the following formula:

$$\text{Mass of evaporated water (MEW) (kg/day/m}^2\text{)} = \frac{\text{solar energy (kJ/day/m}^2\text{)}}{\text{Latent heat of evaporation (kJ/kg)}} \quad \text{4a)}$$

Where

$$\text{Solar energy} = \text{diffuse radiation} + \text{direct radiation}*(1\text{-Albedo}) \quad \text{4b)}$$

An albedo factor defined as the reflected radiation divided by the incident radiation is added to the equation to account for some solar reflection. Table D4 in Appendix D gives albedo values of some common natural surfaces. In the current model, it is assumed that night soil behaves like a black moist soil, and thus a value of 0.08 is used.

Then, once the loading rate, LR (kg/day) with its corresponding moisture content is established, the required area per day to dry the FS for a specific final moisture content can be calculated the using the following formula:

$$\text{Area (m}^2\text{)} = \frac{\text{LR (kg/day)}*(MC_i - MC_f)}{\text{MEW (kg/day/m}^2\text{)}} \quad \text{4c)}$$

where
LR = loading rate
MC_i = initial moisture content
MC_f= final moisture content
MEW = mass of evaporated water
eff = efficiency

The initial moisture content of the night soil is estimated using the mass of urine produced per day over the sum of the masses of urine and feces. As mentioned earlier, the final moisture content can be selected for pathogen control where the final moisture content needs to be around 10% or for ease of transportation with a moisture content of roughly 40%.

$$MC_i = \frac{Mass_{urine}}{Mass_{urine} + Mass_{feces}} \quad \text{4d)}$$

Looking back to equation 4c), one can see that for lower moisture content, a larger area is needed, which increases the cost of the dryer. As a result, final moisture content close to 40% would be more desirable given that the temperature inside the chamber reaches values close to 60°C and treats the waste. To check whether a final moisture content of 40% could be used safely in the design, the following equation is used to find the theoretical temperature inside the chamber:

$$\text{Solar energy (kJ/day/m}^2\text{)} = (1\text{-Albedo})*86400 \text{ s/day}*\sigma*(T^4 - T_{surr}^4) \quad \text{4c)}$$

Where
(1-Albedo)= absorptivity
σ = Stefan-Boltzmann constant ($5.669*10^{-11}$ kJ/s*m^2*K^4)
T = temperature inside the chamber (K)
T_{surr} = ambient temperature (K)
Source: (Holman 2002)

The depth of a drying bed can be calculated for design by using the density of water as an approximation of the waste characteristic.

$$DEPTH\left(\frac{m}{m^2}\right) = \frac{LR\left(\frac{kg/d}{m^2}\right)}{\rho\left(\frac{kg}{m^3}\right)} \tag{4d}$$

Transport

The transport design is centralized for scenarios 1 and 2 and both centralized and decentralized for scenario 3. For scenario 1 and 2 both the human waste and household waste need to be transported to a community treatment location. Human power must be relied on at this point until the village becomes big enough to convert to a privatized collection system similar to that of other Ghanaian cities. Therefore, families must be responsible to transport their own waste or pay a laborer to do it for them.

For scenario 3 it seems simpler to have both the human and household organic waste treated locally with household drying and composting. However, keeping in mind the growth of the area and the desire to move towards more advanced technology, the design includes household drying of human waste and community composting of household organic waste. This way a community transport system will be in place when growth causes the need for community human waste treatment. Also, a continuous composting process will be in action which could benefit a community desiring to co-compost their fecal waste in the future.

Whether centralized or decentralized, the waste needs to be collected for a period of time before treatment. A simple bucket was used in the design because they are readily available and already used commonly. As mentioned in the literature review, bucket latrines are not considered “improved sanitation.” Considering the alternatives to the bucket latrine are more costly and require larger collection vehicles they do not seem practical for the village at the current time. It may be more effective to make small improvements to the typical bucket latrine to make it sanitary, or remove the risk of human contact with fecal matter. Improvements to the typical use of bucket latrines were conceptualized to reflect the goals of toilet facilities as listed in the literature review as well as creating a sanitary transport mechanism.

The bucket could be average size or larger with wheels to suit the family’s need and financial situation. A lid should be attached to and stored with the bucket, which sits below a typical squat-hole platform. Other essential features are ventilation of the storage area, a screen to trap flies and a waterless “flush” consisting of a flat, smooth surface in grooves for sliding. A scraper would be necessary to push all the night soil into the bucket. The drawer flush could be operated with one’s foot. Another improvement would be the presence of some tracks for the bucket to slide in on to ensure proper placement and minimal fecal matter missing the bucket. A conceptual design of a transport and storage system was presented in the proposal for this project, and an improvement on it is seen below. While the size of the container could be varied for household needs, it is suggested that a weekly waste volume of 0.096 m^3 be planned for as calculated below. The improved bucket latrine idea should be discussed among the community members to get a better idea of needed improvements.

$$V = \left(\frac{9.19E^{-3} \, m^3 waste/house}{day} \right) * \left(\frac{7d}{w} \right) * (1.5SF) = 0.096m^3$$

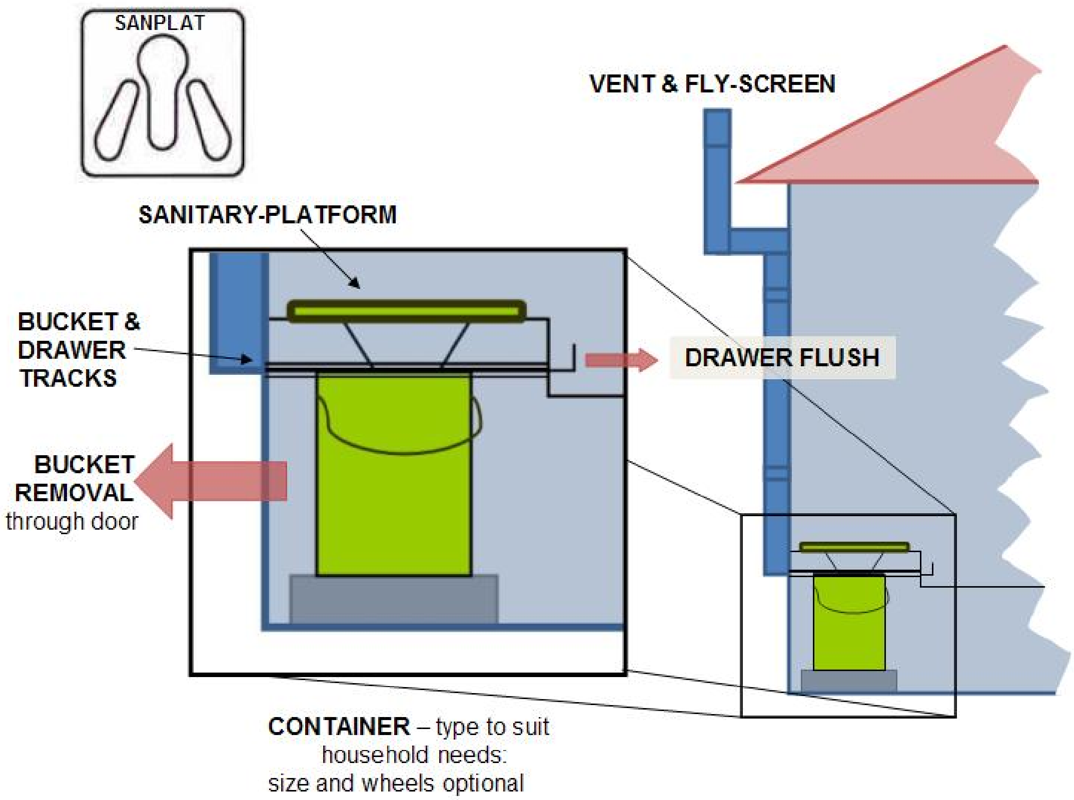


Figure 9: Diagram of improved bucket latrine facility

Social Engineering

Keeping in mind the necessity of the participatory approach, the social design utilizes the ideology and exercises of the PHAST (Participatory Hygiene and Sanitation Transformation) program throughout. The basis of the PHAST program is that, "no lasting change in people's behavior will occur without understanding and believing" (WHO 2004). The PHAST approach has been used successfully in several African Nations and around the world to create positive change in the sanitation and hygiene of people. The program uses targeted exercises and activities for schools and communities to learn about their health and improvements by sanitation. According to the WHO the approach also allows the participants to discover on their own some possible sanitation improvements particular to their locale (2004). The PHAST approach fits into the complete social engineering of this report in two places, as described below.

The structure of social engineering is based on distributing specific responsibilities to community members. A detailed literature review, found in the proposal for this design (Ebner and Leroux 2008), indicated the need for three major access points for educating the population.

First, schools are an important place to raise awareness for sanitation. A school sanitation team program should be initiated utilizing the lessons and projects described in *PHAST step-by-step guide: A participatory approach for the control of diarrhoeal diseases,* a publication of the WHO (Sawyer, Simpson-Hebert et al. 1998). Children, with their open minds and eagerness to learn, are a great place to begin and examples of school-seeded cultural change are many (Talbot 2005). An individual in the school system should be appointed responsible for the sanitation team program and other teachers should be responsible for the coordination of individual activities and lessons.

As mentioned in the introduction to the participatory approach, involvement of women is a priority in the social design. It is suggested that a women's group is formed in order to open communication lines about what women want and need from the community in terms of waste. Women are an essential part of the design and connecting them on common issues will only strengthen their ability to create change. This women's coalition could also do exercises from the PHAST approach as a way of self-education.

Socially, there also needs to be a plan for the long term. This plan is to have proper documentation of the technology in use and of the sanitation concepts being taught. This includes a readily available guide to common materials and the appropriate way to dispose of them, a handbook for the sanitation teams to reference when in need, and a framework for collecting waste data in order to provide a better basis for design in the future. At least one dedicated individual is needed for this role.

Regular community meetings can be held to encourage action and measure the progress of the waste system implementation.

Each area of concentration requires the time of local volunteers to reach success. It is easy to be skeptical about volunteers, but it is refreshing to remind one's self of the vast amounts of change happening in the world due to passionate people volunteering their time. As one study of the PHAST program in Botswana discovered, a few local women and children were able to mobilize an entire village to create hand washing facilities and ensure soap in all the school toilets once they believed it was the best thing for the children (WHO 2004).

The specific task allocation and organization of the social design are the responsibility of the local participants. However, the general structure designed for successful implementation of the educational aspects of the project is depicted below. The illustration shows the three focuses of the social design: women, schools, and documentation. As seen in the diagram the social design is essential since it precludes waste-culture change in households and communities. Without this kind of change a waste treatment system will be a complete failure.

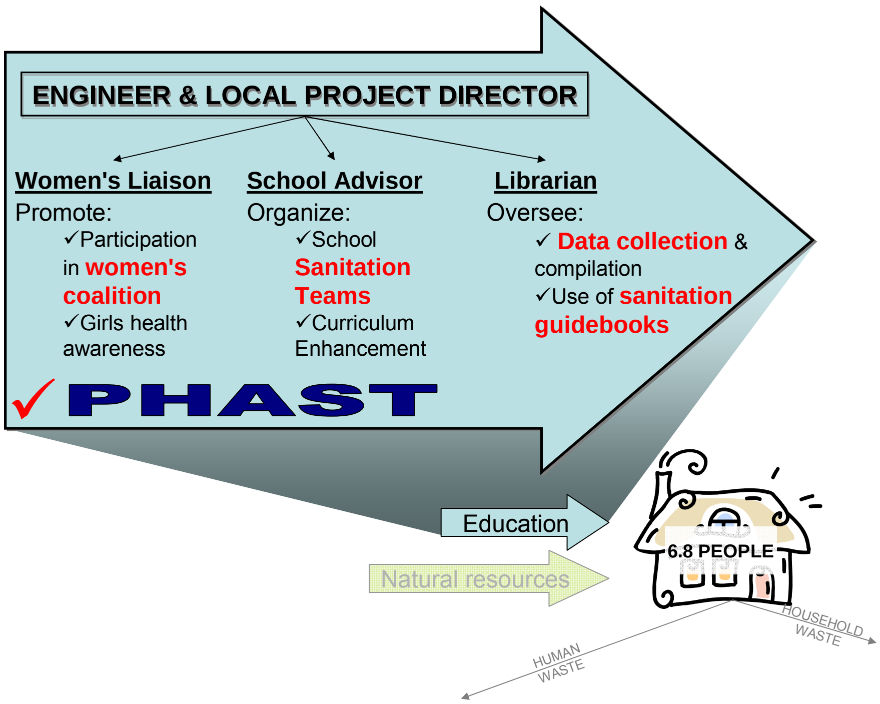


Figure 10. Social Engineering Design Schematic

In order to account for the slow rate of social change expected, the mathematical model will be run for each scenario at the following participation rates (in percent): 5, 10, 25, 50, 75, 90, 95 and 100. The participation ratio can easily be changed once in the model input and results for all three scenarios will change appropriately.

Simulation & Modeling

Inorganic Solid Waste

The model for inorganic waste remains the same in each scenario. Some basic assumptions made to model the process are below. Also the input data used for all the scenarios is recorded below.

Assumptions:

- Closed system: total mass of waste is recycled or land filled
- Recycled waste ultimate disposal is included in the initial waste quantities
- Non-participants: 100% of their waste ends in the landfill

Results:

The results for inorganic solid waste modeling are compiled along with each scenario. See Appendix A for the scenario results tables.

Analysis:

There are two factors that can be changed that will affect the mass of waste ending in the landfill: the participation ratio and the percent recycled for each type of waste. By changing the participation ratio the amount of waste to the landfill will increase by a factor of the solid waste per capita. A change in the percent recycled, however, will affect the model a little differently since the percent recycled only affects the participants and it was assumed that all non-participant waste is ending up in the landfill (see Figure 11).

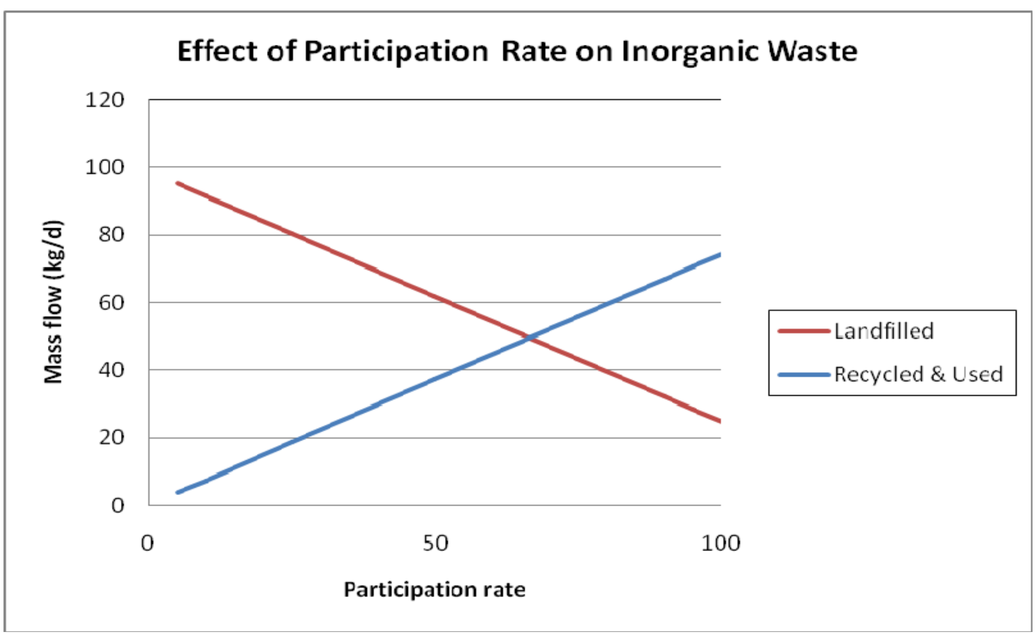


Figure 11: Effect of Participation Rate on Inorganic Waste

Scenario 1

i. Assumptions:

General:

- No loss of waste input due to poor or lacking transport mechanisms
- Participation ratio = Decimal percentage of population who are effectively participating (recycling 75% of waste, transporting 100% of waste appropriately)

Anaerobic Digestion (McCarty Fundamental Equations):

- Feces and urine production equal input to the digester (no other losses)
- Delivery of fecal sludge to the process is uniform and regular
- Digestion process is optimized in terms of:
  - Digester type, shape, volume, operation
  - pH, Temperature
  - Toxicity protection
- Biological growth constants, SRT, and efficiency factor are according to the literature

Anaerobic Digestion (Buswell Equation):

- Complete stabilization of waste
- Waste input is uniform and has the C:H:O:N given ratio
- Other end products are insignificant
- Equal solubility of components of biogas

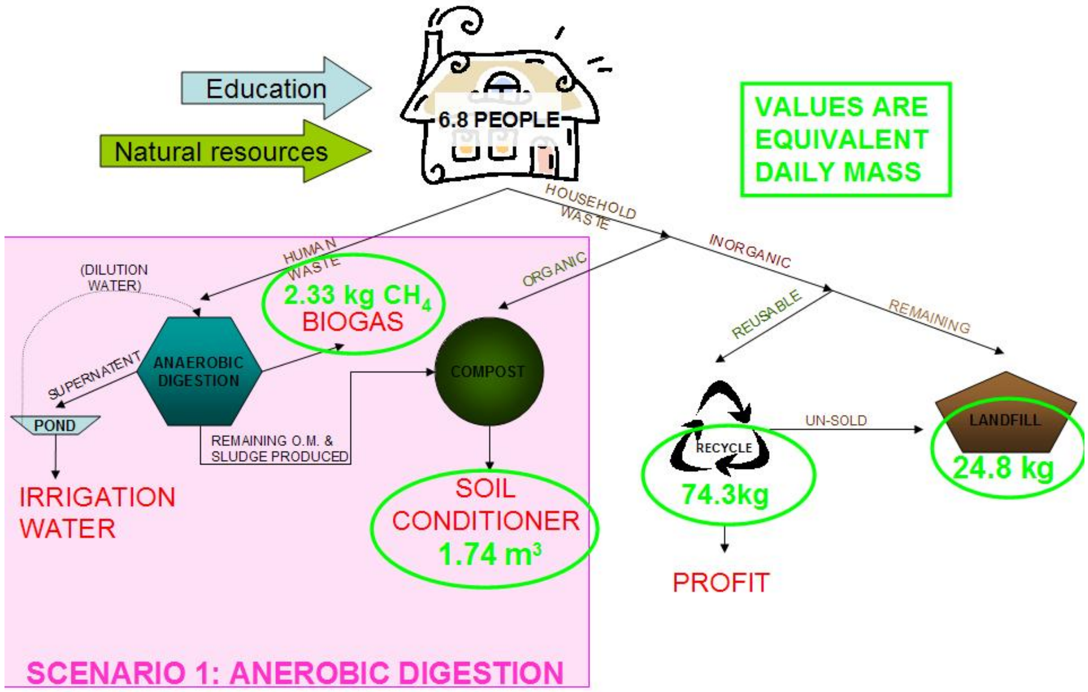
Dewatering (Doulaye Koné and Strauss 2004) :

- Dewatering can bring the fecal sludge to dry matter content of 0.4
- Rain is neglected
- Uniform loading rate

Composting (Barrington 2007):

- Constant physical and chemical properties of the inputs
- No nitrogen loss
- Density of compost during its active phase is 450 kg/m^3
- There is a volume reduction ratio of 33% during the maturation phase

ii. Results: Complete Tabulated Results are available in Appendix A



ii. Analysis:

Anaerobic Digestion:

The results table as printed is in the following form including the three key parameters (A, C, S) as well as the amount of methane produced as predicted by Buswell for comparison. Complete results can be found in Appendix B

Table 6: Results of Anaerobic Digestion

PRODUCTS:	
Volatile Biological Solids Produced, A (kg/d)	1.650935
Methane Produced, C (ft3/d)	114.8779
Methane Produced, C (kg/d)	2.334179
BOD Stabilized, S (%)	67.87437
Methane Produced (kg/d) (Buswell Eqt*S):	2.837045

The stochiometry from the Buswell equation used to calculate the quantity of methane and biogas is printed in the following format:

5a)

Stochiometry:											
CnHaObNd +	2	H2O	.---->.	2.5	CH4 +	2.5	CO2	+	1	NH3

There are some initial observations about the model of anaerobic digestion. Firstly, the model predicted a lower percentage of methane in the biogas than cited in many literature sources. This is most likely because of the excess CO_2 predicted by the Buswell equation. McCarty warns of this effect which is due to the relatively high solubility of CO_2 in water(McCarty 1964). Since the waste is retaining much of the CO_2, the Buswell equation overestimates the amount leaving the digester in biogas, skewing the percent methane content in the biogas.

Secondly, co-digestion of human waste with food waste would improve the A/D process greatly, but since the model wasn't sophisticated enough to incorporate food waste realistically, the A/D and composting processes in scenario 1 remain separate. Further research in the characteristics of the wastes would need to be conducted to include this improvement.

Also, it is noted that with the right type of anaerobic digester, such as the common Upflow Anaerobic Sludge Blanket design or any two stages process, dewatering can be done simultaneously with digestion since the solids will settle and the supernatant can be removed. This type of design would eliminate the need for an extra step of dewatering and decrease the cost of the process. However, since the model is based on mass balances and does not assume a specific digester design, there was no capability to express this improvement mathematically.

The observations and assumptions listed above provide a basis for the many limitations of the two methods of calculating the methane produced and design parameters for a generalized anaerobic digestion process. However, further assumptions made in order to assimilate waste and sludge characteristics are further limiting the accuracy of the model.

The assumption common to all scenarios and processes is the participation ratio. For the most likely scenario run the participation ratio was assumed to be one for simplicity. This is a sure overestimation for the start-up phase of the process and most likely for the entire existence of the facility. Unfortunately, participation ratio is also a strong input parameter. For example, a 10% decrease in the participation ratio causes a quasi-equivalent (9.98%) decrease in the amount of methane produced.

The quality of human waste is documented very differently across the literature causing a margin of error due to the initial BOD value assumed. According to a sensitivity analysis of the influent BOD parameter, there is good reason for concern about this limitation. Changing the BOD by 10% of the initial value yields a change in methane production of 11%. The BOD used for the most realistic case (for results see Appendix B) was selected from a survey of literature citing high strength waste characteristics. There is a relatively high amount of certainty for this value as compared to other inputs.

In comparison, the properties of the sludge have a much smaller effect. Firstly, the growth rate, which is assumed to be 0.24 (see Table 3), decreased by 10% increases the methane production by only 3.5%. More importantly, the endogenous decay rate, b, decreased by 10% causes a 1.7% decrease in the methane production.

The last parameters of concern are representative of the entire process: the SRT and the efficiency factor, e. Methane production decreases by only 1.7% when the SRT is decreased by 10% while the efficiency factor has a large effect on the methane production. A 10% decrease of efficiency, dictated by the type of system chosen and the operation of the system, causes a 12.5% decrease in the methane output. The relevant assumptions behind this parameter are numerous and include optimal pH, temperatures, and toxicity buffering capacity. The efficiency chosen was simply the minimum of the "normal range" given by McCarty (1964). Therefore, this parameter is the most sensitive and any modeling should be done over a wide range on efficiency to get a complete idea of the possibilities for Methane Production.

For graphs of each input parameter under sensitivity analysis, please see Appendix B.

Composting:

Table 7: Results for Compost

Compost - Household Waste	
Putriscible (kg/d)	312.0
A/D (kg/d)	601.3
wood chips (kg/d)	50.0
ash (kg/d)	15.0
corn residue (kg/d)	25.0
dry matter (%)	36.5
C:N	13.2
V_{final} (m^3)	109.6

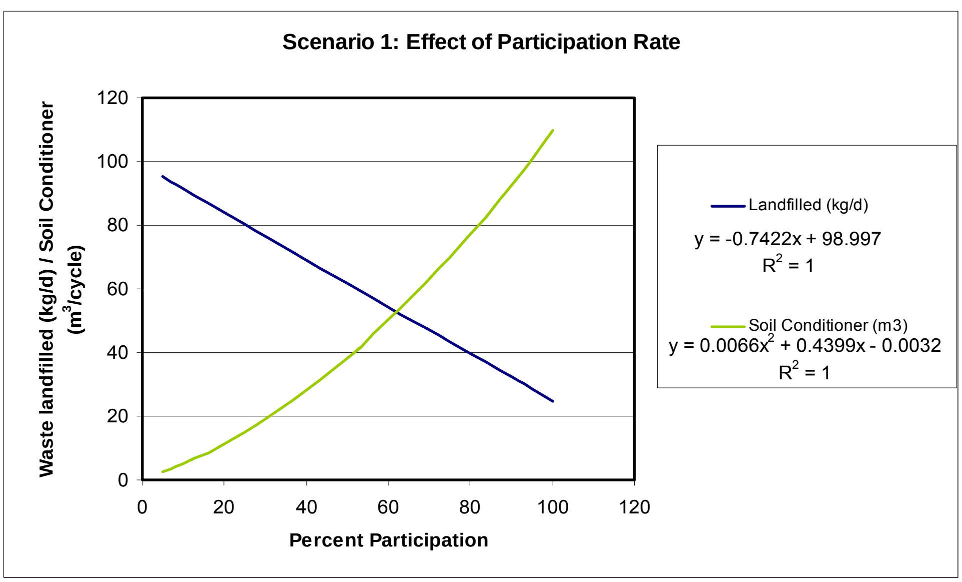


Figure 12: Effect of Participation Rate

Table 7 gives the composting results of scenario 1. This scenario was based on the participation ratio of 1 and thus represents the ideal case recipe. Without any surprise, the participation rate was the most sensitive parameter in the compost model (Figure12) suggesting that social engineering through proper education is the key component in the overall sanitation design strategies.

It is also important to keep in mind the other assumptions underlying the compost model. For example, apart for the loading rate, the putriscible data was based on typical food waste characteristics in North America. Because of the much less diversified food consumption habits in the northern region of Ghana, it is possible that their food waste properties differ (such as C:N ratio and moisture content) from the data used for the modeling. This suggests that an on-site analysis of their food waste would improve the accuracy of this simulation. However, during the sensitivity analysis it was found that the model was not very sensitive to changes in C:N ratio and moisture content. For example, increasing the C:N ratio by five only changed the final C:N ratio by 0.3 while leaving all other outputs constant. As a result, considering the economic background of the study sight, it might not worth spending limited resource in obtaining more food waste characteristics.

The same is true for the corn residue data. In this simulation the high range for the C:N ratio, which might not be true, was selected. The decision was based on the fact that corn production is unlikely to be under maximum potential yield where the optimum level of nitrogen is present. Therefore, it is more probable that the corn grown in northern Ghana be more susceptible to nitrogen deficiency exhibiting a high C:N. We also went in the high range of dryness for the moisture content of the corn residue. This assumption was based on the dry climatic conditions in the northern regions of Ghana. During the sensitivity analysis, it was discovered that the corn residue data used had virtually no impact on the final characteristic due to its low mass fraction in the recipe.

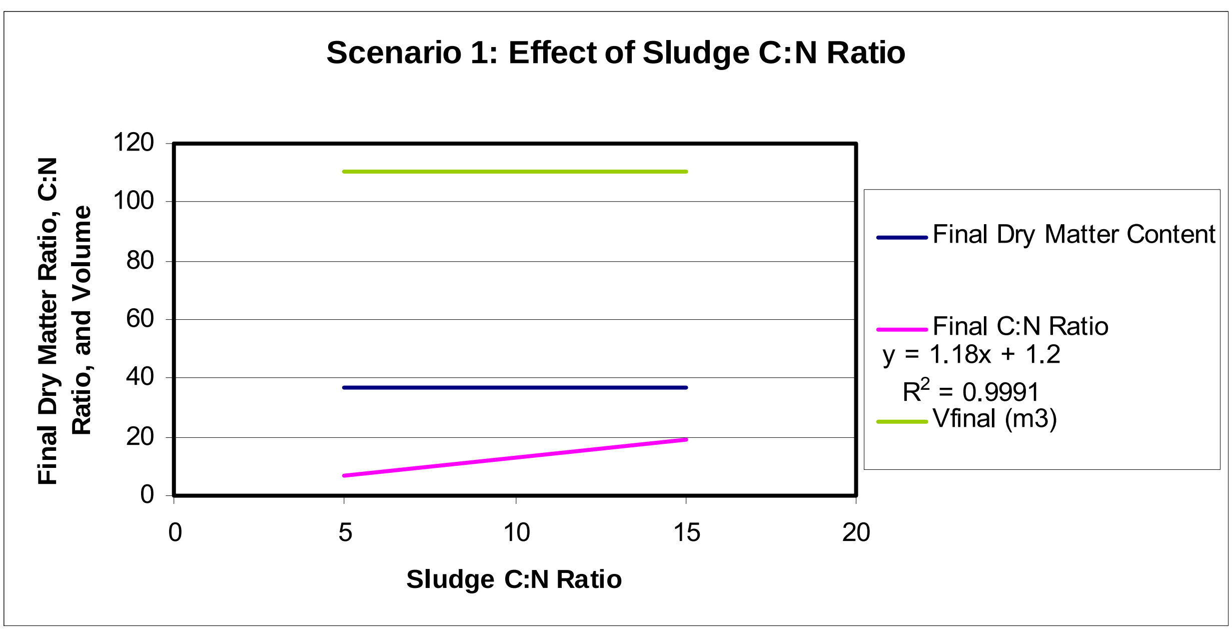


Figure 13: Effect of Sludge C:N ratio

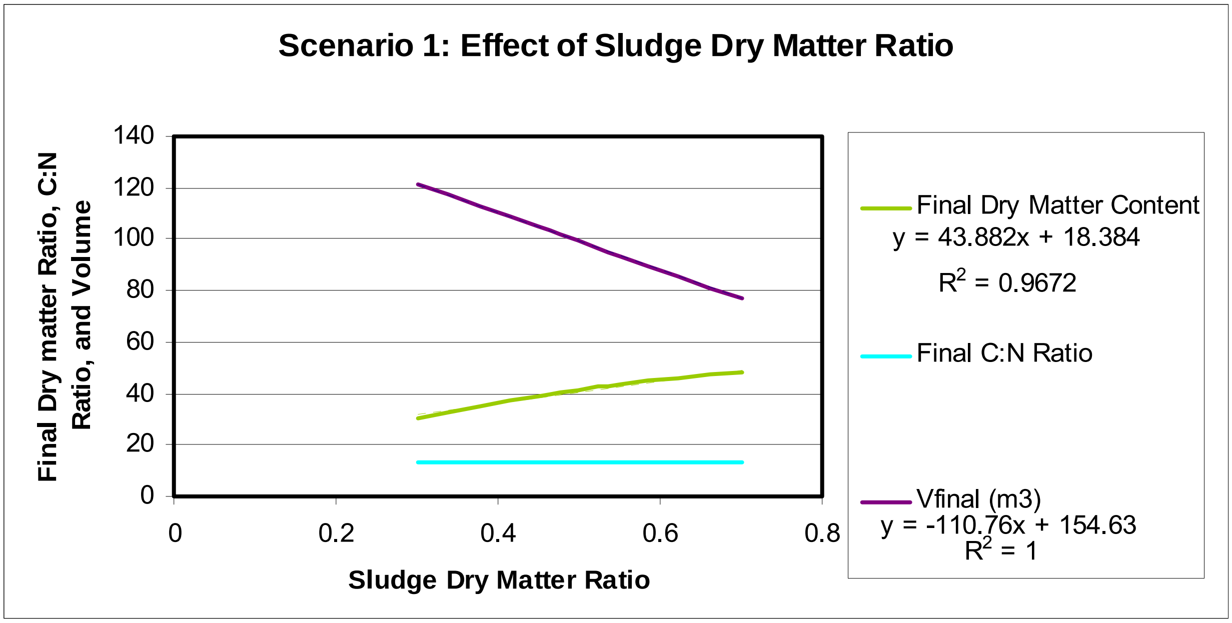


Figure 14: Effect of Sludge Dry Matter Ratio

Finally, in terms of the waste characteristic, it was discovered that only the remaining dewatered fecal sludge had a major impact to the final recipe characteristic due to its high mass ratio (≈0.6)(see Figures 13 and 14). For example, changing the C:N ratio by 5, changed the final C:N ratio by 5.9, whereas changing the moisture content by 5, produced a 3% change in dry matter content and increased/decreased the final volume by roughly 5 m^3. As a result, the fecal sludge characteristics were found to be the most sensitive parameters in the compost modeling and obtaining more accurate data is highly recommended.

Looking back at the final recipe, the final dry matter content is 3.5% below the recommended range of 40-50%. Though this may slow down the treatment process and create potential odor problems for a while, it was decided to leave it as-is for practicality. In order to bring the dry matter content to 40%, one would require twice as much wood chips (100 kg/day), which might not be available in northern Ghana since this region is characterized by a savannah grassland ecosystem. Second, due to the dry climatic conditions of the study site, starting with higher moisture content might be desirable design criteria since moisture deficit is likely to occur later during the maturation phase.

Finally, the final C:N ratio was found to be a bit lower than the optimum range (15-25). Here again, to bring the C:N ratio to 15 would have required twice as much wood chips. Whether or not this could be problematic in terms of leachate contamination needs further analysis. However, due to the uncertainties associated with the characteristic of the fecal sludge and its impact on the overall recipe, it was decided to leave it as-is until more accurate data could be found. For example, changing its C:N ratio from 10 to 11 would solve the problem.

Scenario 2

i. Assumptions:

General:

- No loss of waste input due to poor or lacking transport mechanisms
- Participation ratio = Decimal percentage of population who are effectively participating (recycling 75% of waste, transporting 100% of waste appropriately)

Dewatering:

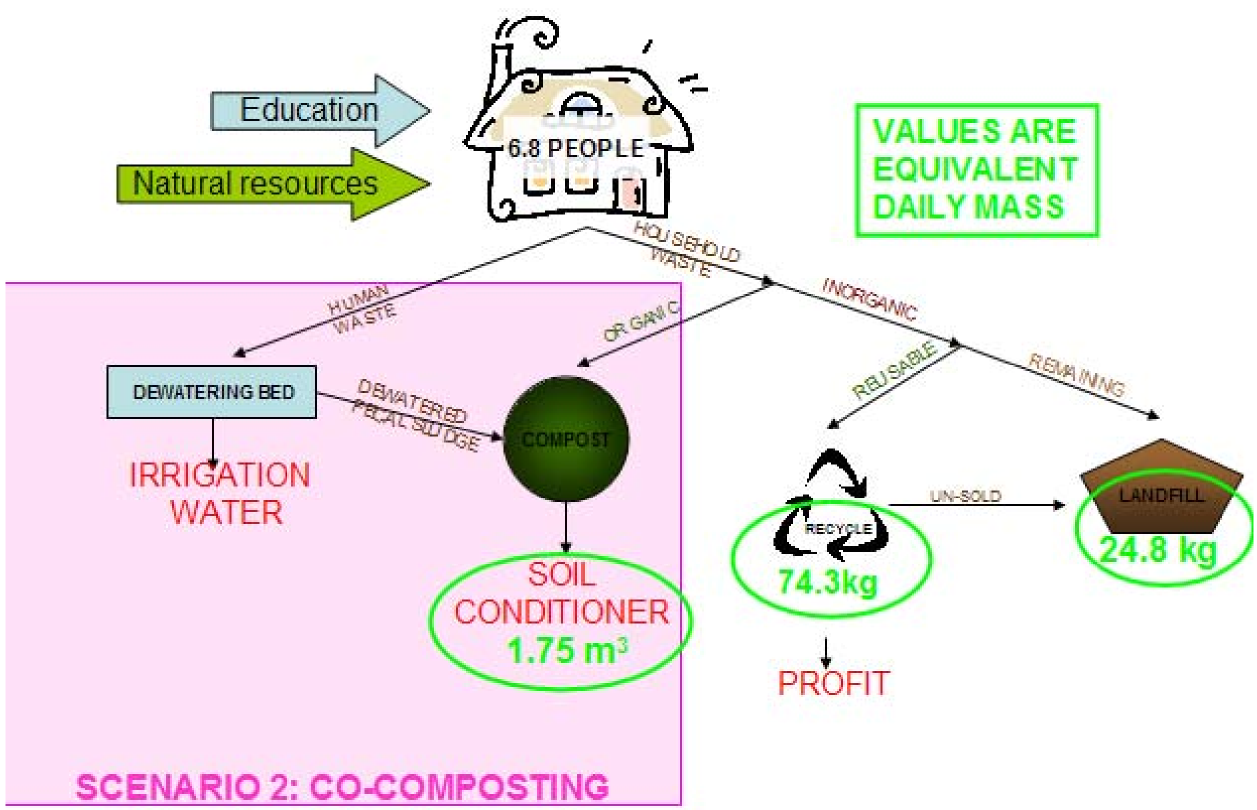
- Same as the dewatering process in Scenario 1 and
- Dewatering beds can sustain high strength waste

Composting:

- Same as the Composting Process in Scenario 1

ii. Results:

Complete Tabulated Results are available in Appendix A



iii. Analysis:

Composting:

Table 8: Results for compost

ORGANIC WASTE	
Co-Compost - Household Waste	
Putriscible (kg/d)	312.0
d/w sluge (kg/d)	608.4
wood chips (kg/d)	50.0
ash (kg/d)	15.0
corn residue (kg/d)	25.0
dry matter (%)	36.5
C:N	13.2
V_{final} (m^3)	110.3

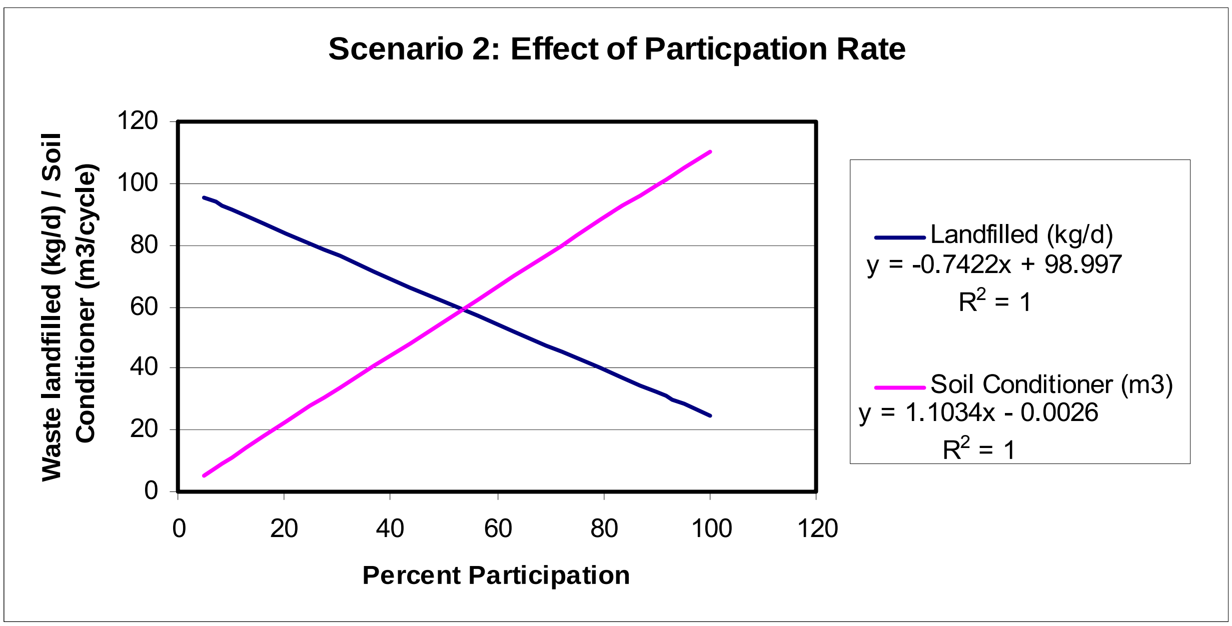


Figure 15: Effect of Participation Rate for Scenario 2

This scenario was based on the participation rate of 1 and thus table 8 represents the ideal case recipe. Here again, the participation rate was the most sensitive parameters in the compost model (Figure 15). Since scenario 2 had similar input characteristics as scenario 1, it yielded a comparable final recipe with only a slight volume change associated with the biogas produce by the anaerobic digestion in scenario 1 prior to the composting phase. As a result, the sensitivity analysis gave way to similar results explained previously in scenario 1. Here again, focus should be aimed at getting better data on the fecal sludge composition.

Scenario 3

i. Assumptions:

General:

- No loss of waste input due to poor or lacking transport mechanisms
- Participation ratio = Decimal percentage of population who are effectively participating (recycling 75% of waste, transporting 100% of waste appropriately)

Solar Drying:

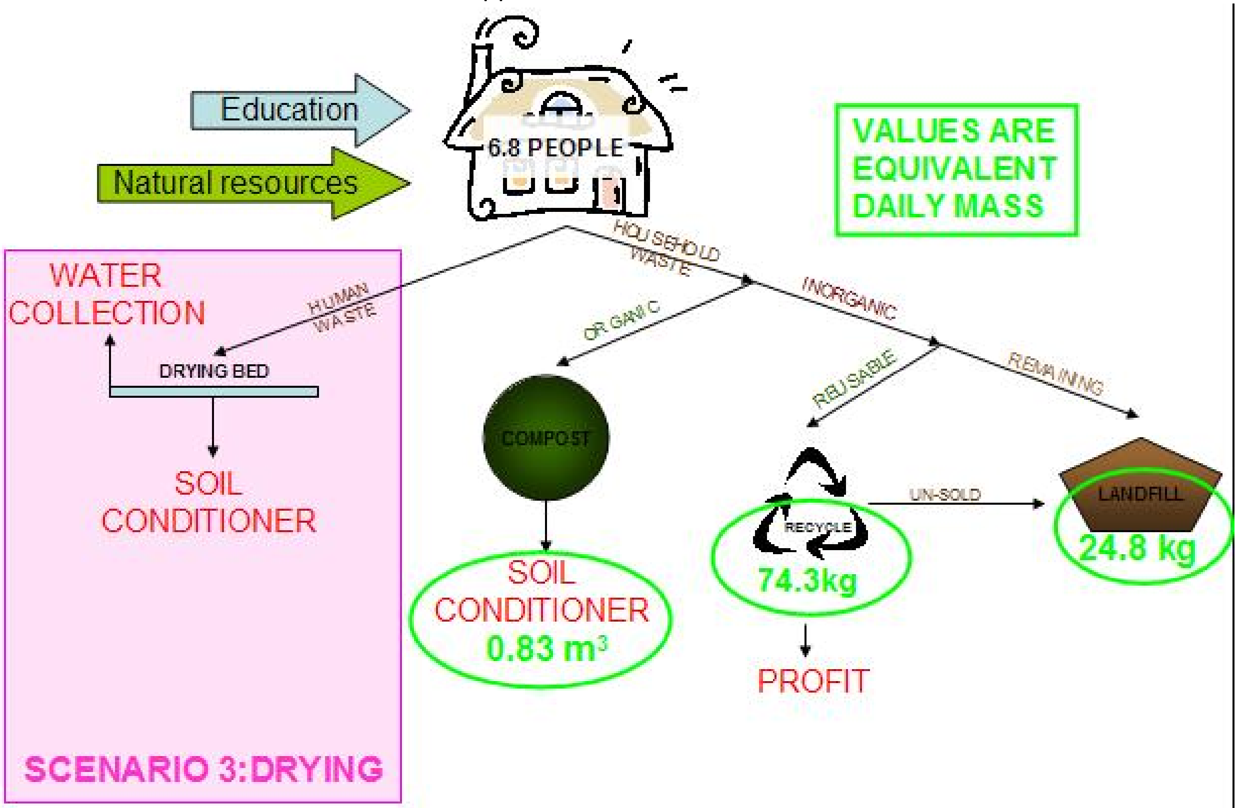
- Closed system
- No convection
- Constant rate of evaporation
- Plastic sheet transmits all incoming radiation
- Fecal sludge is homogenous and uniformly distributed

Composting:

- Same as for Composting in Scenario 1.

ii. Results:

Complete Tabulated Results are available in Appendix A



iii. Analysis:

Solar drying:

Table 9: Solar Dryer from Mali data

Night Soil Drying - Human Waste	
Area needed, per week	
per household, m2	5.0
per village, m2	548.5
square slab size, m	
per household, m	2.2
per village, m	23.4
temperature inside, °C	55.7

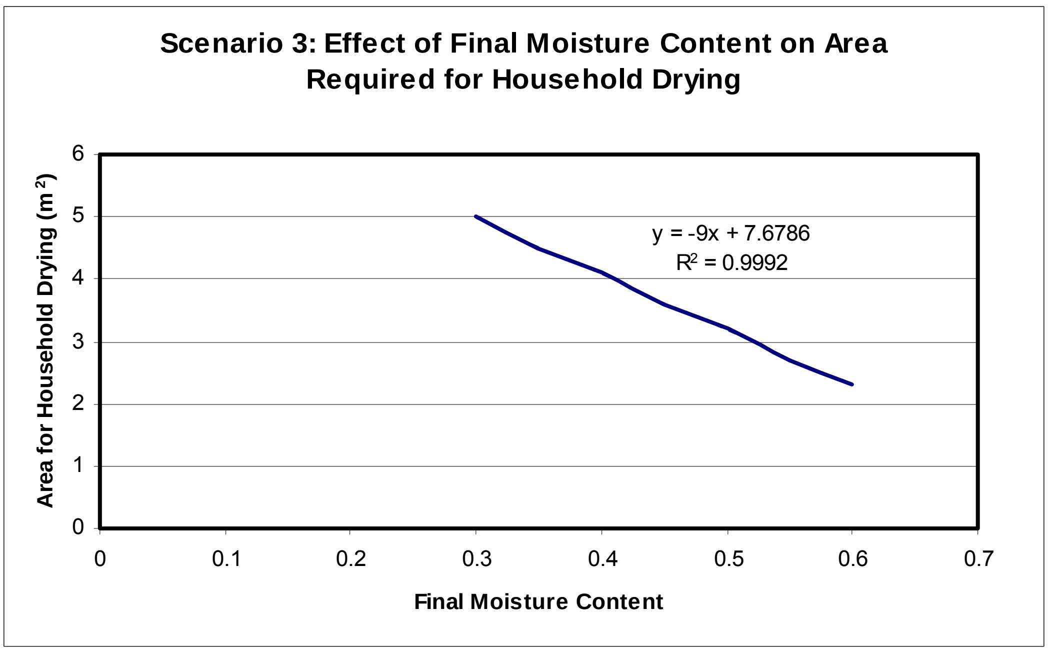


Figure 16: Effect of Final Moisture Content on Area Required for Household Drying

This scenario was based on the participation rate of 1 and thus the area needed per week per village represents a maximum (table 9). For this scenario, the participation rate is not as important as for the two previous ones because the solar drying phase takes place within each household. As a result, area needed per household is irrelevant to the participation rate. During the sensitivity analysis, only the final moisture content was tested as being the major parameter to work within the model. As expected, it had a significant impact on the required area needed (Figure 16). For example, changing it from 0.4 to 0.3 increased the area needed per household by 1.1 m^2.

When interpreting the results, the readers should keep in mind the assumptions under which the modeling was performed. For example, assuming a closed system implies that all radiation was used to evaporate water, which causes an over-estimation of the process given that other energy losses are likely. On the other hand, neglecting air convection would cause an under-estimation of the rate of evaporation. Whether or not these two assumptions balanced each other is beyond the scope of this report and future researches should look upon incorporating kinematic equations on solar drying into the model.

Another interesting assumption made is the constant rate of evaporation. This statement implies that there is no change in evaporation as the sludge is getting dryer, which might not be valid (IDRC 1986). However, when looking at the required depth (equation 4d) we found that a depth of 1 cm is necessary; assuming that the sludge is homogenous and uniformly distributed over the unit area, another important assumption in the solar drying model. Finally, the last assumption made in this model is that the plastic sheet used transmits all incoming radiation. An appropriate factor should be added to the model to compensate for the likely over-estimation of evaporation caused by it. As a result, the 5 m^2 needed per household should be considered as a minimum area requirement for the design. Applying a safety factor of 1.5 to the design would yield a minimal area requirement of 7.5 m^2.

Another parameter in the design is the average temperature inside the drying chamber. This parameter was used to check whether using a final moisture content of 0.4 was sufficient to consider the sludge stabilized. Ideally the temperature should range close to 60°C (Golueke 1977). From table 9, we see that the average temperature is only 55.7°C. However, the average inside temperature was calculated using the average solar radiation per day, where the peak radiation period is buffered with the two lower periods; mainly the early morning and late afternoon. As a result, it is expected that the temperature inside the chamber reaches values higher than 60°C during the day and thus, we feel confident that the system will be efficient in treating the sludge in terms of its pathogen content under the previously mentioned assumptions.

Another limitation in this model, apart from the assumptions associated with it, is the relevancy of the solar data used in it. As mentioned previously, the solar data came from a survey done in the early 80's in Mali. Since Mali is located north of Ghana and thus, further away from the equator, using these data may under-estimate the real solar radiance of Ghana, which adds some safety in the design.

Composting:

See scenario 1 for sensitivity analysis discussions

Table 11: Results for Compost

Compost - Household Waste	
Putriscible (kg/d)	312.0
wood chips (kg/d)	20.0
ash (kg/d)	20.0
corn residue (kg/d)	20.0
dry matter (%)	26.6
C:N	31.0
V_{final} (m^3)	40.6

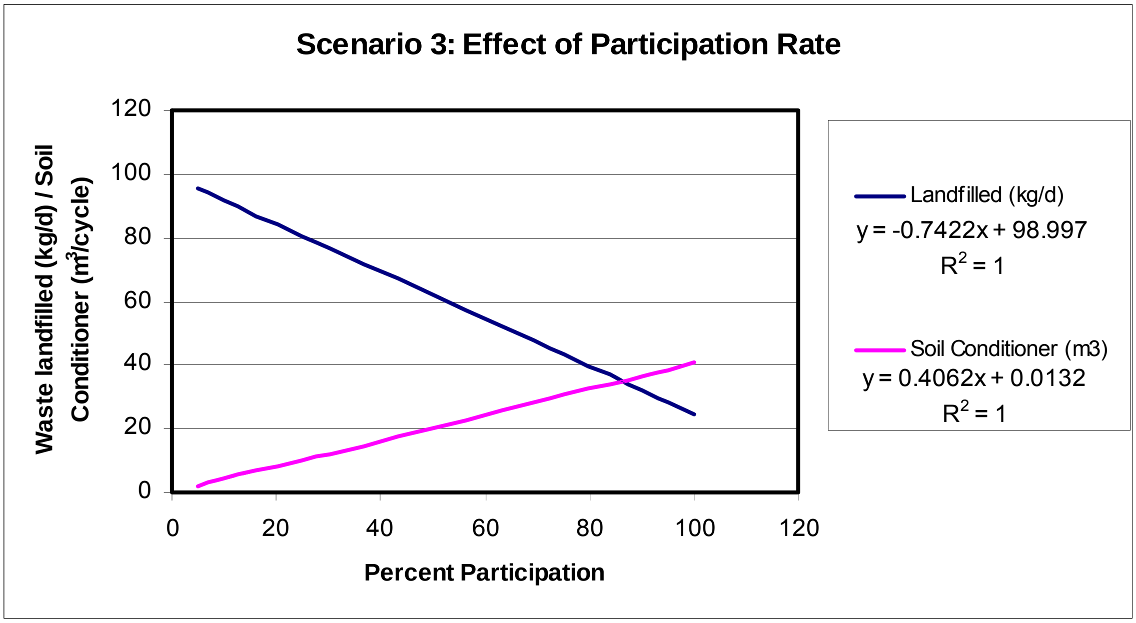


Figure 17: Effect of Participation Rate for Scenario 3

In this scenario, only the food waste was considered. Table 11 shows the recipe associated with it. Note the major difference in the final volume compared to the two previous scenarios. Here again, the participation rate was found to be the major factor affecting the compost modeling (see Figure 17). However, contrary to the two previous scenarios, the model was found to be very sensitive with the food waste composition like the C:N ratio and the moisture content. This could be explained by the high fraction of food waste (0.84) in the overall mass balance equation. For example, a reduction of 5 of the C:N ratio decreased the final C:N ratio by 7. Similar observations were found according to the moisture content.

Looking at the characteristics of the final recipe, we found that the dry matter content was very low compared to the ideal value of 40-50%. As a result, potential odor problem is likely to occur with this scenario. To obtain similar moisture content than the two previous scenarios, the moisture content of the food waste should be reduced to 75% instead of 85%. Interestingly, this would also bring the C:N ratio (27) within the optimum range. In this model, the final C:N ratio was considered as the limiting factor in the design and therefore, bulking agent were added until the C:N ratio reach a value slightly above the optimum range. However, as mentioned earlier, the model was very sensitive to the food waste C:N ratio and thus, changing the food waste C:N ratio from 20 to 18 would bring the final C:N ratio within the optimum range.

In terms of volume, it is likely that the current recipe under-estimate the final volume of the compost. This hypothesis is based on the fact the none of the major factors affecting the rate of decomposition, such as the C:N ratio and moisture content are within their optimum range. As a result, it is expected that the rate of decomposition would be slower and thus, the retention time associated with the active and maturation phase should be increased to compensate. For example, assuming an extra five and forteen days for the active and maturation phases respectively would yield a final volume of 52.5 m^3 instead of 40.6 m^3. In sums, this scenario highlights the beneficial outcome of co-composting when food waste characteristics do not allow the generation of proper composting recipe.

Economic Analysis

An economic break-down of each scenario is to follow. First the financial capacity of the households must be realized. The World Health Organization (WHO) judged that households are capable of spending 5% of their income on water and sanitation (Vodounhessi 2006).

The average income for villages in Northern Ghana ranges between 135,000 Cedis to 281,000 Cedis (Fathelrahman). The average, 208,000 Cedis will be used for the village in study. According to the WHO standard, each household should be able to pay 14,050 Cedis per month for water and sanitation services. Assuming a 60:40 water:sanitation spending ratio since water services are historically given more importance than sanitation, 5,620 Cedis per month are available in each household for sanitation costs (Vodounhessi 2006).

According to the current exchange rate, this is about USD$0.5 available for sanitation per month. According to the WHO Water Supply and Sanitation Assessment (2000), 52% of the investment in sanitation in rural Ghana is from external sources such as the World Bank. Therefore, it can be said that each household's capacity is only about 48% of the effective financial capacity. With external funding, each household can pay about $1 per month on sanitation. So, as a village, that is about $110 per month.

Another consideration is the benefit that will come from community composting. In a study in the Kumasi area, farmers were surveyed to see how much they would pay for compost. Stable crop farmers would pay about USD$0.19 for a 50kg bag of compost. This is considered part of the business budget of a household, but it is also an investment the farmer is willing to make towards composting waste on top of the household $1 per month available (Vodounhessi 2006).

In addition to the above sources of funding for a waste treatment project there is the municipality. As the village grows it will most likely adapt a similar kind of government as seen in Accra and Kumasi. In both cities there is a Waste Management Department (WMD) responsible for ensuring all residents have access to waste collection. In Kumasi the WMD offers a 50% subsidy for the cost of collection to low-income households. This money is from tax-payers and national funding from the Government of Ghana (GoG) (Vodounhessi 2006).

The last source of funding to be considered is the private sector. In the cities of Ghana the public organization is responsible for regulating and ensuring waste collection and treatment, but the private sector is responsible for carrying out these operations. Therefore, a private company will make investments in collection and treatment in order to someday make a steady monetary return in the business.

Therefore, there is a substantial amount of capital available for waste treatment. In Kumasi, for example, there is five times the amount of money available from the above sources than the cost of a standard FSTP (Fecal Sludge Treatment Plant) (Vodounhessi 2006). The reason for poor sanitation in that case is not the money but the lack of appropriate technology in the FSTP process and commitment to improvement.

The ability of a household to pay for waste improvements is summarized below:

Ability to Pay (USD)

		Monthly	Annual
Household			
	Sanitation Budget	0.48	5.76
	External Funding	0.52	6.24
	TOTAL:		**$12.00**
Village			
	Residents	750.00	**$9000.00**

The scenarios were each analyzed on a cost-benefit basis and are summarized below:

Economic Balance by Scenario

		Unit Cost (CapEx +O&M)	Units	Village cost per year (USD)
Scenario 1				
	A/D	60.00	$/t-TS	1182
	Biogas	-0.20	$/litre	-126
	Composting	9.20	$/m^3	5841
	Soil Conditioner	-1.10	$/50kg	-4190
	Recycling	2.28	$/tonne	61.44
	Landfill	9.12	$/tonne	171.55
	TOTAL:			**$2,940**
Scenario 2				
	Co-Composting	9.2	$/m^3	5879
	Soil Conditioner	-1.10	$/50kg	-4217
	Recycling	2.28	$/tonne	61.44
	Landfill	9.12	$/tonne	171.55
	TOTAL:			**1894.99**
Scenario 3				
	Drying	14.00	$/structure	14
	Soil Conditioner	-1.1	$/50 kg	-33.24
	Recycling	2.28	$/tonne	61.44
	Landfill	9.12	$/tonne	171.55
	TOTAL:			**213.75**

Immediately, one is shocked at the amount the village is capable of paying with respect to the yearly cost of waste treatment technology. However, this data is similar to studies done in Kumasi by Vodounhessi (2006). Once all the sources of funding are properly aligned and the private sector, which was not included in the above estimate, has made an investment, the funding is theoretically available.

The reason that these economic findings are not representative of reality is that all the sources of funding are not just lying around. There needs to be leaders willing to organize the system, seek the external funding and make locals believe in the technology. When the funding is realized it needs to be invested in appropriate technology for high strength waste. If the technology fails, like the FSTP process in several cases, the capital may not be available for repair or modification and the people are likely to revert to old habits rather than beginning a capital campaign for a new technology solution.

A major limiting factor of the ability of the village to invest is the individual household budgeting techniques. For successful implementation households have to be rigorous at setting aside money to cover large capital expenditures. Secondly, since the benefits from fertilizer and gas were considered as negative costs and they are not immediate gains, the initial yearly cost becomes much higher. Households would need to be able to put extra money forward in the beginning understanding that benefits from biogas and soil conditioner are to come. Thirdly, since the economic return would be effective over time it implies that the value of fertilizer and biogas are also major factors. If the demand for either product changed causing a drop in price, households would need to be able to absorb the loss. These three aspects of financial planning are a lot to expect from low income households in an area where subsistence is a way of life. It is likely these limitations that are most greatly preventing villages from progressing in waste treatment.

A brief summary of the sources and assumptions made for each process is below. Please see the Appendix E for detailed explanation of assumptions and a complete set of the equations used to calculate the yearly costs and benefits.

	Source:
A/D	Estimation based on cost of Sedimentation tank, and TS data from Kone and Strauss (2004)
Biogas	Equivalent energy values and cost of Diesel from McCarty (1964) and BBC (2008)
Composting	Price of Co-composting from Guidance Pack (Cointreau-Levine and Coad, 2000)
Soil Conditioner	Willingness to Pay as cited in Guidance Pack
Drying	Cost of major material, plastic, computed for area needed
Recycling	Source: Assumption made by authors based on equations from Pearce and Turner on the extra cost of a recycling system
Landfill	Cost of collection, transport and disposal of SW range estimated by Pearce and Turner. Authors assumed min. value since much transport is manual. Also, fits in range given by Ruskbrook and Pugh

Conclusion

The objectives of this report were met through the study and modeling of waste management in Ghana, but the overall strategy mentioned as early as the title remains to be elaborated. The motivation for this report was to create a sustainable basis of waste ideology and knowledge for the village to benefit from as it grows. From the modeling of three scenarios a strategy was realized clearly. A review of the contents of this report will show that as a community grows one organic waste technology can lead to the next and the benefits from each process can be used towards further improvement.

Three scenarios were modeled in this report; anaerobic digestion combined with co-composting, co-composting with prior dewatering, and night soil solar drying combined with food waste composting. These models were tested in the context of a village located in the northern region of Ghana about 20 kilometers south-east of Bawku with roughly 110 households for a total of 750 habitants. Each scenario was run according to a participation ratio to simulate a hypothetical learning curve through proper social engineering strategies, such as the PHAST program and women's involvement to name just a few. For example, it is approximated that low participation rate is likely to occur at the early phase of the sanitation strategy program outlined.

During the early stage of a community's growth, it is recommended to promote scenario 3, where decentralized solar dryer units are installed at each household with a centralized composting center for the village. It is likely that external funding would be necessary for villager's transitions toward better sanitation. As mentioned previously, though having decentralized compost seems as a much more convenient way to treat household organic waste at this stage, it is still recommended to push for community composting in order to set a transporting system, management team and active compost in place for future developments and growth. When sufficient resources become available within the village, it is suggested to move toward scenario 2, which implies more advanced technologies, such as dewatering beds and co-composting.

In scenario 2, it is believed that local participants would have gained sufficient knowledge on sanitation and composting processes such that there would be willingness inside the community to invest toward even better sanitation strategies. Moreover, this scenario assumed a complete change from decentralized to centralized handling of organic waste combined with an increase in the village participation. At this stage, it is possible that some private companies invest in the collection and treatment of the waste and ease the transitions.

Finally, as population and participation grow, the community should aim at implementing scenario 1, where anaerobic digestion is incorporated in their sanitation strategies. At this stage, skilled and trained villagers would be in charge of running the installation along with the private sectors, creating jobs at the same times. The village would be fully equipped to deal with organic waste and population growth. Future developments should focus on improving the recycling ability of the community.

To conclude, an economical model analysis was also performed on these scenarios to check the viability of their implementation in the studied community. Primary results indicated that the village was capable of paying with respect to the yearly cost of waste treatment technology. However, it is important to remind the reader that the models used and developed in this report are aimed at helping the decision making process on sanitation strategies by the village leaders and thus, further investigation of the processes explored with the help of the community is necessary before beginning on-site engineering designs of the waste system components.

Appendix A: Main Inputs and Results for the Three Scenarios

Table A1: Main Inputs for the Model

INPUT:	MASS PER CAPITA (kg/d)	PERCENT RECYCLE
PAPER	0.036	75
GLASS	0.003	75
METALS	0.014	75
PLASTIC/RUBBER/ LEATHER	0.022	75
TEXTILES	0.008	75
CERAMICS/ETC.	0.049	75
PUTRISCIBLES	0.416	
FEACES	0.202	
URINES	1.15	
HOUSEHOLD SIZE	6.8	
VILLAGE SIZE	750	
PARTICIPATION RATIO	1	

Source: (David Pearce and Turner 1994)

Table A2: Summary of the Results for Scenario 1

ORGANIC WASTE				INORGANIC SOLID WASTE		
Anaerobic Digestion - Human Waste		Compost - Household Waste		Village Waste (kg/d)	Reuse &Recycle	Landfill
Biogas Produced (kg/d)[1]:	11.8	Putriscible (kg/d)	312.0	Paper	20.3	6.8
Methane (kg/d):	**2.334**	A/D (kg/d)	601.3	Glass	1.7	0.6
BOD Remaining (kg/d):	4.4	wood chips (kg/d)	50.0	Metals	7.9	2.6
Sludge Produced (kg/d)	1.7	ash (kg/d)	15.0	Plastic/Rubber	12.4	4.1
Total Effluent (kg/d)	1002.2	corn residue (kg/d)	25.0	Textiles	4.5	1.5
		dry matter (%)	36.5	Ceramics/ect.	27.6	9.2
		C:N	13.5	**TOTAL MASS (kg/d):**	**74.3**	**24.8**
1: From Buswell Equation		**V_{final} (m^3)**	**109.6**			

Table A3: Summary of the Results for Scenario 2

ORGANIC WASTE		INORGANIC WASTE		
Co-Compost - Household Waste		Village Waste (kg/d)	Reuse &Recycle	Landfill
Putriscible (kg/d)	312.0	Paper	20.3	6.8
d/w sluge (kg/d)	608.4	Glass	1.7	0.6
wood chips (kg/d)	50.0	Metals	7.9	2.6
ash (kg/d)	15.0	Plastic/Rubber	12.4	4.1
corn residue (kg/d)	25.0	Textiles	4.5	1.5
dry matter (%)	36.5	Ceramics/ect.	27.6	9.2
C:N	13.2	**TOTAL MASS kg/d):**	**74.3**	**24.8**
V_{final} (m^3)	**110.3**			

Table A4: Summary of the Results for Scenario 3

ORGANIC WASTE				INORGANIC WASTE		
Night Soil Drying - Human Waste		Compost - Household Waste		Village Waste (kg/d)	Reuse &Recycle	Landfill
Area needed, per week		Putriscible (kg/d)	312.0	Paper	20.3	6.8
per household, m2	**5.0**	wood chips (kg/d)	20.0	Glass	1.7	0.6
per village, m2	548.5	ash (kg/d)	20.0	Metals	7.9	2.6
square slab size, m		corn residue (kg/d)	20.0	Plastic/Rubber	12.4	4.1
per household, m	2.2	dry matter (%)	26.6	Textiles	4.5	1.5
per village, m	23.4	C:N	31.0	Ceramics/ect.	27.6	9.2
temperature inside, °C	55.7	**V_{final} (m^3)**	**52.5**	**TOTAL MASS (kg/d):**	**74.3**	**24.8**

Appendix B: Anaerobic Digestion

Table B1: Feacal Sludge, night soil, and public toilet sludge characteristics

Terminology	"sewage "	"public toilet"	"human excreta"	"nightsoil/ toilet sludge Kumasi"	"Public toilet/ bucket latrine"	"Public Toilet Sludge Accra"	"fresh Excreta"	"urine and feaces"	
Source	1	2	3	5	5	5	5	6	
TS (mg/l)	x	52500	x	x	> 3.5%	x	110 g/cap.d	x	x
TSS (mg/l)	980	x	x	64000	> 30000	6.40%	x	x	x
VSS (mg/l)	769	35700	10520	37000	x	58% of TSS	x	30 (g/pers/da y)	20000
BOD (mg/l)	879	11400	13500	13,200	10,000	8800	45 g/cap.d	x	x
COD (mg/l)	1546	49000	x	47600	30,000	47600	x	x	x
Total N (mg N/l)	93	x	5500	x	x	x	x	12.5 (g/pers/da y)	8300
NH4-N	x	3300	1750	x	3,000	x	x	x	x
Total P	16	x	x	x	x	x	x	C (g/pers/d)	16.393
Alkalinity	491	x	x	x	x	x	x	C/N	1.3115

Note: All values in mg/l unless otherwise noted, x = no data given, volume of excreta = 1.5 l/cap/d as given by Doku (2003)

1 "Bio-Methane and Bio-Hydrogen" (T.Z.D. de Mes, A.J.M. Stams et al. 2003)

2 "Low-cost Options for Treating Faecal Sludges (FS) in Developing Countries" (Doulaye Koné and Strauss 2004)

3 "(Itokawa, Hanaki et al. 2001)

4 (Heinonen-Tanski and van Wijk-Sijbesma 2005)

5 "The Potential for the use of Upflow Anaerobic Sludge Blanket (UASB) Reactor for the Treatment of Faecal Sludges in Ghana" (Doku, 2003)

Table B2: Parameter Input data for McCarty Equation

Table 2—Growth Constants and Endogenous Respiration Rates

(after Speece[1])

Waste	Growth Constant a	Endogenous Respiration Rate b
Fatty Acid	0.054	0.038
Carbohydrate	0.240	0.033
Protein	0.076	0.014

Table 3—Design for Solids Retention Times

Operating Temperature °F	*Solids Retention Times, Days* Minimum	Suggested for Design
65	11	28
75	8	20
85	6	14
95	4	10
105	4	10

Table B3: Buswell Inputs/Products

INPUT	
C	5
H	9
O	3
N	1
Waste Inflow (m^3/d)	1.014
PRODUCTS:	
Methane (kg/d):	4.179847
Carbon Dioxide (kg/d):	11.49458
Ammonia (kg/d):	1.776435

Table B4: A/D McCarty Fundamental Inputs

INPUT:	
growth constant, a	0.24
endogenous decay rate, b	0.033
SRT (days)	30
Efficiency, e	0.85
BOD (mg/l)	13500
F, (lbs. BOD added/d)	30.1158

Table B5: A/D Fundamentals Output

PRODUCTS:	
Volatile Biological Solids Produced, A (kg/d)	1.650935
Methane Produced, C (ft^3/d)	114.8779
Methane Produced, C (kg/d)	2.334179
BOD Stabilized, S (%)	67.87437
Methane Produced (kg/d) (Buswell Eqt*S):	2.837045

Sensitivity Analysis:

Figure B1: Participation Rate

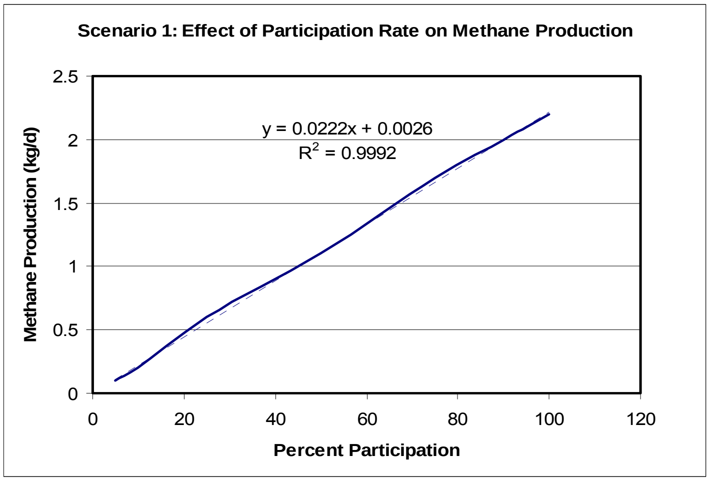


Figure B2: BOD

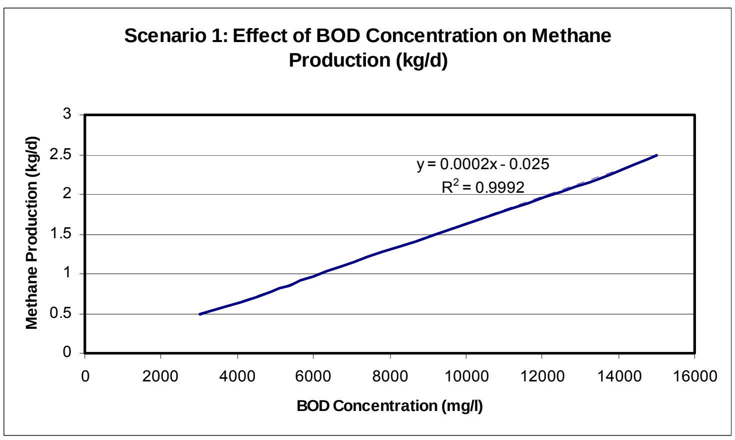


Figure B3: Growth Coefficient A

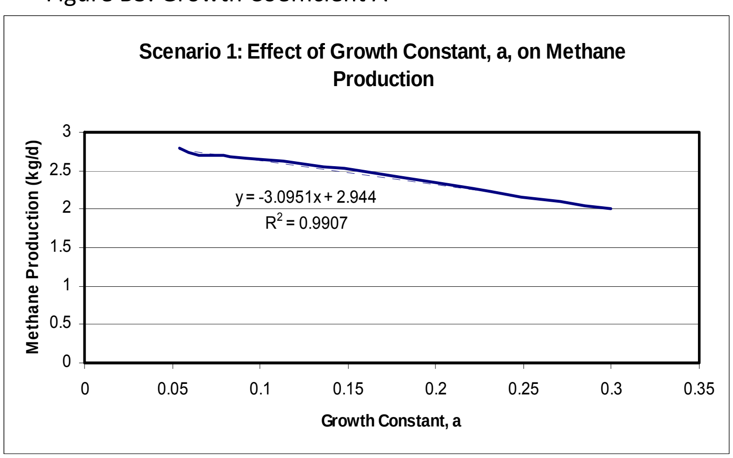


Figure B4: Endogenous Decay Rate, b

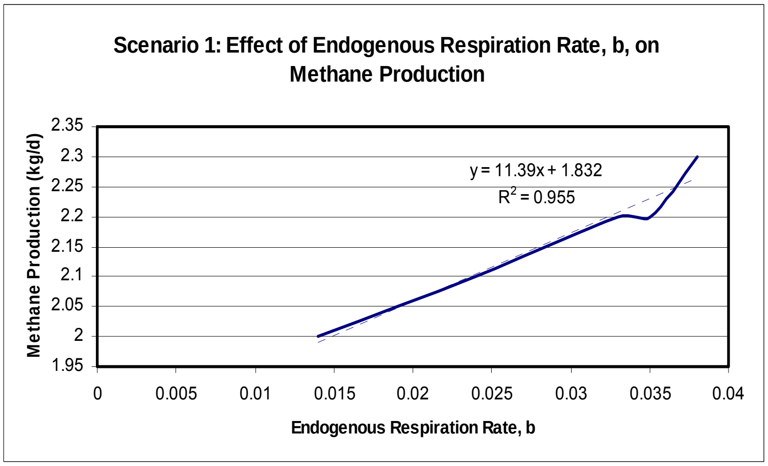


Figure B5: SRT

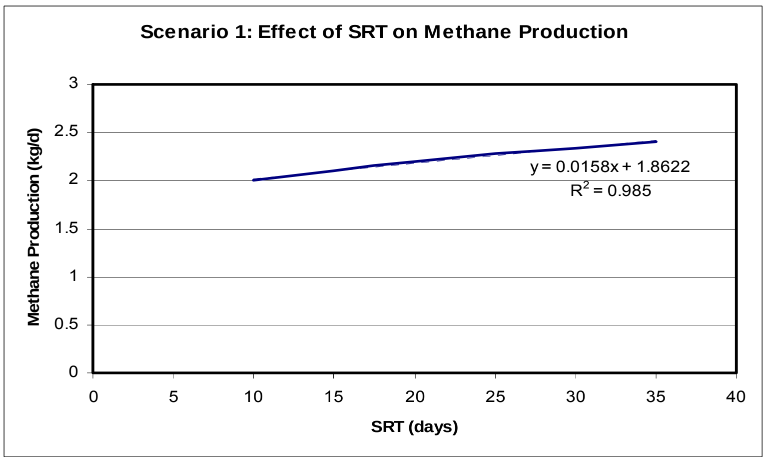
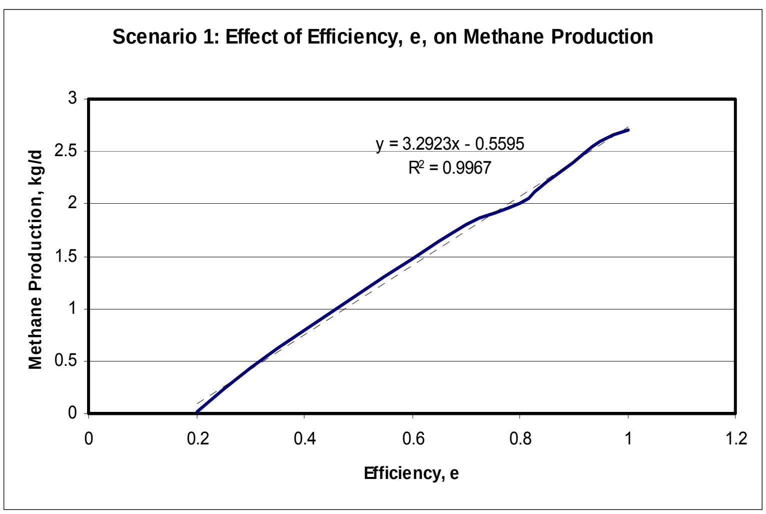


Figure B6: Efficiency, e



Appendix C: Composting

Table C1: Result for Composting for Scenario 1

model case 1	participation ratio		Bulking agent				
	1						
	After A/D+d/w	putriscible	wood chips	ash	corn residue		
dry matter ratio	0.4	0.15	0.9	0.9	0.8		
VS	0.9	0.9	0.99	0	0.85		
C/N	10	25	240	0	70		
C, fraction VS	0.49180328	0.4918033	0.540983607	0	0.464		
N, fraction VS	0.04918033	0.0196721	0.002254098	0	0.007		
production,kg/d	601.293	312	**50**	**15**	**25**		
						final mixture	
wet mass, kg	601.293	312	50	15	25	1003.293	kg/day
dry mass, kg	240.517	46.8	45	13.5	20	365.817	kg/day
C, kg	118.287	23.016393	24.3442623	0	9.289617486	174.937	kg/day
N, kg	11.829	0.9206557	0.101	0.000	0.133	12.984	kg/day
density, kg/m3	450	$RT_{maturation}$	42		V_{day}	2.230	m3/day
RT_{active}	21	VRR	0.33		dry matter	36.5	%
V_{active}	46.8203494	$V_{maturation}$	62.73926823		C:N	13.5	
					V_{final}	109.6	m3

Table C2: Result for Composting for Scenario 2

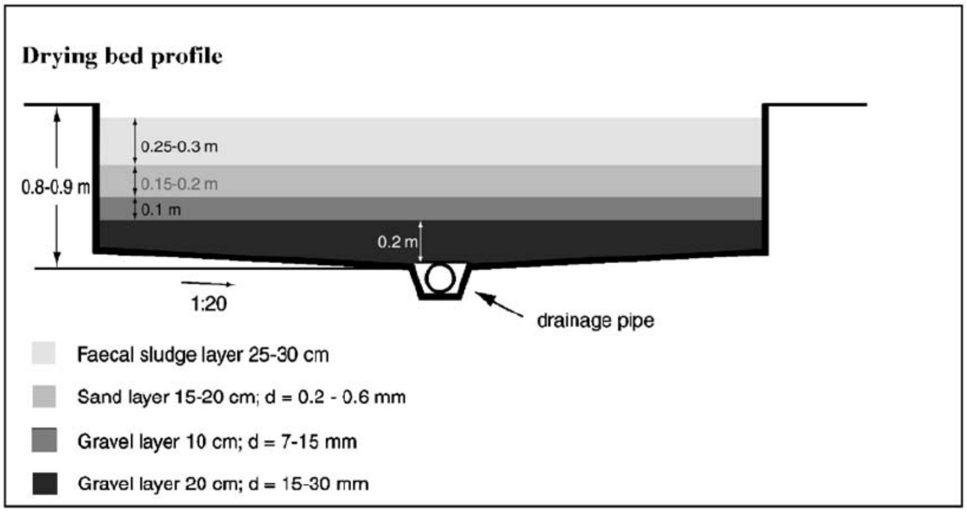
model case 2	**participation ratio**		**Bulking agent**				
	1						
	d/w slugde	**putriscible**	**wood chips**	**ash**	**corn residue**		
dry matter ratio	0.4	0.15	0.9	0.9	0.8		
VS	0.9	0.9	0.99	0	0.85		
C/N	10	20	240	0	70		
C, fraction VS	0.49180328	0.49	0.540983607	0	0.464		
N, fraction VS	0.04918033	0.0245	0.002254098	0	0.007		
production,kg/d	608.400	312	**50**	**15**	**25**		
						final mixture	
wet mass, kg	608.400	312	50	15	25	1010.400	kg/day
dry mass, kg	243.360	46.8	45	13.5	20	368.660	kg/day
C, kg	119.685	22.932	24.3442623	0	9.289617486	176.251	kg/day
N, kg	11.969	1.1466	0.101	0.000	0.133	13.349	kg/day
density, kg/m3	450	**$RT_{maturation}$**	42		**V_{day}**	2.245	m3/day
RT_{active}	21	**VRR**	0.33		**dry matter**	36.5	%
V_{active}	47.152	**$V_{maturation}$**	63.18368		**C:N**	13.2	
					V_{final}	110.3	m3

Table C3: Result for Composting for Scenario 3

model case 3	**participation ratio**		**Bulking agent**				
	1						
	dry slugde	**putriscible**	**wood chips**	**ash**	**corn residue**		
dry matter ratio	0.4	0.15	0.9	0.9	0.8		
VS	0.9	0.9	0.99	0	0.85		
C/N	10	20	240	0	70		
C, fraction VS	0.49180328	0.49	0.540983607	0	0.464		
N, fraction VS	0.04918033	0.0245	0.002254098	0	0.007		
production,kg/day	0.000	312	**20**	**20**	**20**		
						final mixture	
wet mass, kg	0.000	312	20	20	20	372.000	kg/day
dry mass, kg	0.000	46.8	18	18	16	98.800	kg/day
C, kg	0.000	22.932	9.737704918	0	7.431693989	40.101	kg/day
N, kg	0.000	1.1466	0.041	0.000	0.106	1.293	kg/day
density, kg/m3	450	**$RT_{maturation}$**	56		**V_{day}**	0.827	m3/day
RT_{active}	26	**VRR**	0.33		**dry matter**	26.56	%
V_{active}	21.49	**$V_{maturation}$**	31.02		**C:N**	31.006	
					V_{final}	52.51	m3

Appendix D: Solar Drying

Figure D1. Box recommandations for dewatering



Sizing of the beds

⇒ 15 days drying cycle
⇒ 25-30 cm sludge layer on beds
⇒ 100-200 kg TS/m^{2}y
⇒ 0.08 m^2/cap

Sand characteristics

⇒ Sand particles do not crumble
⇒ Sand easily available locally
⇒ Sand thoroughly washed prior to application unto the gravel base

Drying bed removal efficiency

⇒ 97 % SS, 87 % COD, 100 % HE

Raw sludge characteristics

⇒ Partly stabilised (septage or mixture septage / public toilet sludge with ≤ 30 % share of public toilet sludge)

Protection of filter layers

Reduce pressure flow via:

⇒ Splitting chamber, inlet channel, and splash plates

Biosolids

⇒ 0.1m^3 /m^3 fresh FS
⇒ Hygienisation necessary prior to use in agriculture as biosolids

Percolate

⇒ 50-80 % of raw FS volume
⇒ Quality fairly comparable to tropical wastewater
⇒ Salinity too high for irrigation
⇒ Percolate treatment: e.g. waste stabilisation ponds or constructed wetlands

Source*: (Cofie, Agbottah et al. 2006)*

Table D1: Removal efficiencies of drying beds at the Kumasi pilot co-composting plant

	TS (mg/l)	SS (mg/l)	COD (mg/l)	BOD (mg/l)	Helminth eggs (no./l)
Raw sludge	30,450	14,600	38,200	10,000	14,600
Percolate	5700–6100	290–600	3600–5600	870–1350	0
% Removal	80–81	96–98	85–90	86–91	100

Source: (Cofie, Agbottah et al. 2006)

Table D2: Thermal Deathpoints of Common Pathogens and Parasites

Organism	Thermal Deathpoint		Remarks
	Temp (°C)	Exposure Time (min)	
Salmonella typhosa	55-60	30	No growth beyond 46°C
Salmonella spp.	56	60	
	60	15	
Shigella spp.	55	60	
Escherichia coli	55	15-20	
	60		
Micrococcus pyogenes var. aureus	50	10	
Streptococcus pyogenes	54	10	
Mycobacterium tuberculosis var. hominis	66	15-20	
Mycobacteriumdiptheriae	55	45	
Brucella abortus or sirus	61	3	
Endamoeba histolytica	55		
Taenia saginata	55-60	5	
trichinella spiralis	62-65		Infectively reduced on 1 hour exposure to 50°C
Necator americanus	45	50	
ascaris lumbricoides (eggs)	60	15-20	

Source: (Golueke 1977)

Table D3: Mean Monthly Solar Radiation for Mali (kJ/day/m^2)

Radiation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
total	17172	16452	16452	15660	14616	14040	14040	13968	14796	14148	14292	14508
diffuse	3744	4428	4680	4860	4104	4896	4464	4824	3996	3528	2772	3600
direct	13428	12024	11772	10800	10512	9144	9576	9144	10800	10620	11520	10908

Source: Solar Drying in Africa (IDRC 1986)

Table D4: Albedos for some natural surfaces

Surface	Albedo
water	0.03-0.4
black dry soil	0.14
black moist soil	**0.08**
gray dry soil	0.25-0.30
gray moist soil	0.10-0.12
desert loam	0.29-0.31
bright fine sand	0.37
snow	0.4-0.85
sea ice	0.36-0.50

Source: (Holman 2002)

Table D7: Complete Results for Solar Drying using data from Mali and Participation Ratio of 1

From Mali Data		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
total rad., kJ/d/m2		17172	16452	16452	15660	14616	14040	14040	13968	14796	14148	14292	14508
diffuse rad., kJ/d/m2		3744	4428	4680	4860	4104	4896	4464	4824	3996	3528	2772	3600
direct rad., kJ/d/m2		13428	12024	11772	10800	10512	9144	9576	9144	10800	10620	11520	10908
corr. dif. rad., kJ/d/m2		12354	11062	10830	9936	9671	8412	8810	8412	9936	9770	10598	10035
tot. rad. Corr., kJ/d/m2		16098	15490	15510	14796	13775	13308	13274	13236	13932	13298	13370	13635
temp. chamber, °C	55.73	58.75	57.82	57.86	56.76	55.17	54.43	54.38	54.32	55.41	54.41	54.53	54.95
FS, kg/cap/d													
per household, kg/d		9.194	9.194	9.194	9.194	9.194	9.194	9.194	9.194	9.194	9.194	9.194	9.194
per village, kg/day		1014	1014	1014	1014	1014	1014	1014	1014	1014	1014	1014	1014
water evap., kg/d/m2		7.092	6.824	6.833	6.518	6.068	5.863	5.848	5.831	6.137	5.858	5.89	6.007
area needed, m2/d													
per household, m2		0.584	0.607	0.606	0.636	0.683	0.707	0.708	0.71	0.675	0.707	0.703	0.69
per village, m2		64.43	66.96	66.87	70.1	75.29	77.93	78.14	78.36	74.44	77.99	77.57	76.06
weekly basis													
per household, m2		4.089	4.25	4.244	4.449	4.779	4.946	4.959	4.973	4.725	4.95	4.923	4.828
per village, m2		451	468.7	468.1	490.7	527.1	545.5	546.9	548.5	521.1	545.9	543	532.4
square slab size, m													
per household, m		2.022	2.061	2.06	2.109	2.186	2.224	2.227	2.23	2.174	2.225	2.219	2.197
per village, m		21.24	21.65	21.64	22.15	22.96	23.36	23.39	23.42	22.83	23.37	23.3	23.07
latent heat of vap., kJ/kg	2270												
albedo	0.08												
MCi	0.851												
MCf	0.4												
LR	1.352												
people, house	6.8												
people, village	750												
temp. surr., °C	31												

assumptions

constant rate of evaporation
closed system
no convection
plastic sheet transmit all incoming radiation
FS is homogenous
sludge is uniformly distributed over the area

limitations

radiation data taken from Mali over a 5 years average

Appendix E: Economics

To do the economic calculations, it is assumed that there is a 100% percent participation to keep with the scenario results. In most cases this will raise costs of waste treatment, but it will lower the cost of landfill disposal due to the increased use of the much cheaper option, recycling. Due to the scarcity of data on costs of construction, operation and maintenance and labor in Ghana, all economic calculations for this study have a large margin of error. In an effort towards transparency on the inadequacy of the economic analysis of waste treatment in Ghana, the formulas and assumptions behind the economic analysis are below.

Inorganic Waste:

Pearce and Turner estimate the cost of collection, transfer and disposal of solid waste as 19-38 $/tonne in Ghana (1994). Since the use of collection vehicles is assumed and the village in question will rely upon manual labor, the lower value of *19$/tonne* of solid waste is assumed for calculations.

Annual Cost of Landfill to Community = $24.8 \, {}^{kg}\!/_{d} * \left(\frac{1t}{1000kg}\right) * \left(\frac{19\$}{1t}\right) * \left(\frac{365d}{yr}\right) = \$172$

The cost of recycling is analyzed in detail in Pearce and Turner's work as well. Especially at the beginning of implementation, recycling is a benefit financially because of the decrease in cost of landfills offered by the reuse of goods. However there is a cost associated with recycling operations that is less than that of the cost of disposal of goods. Using the example provided in the literature, where the marginal cost of recycling over time is about equal to the marginal cost of landfill disposal, it is assumed for cost analysis that the cost of recycling (including initial benefits) is one quarter of the cost to landfill goods. (0.25*$19/t = $4.75/t-recycled)

Annual Net Cost of Recycling to Community = $(98.63 - 24.8)kg * \left(\frac{\$4.75}{t}\right) * \left(\frac{1t}{1000kg}\right) * \left(\frac{365d}{yr}\right) = \$126$

Organic Waste, Scenario 1:

Anaerobic Digestion:

Data for the cost of anaerobic digestion in Ghana was unavailable. However, data for the cost of some similar waste technologies will be adjusted for a rough estimate. According to Strauss (CITE), the annualized costs of a settling pond (including capital expenditure as well as operation and maintenance) are about $45/t-sludge. A settling tank would be similar to an anaerobic digester because it includes influent storage, some excavation, a tank, minor pipe-work and some foundation costs. However, since a digester must have a lid and gas collection pipe and tank, an annualized $15 of extra capital expenditure is assumed. Therefore, annually $60/t-TS (TS = Total Solids) will be the cost associated with the anaerobic digester. This does not include the economic benefit of the methane collected.

TS of waste = $52500^{1} \, {}^{mg}\!/_{l} * 1.014 \, {}^{m^3}\!/_{d} * \left(\frac{10^3 l}{m^3}\right) * \left(\frac{kg}{10^6 mg}\right) = 53.24 \, {}^{kgTS}\!/_{d}$

(1)(Doulaye Koné and Strauss 2004)

Annual cost of A/D = $1.014\, {}^{m^3}\!/_{d} * .05324\, {}^{tTS}\!/_{d} * \left(\frac{\$60}{tTS}\right) * \left(\frac{365d}{yr}\right) = \$1{,}182 / yr$

The benefit of A/D:

According to the McCarty Equations: Methane production = 114.88 ft^3/d and each cubic foot of methane contains 960 Btu's of energy (McCarty 1964).

Since $114.88\, {}^{ft^3}\!/_{d} * 960 Btu * \left(1054\, {}^{J}\!/_{Btu}\right) = 116.24\, {}^{MJ}\!/_{d}$ and Diesel contains 139,000 Btu/gal (EIA 2008)

It follows that the daily methane production from anaerobic digestion is equivalent to 1.75 liters of Diesel.

The cost of diesel in Ghana, which has risen greatly in the recent global economic crisis, is 8800 Cedis (about USD$0.75) (BBC 2008). Therefore, the cost savings per year in Ghana follows.

Annual worth of Biogas = $1.75\, {}^{l}\!/_{d} * \left(\frac{1gal}{3.785l}\right) * \left(\frac{8800Cedis}{gal}\right) * \left(\frac{365d}{yr}\right) = 1{,}487{,}037\ Cedis$

According to the OANDA Currency Site, the official Cedis-USD exchange rate as of November 16th, 2008 is: 1 Ghanaian Cedi = 0.00008497 US Dollar (OANDA 2008). Therefore, the annual potential earning from biogas amounts to *USD$126*.

Composting:

The costs associated with composting food waste with the sludge from anaerobic digestion are similar to the costs of co-composting in section 2. The benefits will also be the same. Since there is such a small difference in the volume of compost produced every 63 days, please see section two for the composting economic analysis.

Scenario 2: Co-Composting

According to Cointreau-Levine and Coad (2000), $9.2 is spent to produce one cubic meter of compost in the Accra co-composting operation. It is suspected that this cost would be significantly lower in a smaller-scale operation due to the reduction in machinery required for turning and transporting the sludge and the management cost reductions. Still, $9.2 will be used to estimate the cost of co-composting in the study village.

Annual cost of co-compost = $\$9.2 / m^3 * \left(\frac{110.3m^3}{63d}\right) * \left(\frac{365d}{yr}\right) = \$5879$

Since the willingness to pay for a 50 kg bag of compost is about USD$1.1 (Cointreau-Levine and Coad 2000), given that the final density of compost is about 0.67*450kg/m^3=300kg/m^3 (Barrington 2007) the income for a year of composting can be computed as follows:

Annual Benefit of co-compost = $\left(\frac{\$1.1}{50kg}\right)*\left(\frac{110.3m^3}{63d}\right)*\left(\frac{365d}{yr}\right)*\left(\frac{300kg}{m^3}\right)=\$4217.7$

Scenario 3:
Household drying:

1200 Sq. feet of greenhouse plastic can be purchased for about $165. Each household needs 5 m^2 drying space with roof. If plastic is used as a impermeable liner as well as the roof, approximately 10m^2 is needed for a household which is about 100 sq. feet. Therefore,

Cost per household for drying = $100\,ft^2*\left(\frac{\$165}{1200\,ft^2}\right)=\$14$

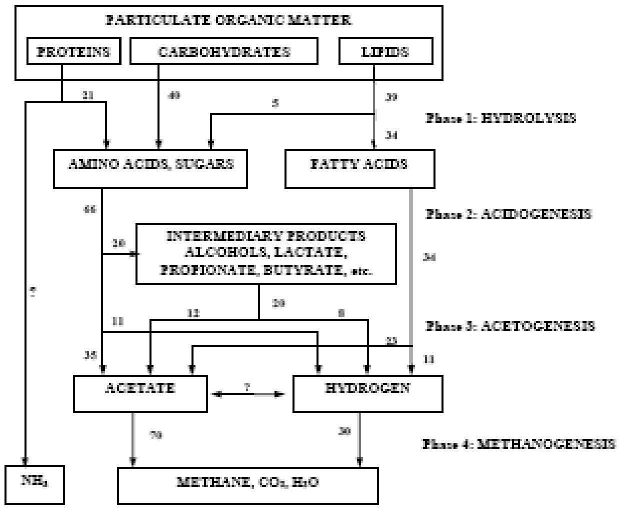
This is assuming that the community can work together to purchase the plastic and split it accordingly. This cost could be lowered by using a concrete slab instead of clear plastic as the impermeable layer, but would require skilled labor. Not-included costs of plastic supports and netting to keep out pests offset the likely overestimation of drying costs.

Potential Benefit from Drying in Soil Conditioner = $4.14\,{}^{kgdried}/_{d}*\left(\frac{365d}{yr}\right)*\left(\frac{\$1.1}{50kg}\right)=\$33.24/yr$

This benefit is expressed by the price of fertilizer potential, but the farmer would likely see benefits expressed in higher crop yields and less transportation costs for fertilizer.

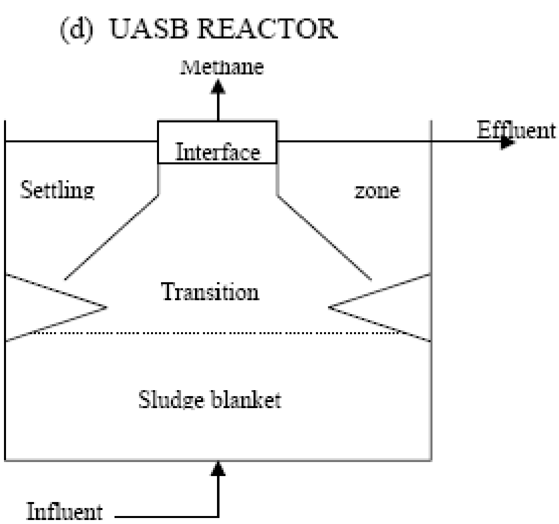
Appendix F:

Diagram of biological processes in anaerobic digestion



Source: (Doku 2003)

Diagram of a UASB (upflow anaerobic sludge blanket reactor)



Source: (Doku 2003)

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