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Economic and Environmental Analysis of Farm-Scale Biodigesters to Produce Energy for Kitchen Stove Use

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Abstract. Developing countries throughout the world currently fuel kitchen stoves for cooking by burning wood which is responsible for many health and environmental problems. Producing fuel for cooking via anaerobic digestion is a very ecofriendly and resourceful solution that is being explored. To determine the sustainability of anaerobic digestion throughout these regions, multiple biodigester designs were tested under conditions specific to various third-world countries; the countries tested were Nicaragua, Bolivia, Nigeria, India and Indonesia. Factors to be considered included the use of local biomass resources and building materials. Determining the fueling efficiency of anaerobic digestion in comparison to burning wood consisted of evaluating the production costs and environmental impacts. This was accomplished utilizing techno-economic analysis (TEA) and life cycle assessment (LCA). TEA results indicated that tube digesters are the most cost effective method of anaerobic digestion in all countries tested; tube digestion at a family scale ranged from approximately \$0.24 per meal to \$0.73 per meal. The LCA showed that operation of anaerobic digestion required much more water than previously considered which may cause it to not be a sustainable method. However, it did emit a much lower amount of carbon dioxide than burning wood. The CO_2 emissions per meal ranged from 0.97 kg per meal to 1.29 kg per meal. The water impacts ranged from 76 L/meal to 100 L/meal. Comparing the two fueling methods proved that anaerobic digestion was a more economically and environmentally effective process.

Keywords. *biogas, bioreactors, food, economic analysis, economic evaluation.*

Introduction

Wood Burning Stoves

In many rural areas throughout developing countries, the only means of cooking food is from wood burning kitchen stoves. The smoke created using this method of cooking contributes to air pollution. It is hazardous to one's health since pollutants are released. These pollutants are in the form of toxic gasses and particle pollution. Constant use of wood burning stoves for cooking is dangerous due to the continual buildup of particulate matter that is breathed deep into the lungs. Once the matter is trapped into the lungs, it damages cells and makes breathing more difficult. This eventually causes deteriorating lung and heart conditions. Constant inhalation of these contaminants can lead to thermal injury to the upper airway, irritation/chemical injury to the airways from soot, asphyxiation, carbon monoxide poisoning, heart and lung disease, and possible death.

In addition to smoke, another negative side effect of wood burning kitchen stoves is creosote. Creosote is an adhesive, malodourous residue that is formed from wood gases that are not completely burned. Large buildup of this deposit can eventually lead to a house fire.

Fueling kitchen stoves with wood is also a contributing factor in local deforestation. The most obvious negative impact is the loss of habitat for indigenous wildlife. Deforestation also influences climate change. Lack of tree cover from the sun can also cause soils to lose moisture. Adequate tree coverage is also necessary for maintaining the water cycle, since trees return water vapor back into the atmosphere. Trees are much needed for sequestering carbon dioxide. Not only does the smoke from wood burning stoves release pollutants into the air, but the deforestation it causes allows a larger amount of greenhouse gas emissions to be released into the atmosphere.

Table 1 below shows the number of people in various developing countries currently harmed by the smoke of wood-burning stoves (Global NRG n.d.).

Table 1. People affected by household air pollutants.

People Affected by Household Air Pollutants		
Country	**Persons**	**Percentage**
Nicaragua	3,473,476	64%
Bolivia	3,099,111	34%
Nigeria	92,460,728	67%
India	913,896,934	82%
Indonesia	161,168,381	72%

As the data indicates, this is a very serious problem impacting many people's lives. As a result, alternative fueling methods for cooking need to be considered. The most common methods currently used throughout the world include propane/natural gas and electricity. Since these developing areas have limited access to such resources, more innovative possibilities need to be explored. Anaerobic digestion is possible alternative fueling method already implemented into some of these regions and will be examined thoroughly in this project.

Anaerobic Digestion

Anaerobic digestion is a complex biochemical process in which microorganisms break down biodegradable material in the absence of oxygen in order to convert solid and liquid biomass into combustible biogas. Figure 1 below shows the essential steps of this process.
The biodegradable material used in this experiment was a mixture of animal feces and water with a ratio of 1:4. The products of anaerobic digestion include biogas, digestate, and water. All trace compounds found in biogas are listed in table 2 below.

Table 2. Components of typical biogas.

Compound	Percentage
Methane (CH_4)	50-75 %
Carbon Dioxide (CO_2)	25-50 %
Nitrogen (N_2)	0-10 %
Hydrogen (H_2)	0-1 %
Hydrogen Sulfide (H_2S)	0-3 %
Oxygen (O_2)	0-2 %

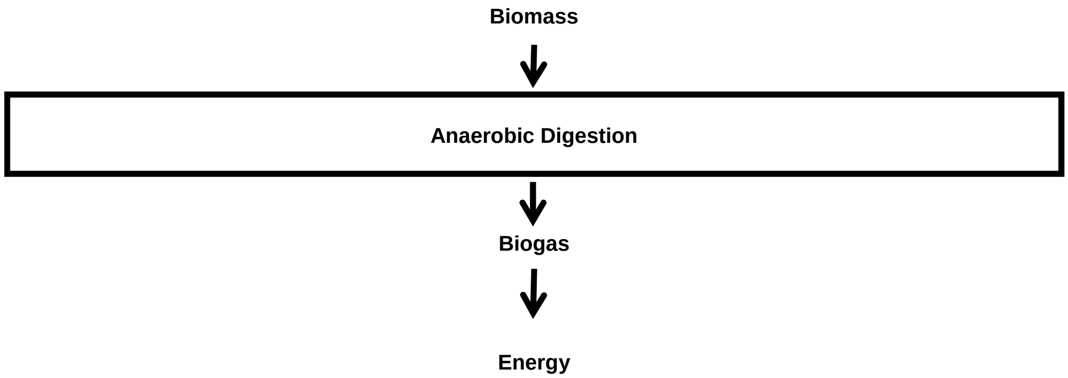


Figure 1. Primary steps of anaerobic digestion.

Methane is the vital compound in biogas since burning it produces heat and electricity. Once the entire process is completed, the solid effluent left behind can be used as fertilizer.

Anaerobic digestion consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis that each contains distinctive types of microorganisms (Kusch, 2008).

During hydrolysis, particulates within the organic substrate are solubilized, and bacteria converts complex polymers into simpler monomers. More specifically, carbohydrates, fats, and proteins are transformed into amino acids, monosaccharides, and fatty acids.

While undergoing acidogenesis, the acidogenic bacteria transforms the products of hydrolysis into volatile acids, ketones, alcohols, hydrogen, and carbon dioxide. The significant products of this stage include propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH). The hydrogen, carbon dioxide, and acetic acid produced will be used during methanogenesis (Okeh, 2013).

In the third stage, acetogenesis, acetogenic bacteria convert the propionic acid, butyric acid, and alcohols into hydrogen, carbon dioxide, and acetic acid. The final stage of anaerobic digestion is methanogenesis. During this time, methanogens convert the hydrogen and acetic acid to methane gas and carbon dioxide.

For optimum biogas production, certain conditions must be met. Some factors that can affect the process include the following (Chanakya, 1997):

- Biomass composition and structure
- Temperature and retention time
- Presence of toxic materials
- pH

The pH of the substrate must be within the range of 6.8-7.2. This is because the ideal pH for the microbes utilized during the hydrolysis stage is 5-7 and methanogens are most efficient at a pH of 7-8. The temperature should also be between 32-35 °C (Arthur, 2011). These are important for promoting bacterial growth since the microbes are very sensitive to physical conditions. The ideal carbon to nitrogen ratio must be approximately 25:1. This is important to consider when selecting which animals' feces to use. Since different species vary in diet and digestion, their feces contain different molecular compounds. The most important component of the animal manure is the amount of volatile solids in the manure. This is the part that is converted into biogas. Details on varieties of animal manure are found in the Appendix B (Khalid, 2011).

Although different methods of anaerobic digestion vary in their total retention time and production quantities, all processes contain the same trend in biogas production. As seen below, an unsubstantial amount of gas is produced at the beginning and end of each cycle. This is because the microbes require initial time to build up. Once they start producing, the population thrives at an exponential rate (evident in Figure 2 below). The amount of time in which the bacteria flourish is referred to as the effective time (Jiang, 2012). The effective time is extremely critical since this is when significant biogas is produced. Since biogas production is dependent on bacterial growth, it has the same lifecycle pattern as the microbes. Figure 2 shows this since both bacterial growth and biogas production have identical rates throughout the cycle time. There is a point during the process when the biomass has been utilized as much as possible so the microbes die off. This is because the microorganisms have reacted with nearly all of the hydrocarbon molecules within the slurry. The culture dies away at the same exponential rate in which they came to live. Although some microorganisms do remain in the mixture, there are not enough to produce an adequate amount of biogas. As a result, it is most practical to end the cycle and restart with a new slurry mix (Day, 1990).

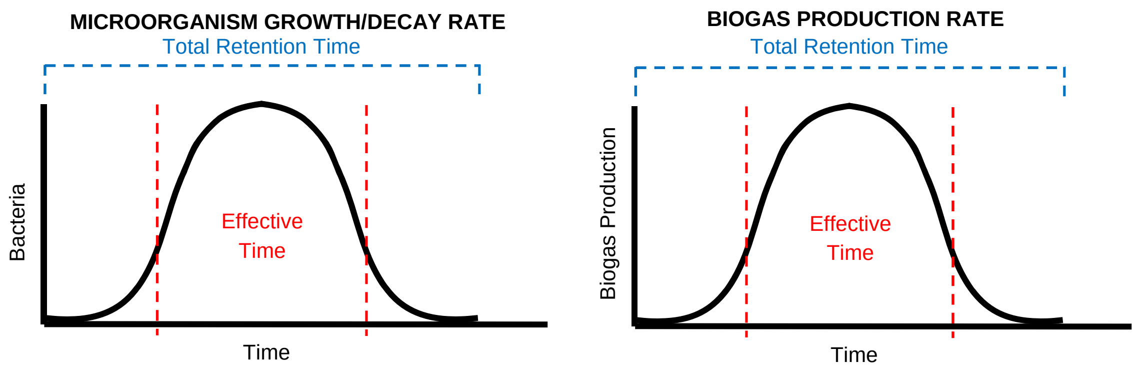


Figure 2. Typical anaerobic digestion cycle.

Methods

Design Constraints

The anaerobic digester designs that will be chosen must be able to be constructed by the local people. The designs must be simple enough to be built and maintained by the local people. In addition, the designs being considered must be safer to be around than the current method of using wood stoves. Since anaerobic digesters are dealing with manure, the designs must be sealed off properly to avoid contact with the manure and the slurry mixtures. Ideally, the design will take up minimal space.

Biogas Requirements

The anaerobic digesters evaluated must produce enough gas to cook meals for the families in the target countries. The designs evaluated will be sized according to these biogas needs. To size the biodigesters, the average family size was found in each of the target countries (Global Alliance for Clean Cookstoves, 2013). From there, the family size was multiplied by 0.4 m^3 biogas/day-person to find the daily biogas requirement for the family size scale (K.S.K. 2013). For the community scale, it was assumed that 10 families made up a community.

Table 3. Family scale biogas requirements.

Country	Family Size	Biogas (m^3/day-family)
Nicaragua	4	1.6
Bolivia	4	1.6
Nigeria	5	2.0
India	5.3	2.12
Indonesia	4.57	1.83

Table 4. Community scale biogas requirements.

Country	Community Size	Biogas (m^3/day-community)
Nicaragua	40	16
Bolivia	40	16
Nigeria	50	20
India	53	21.2
Indonesia	45.7	18.3

Animal Requirements

In order to produce the daily biogas requirements, animal manure production information is needed. Since each country has different types of livestock available a number of animals were evaluated. Each animal produces different quantities of manure as well as the content of manure changes from animal to animal (ASAE 2003). This means that different types of animal manure has different conversion ratios into biogas. Five different animals were evaluated for this project which included cattle, dairy cattle, pigs, poultry layers, and poultry boilers. Details on the calculations are in Appendix B.

Table 5. Number of animals needed to sustain biogas production in each scenario.

Scenario	Cows	Dairy Cattle	Pigs	Poultry, Layers	Poultry, Broilers
Nicaragua	1	1	5	203	217
Bolivia	1	1	5	203	217
Nigeria	2	2	6	254	271
India	2	2	6	269	288
Indonesia	2	2	5	232	248

Sustainability Constraints

The sustainability of each of the design alternatives will be considered. The results from the Techno-Economic Analysis and the Life-Cycle Assessment will help us determining the sustainability of each of the designs. Some important issues to consider in developing the TEA and LCA include:

- Is the design more sustainable than current methods of cooking with wood?
- Is the design economically feasible?
- Are there opportunities for locals to participate in the construction of the designs?
- Can the technology be sustained by the user?
- Does it increase the livelihood of the user?

Flow-Thru Digester Design

A flow-thru digester is a low cost digester that can be made from any size container. Normally, they are made out of three 55 gallon metal drums welded end to end. These drums can be recycled metal drums as long as they are clean and in good shape. The top drum needs to have two threaded holes for the biogas exit made out of PVC pipe. The bottom of the top drum, the top and bottom of the middle drum, and the top of the bottom drum are cut off and welded together from end to end.

Figure 3. Example flow-thru digester.

The three drums are then placed on a stand at a slight angle. This is due to the fact that the most micro-organism activity takes place near the surface of the slurry at the top. A 5cm slurry inlet is installed on the top drum. A fitting for the biogas exit is also installed at the highest point of the lid. A 5cm outlet is also installed on the bottom drum to release expended slurry. The stove needs to be outfitted with a biogas burner which can be any standard burner from a grill. Gas lines (PVC pipe) and a gas collection reservoir (polyethylene plastic bags) are connected to the drums and the unit can be filled with slurry. A schematic of the design is listed below.

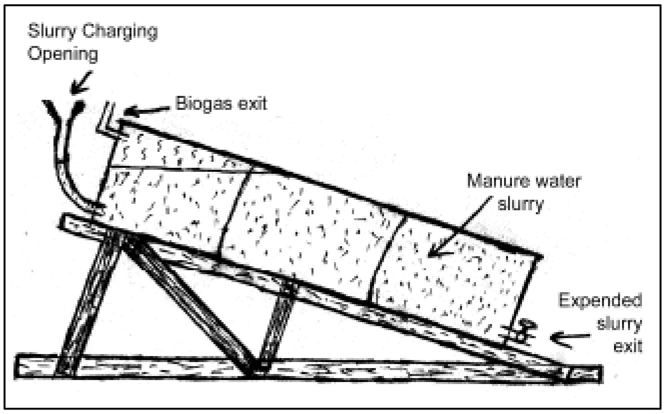


Figure 4. Flow-thru digester schematic.

The slurry mixture should be a 1:4 ratio of manure to water. When the unit begins producing biogas, the gas should be released from the system for the first week to ensure there is no air in the system. Each unit is capable of producing 27 ft^3 biogas/day. To maintain production, 20 liters of slurry can be processed daily. This design is estimated to have a lifespan of 15 years if maintained properly (Doerr, 2008). An advantage of this design is that it is made out of materials that would be easy to find in the target countries. A disadvantage of this design is that it is a fixed size. This means that if more biogas is required than one unit produces, multiple units will have to be constructed.

Deenbandhu Digester Design

A Deenbandhu biogas plant is a version of a fixed dome plant. The main design feature of the Deenbandhu biogas plant is the fixed underground digester chamber. It is constructed with a layer of bricks and an additional layer of cement mortar forming the roof above. It is a continuous flow digester that has roughly a 50-55 day retention time.

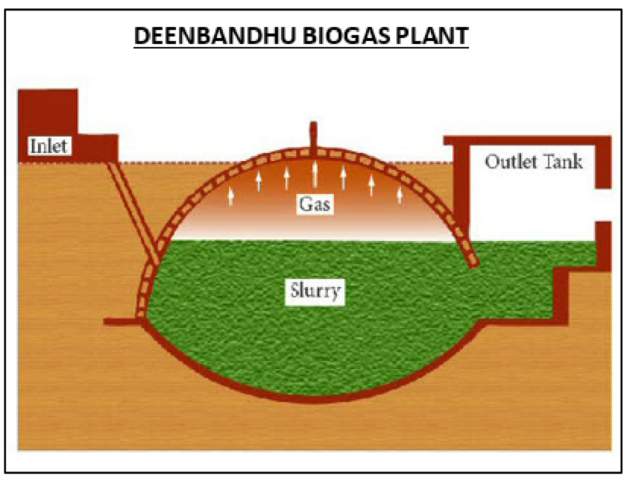


Figure 5. Typical Deenbandhu biogas schematic.

The diagram below shows all components of the Deenbandhu Biogas Plant. To begin the process, the slurry must be placed into the mixing tank. After traveling down the inlet pipe, the slurry will then settle into the dome. The dome consists of two parts; the bottom part is the digester and the upper part is the gas storage. Anaerobic digestion begins once the microbes start decomposing the slurry. Once biogas is produced, it will rise into the gas storage. When needed, the gas can exit the digester via the gas outlet pipe on the top. This pipe can either connect directly to the kitchen stove, or it can lead to a holding tank for storage. The continuous addition of slurry causes the level of solids to increase. When this occurs, the slurry accumulates into the outlet tank, and the levels of expended slurry increase until it starts to fill the displacement chamber (K.S.K. 2013). Advantages of this design are that since it is underground, it acts as a naturally insulator from the elements. Also, it is very easy to mix and prepare the slurry. A disadvantage of this design is that it requires skilled labor to construct.

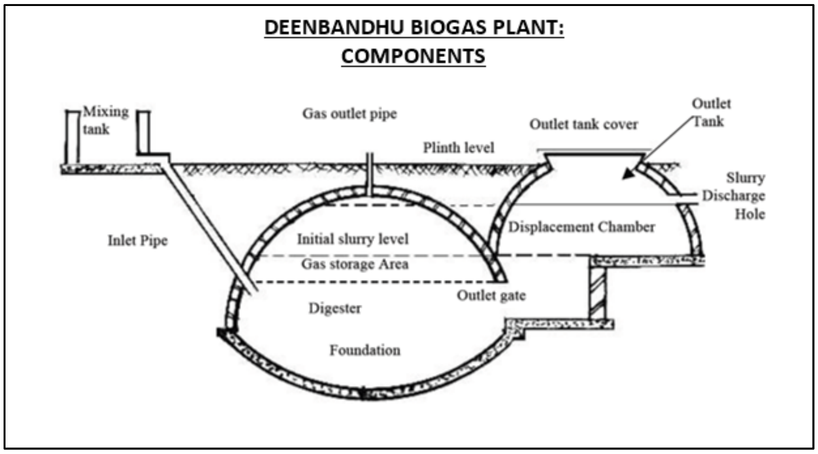


Figure 6. Typical Deenbandhu biogas plant components.

Figure 7. Example Deenbandhu biogas plant in India.

Low-Cost Polyethylene Tube Digester Design

A low-cost polyethylene tube digester is a relatively simple design for an anaerobic digester. It consists of a large tubular structure made of polyethylene plastic that has an inlet for manure addition and an outlet for expelling decomposed material (Kumar, 2005). A trench is dug out that the tube is laid in. This helps insulate the digester. The slurry is filled into the tube digester up to ground level. The biogas collects on top and the pressure in the tube allows it to travel to the biogas storage reservoirs or the stove. Tubular digesters have a retention time of between 20-50 days depending on the climate (Lansing, 2010). Since the digester is made out of plastic, a support structure is usually constructed to protect the digester from the elements and from being torn. An advantage of this design is that it is the easiest of the three designs to install and construct. This design is also the easiest of the three alternatives to size according to biogas needs. A disadvantage of this design is that it has the lowest lifespan of the three designs, and a support structure is required to protect the design from the elements. However, it does not have to be an elaborate support structure as shown below. Components of the tubular digester are listed below.

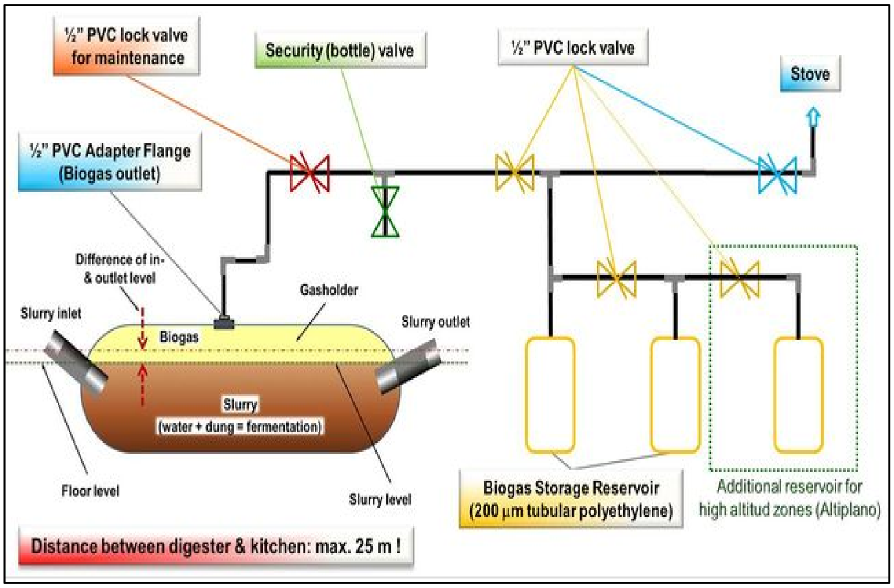


Figure 8. Typical components of a tubular digester.

Figure 9. Example tube digester in Bolivia.

Results and Discussion

Flow-Thru Techno-Economic Analysis

A TEA of the Flow-Thru design is laid out in Appendix B including a detailed parts list. The main performance matrices we examined were cost per unit of biogas and $/meal. Results of the TEA are laid out below. Economically, these numbers are feasible considering the price of natural gas is roughly $0.15/m^3 (Quandl, 2013). In the scenarios that require multiple flow-thru units, it may not be reasonable. For example in India, 36 Flow-Thru units were needed at a community scale. Constructing this many units would not be a reasonable solution.

Table 6. Flow-thru digester unit costs and meal costs.

Scenario	Cost Per Unit ($/m^3 biogas)	$/meal
Nicaragua Farm	$0.10	$0.54
Nicaragua Community	$0.09	$0.50
Bolivia Farm	$0.15	$0.80
Bolivia Community	$0.14	$0.74
Nigeria Farm	$0.10	$0.67
Nigeria Community	$0.09	$0.62
India Farm	$0.06	$0.40
India Community	$0.05	$0.38
Indonesia Farm	$0.09	$0.52
Indonesia Community	$0.08	$0.49

Deenbandhu Techno-Economic Analysis

Calculations for the TEA are laid out in Appendix B. The results of the TEA put this design as the second best option economically. The costs are similar to the current price of natural gas. However, feasibility of this design needs to be considered. At the farm scale, each of the target countries only needs one unit constructed. At a community scale, multiple units needed to be constructed and it is not reasonable to do so.

Table 7. Deenbandhu digester unit costs and meal costs.

Scenario	Cost Per Unit ($/m^3 biogas)	$/meal
Nicaragua Farm	$0.09	$0.50
Nicaragua Community	$0.08	$0.42
Bolivia Farm	$0.15	$0.78
Bolivia Community	$0.12	$0.66
Nigeria Farm	$0.09	$0.60
Nigeria Community	$0.08	$0.52
India Farm	$0.04	$0.31
India Community	$0.03	$0.23
Indonesia Farm	$0.08	$0.47
Indonesia Community	$0.06	$0.38

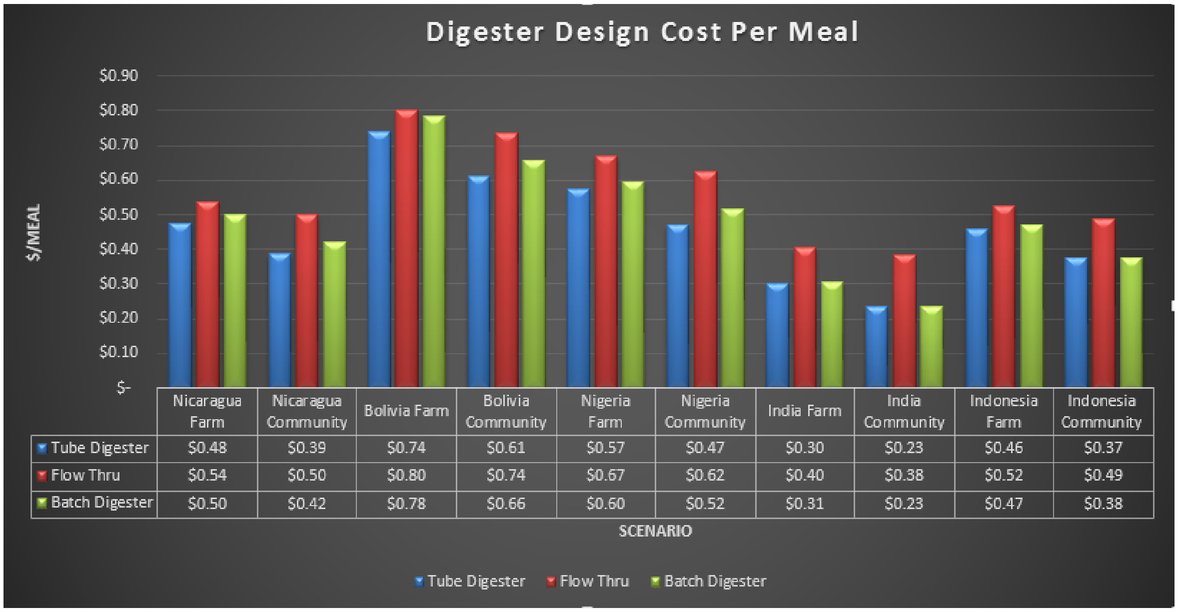
Low-Cost Polyethylene Tube Digester Techno-Economic Analysis

Calculations for the TEA are laid out in Appendix B. The tube digester was the cheapest option in each of the scenarios. Also, it is the most feasible design to construct. This is due to the fact that the size of the biodigester can be adjusted rather than having to construct multiple units. If a large size is needed, the length of the tube is just increased. Like the previous two designs, the unit price was similar to that of natural gas.

Table 8. Tube digester unit costs and meal costs.

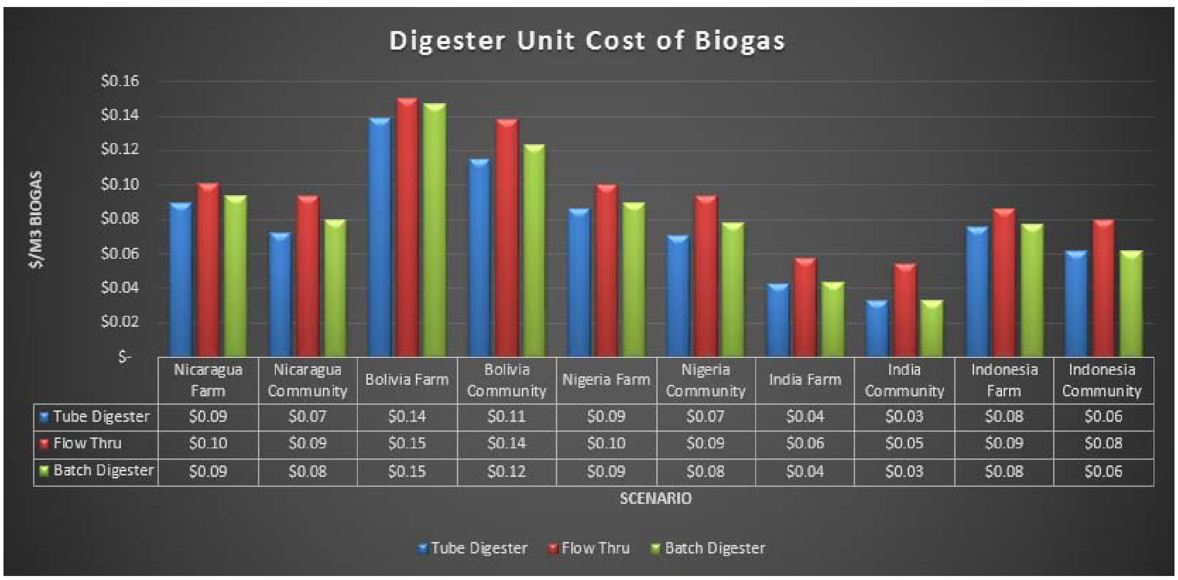
Scenario	Cost Per Unit ($/m^3 biogas)	$/meal
Nicaragua Farm	$0.09	$0.48
Nicaragua Community	$0.07	$0.39
Bolivia Farm	$0.14	$0.74
Bolivia Community	$0.11	$0.61
Nigeria Farm	$0.09	$0.57
Nigeria Community	$0.07	$0.47
India Farm	$0.04	$0.30
India Community	$0.03	$0.23
Indonesia Farm	$0.08	$0.46
Indonesia Community	$0.06	$0.37

The data accumulated in tables 6, 7, and 8 are shown below:



	Nicaragua Farm	Nicaragua Community	Bolivia Farm	Bolivia Community	Nigeria Farm	Nigeria Community	India Farm	India Community	Indonesia Farm	Indonesia Community
Tube Digester	$0.48	$0.39	$0.74	$0.61	$0.57	$0.47	$0.30	$0.23	$0.46	$0.37
Flow Thru	$0.54	$0.50	$0.80	$0.74	$0.67	$0.62	$0.40	$0.38	$0.52	$0.49
Batch Digester	$0.50	$0.42	$0.78	$0.66	$0.60	$0.52	$0.31	$0.23	$0.47	$0.38

Figure 10. TEA summary of cost per meal.



	Nicaragua Farm	Nicaragua Community	Bolivia Farm	Bolivia Community	Nigeria Farm	Nigeria Community	India Farm	India Community	Indonesia Farm	Indonesia Community
Tube Digester	$0.09	$0.07	$0.14	$0.11	$0.09	$0.07	$0.04	$0.03	$0.08	$0.06
Flow Thru	$0.10	$0.09	$0.15	$0.14	$0.10	$0.09	$0.06	$0.05	$0.09	$0.08
Batch Digester	$0.09	$0.08	$0.15	$0.12	$0.09	$0.08	$0.04	$0.03	$0.08	$0.06

Figure 11. TEA summary of unit cost of biogas.

Life Cycle Assessment

The main goal of the life cycle assessment was to help determine the sustainability of implementing the designs in each target country. Carbon dioxide emissions and water consumption were evaluated for the designs. Carbon dioxide emissions were considered to be at a sustainable level and are indicated in the graph below. Carbon dioxide emissions were broken down to kg CO_2 per meal per family. Values ranged from 0.97 kg CO_2 per meal per family to 1.29 kg CO_2 per meal per family. These values were determined to be sustainable. It is estimated that burning wood emits over double the CO_2 emissions than burning biogas (van Buren, 1979). The water usage was determined to be unsustainable. Since water shortage is already a problem in the target countries, the high values that were found are unreasonable. One of the main reasons for the high water demands are that for every 1 kg of manure 4 kg of water are needed. Water usage per meal per family was found, and these values ranged from 76 L water per meal per family to 100 L water per meal per family. Since it was assumed they were cooking three meals a day, the water requirements are hundreds of liters per day. The only way the system could be sustainable is if they had easy access to a water source. In addition to the high water demands, there also is the problem of dealing with the byproduct. If the families do not grow crops, the byproduct cannot be used as fertilizer and must be disposed of in a different way. Life cycle assessment graphs are listed below.

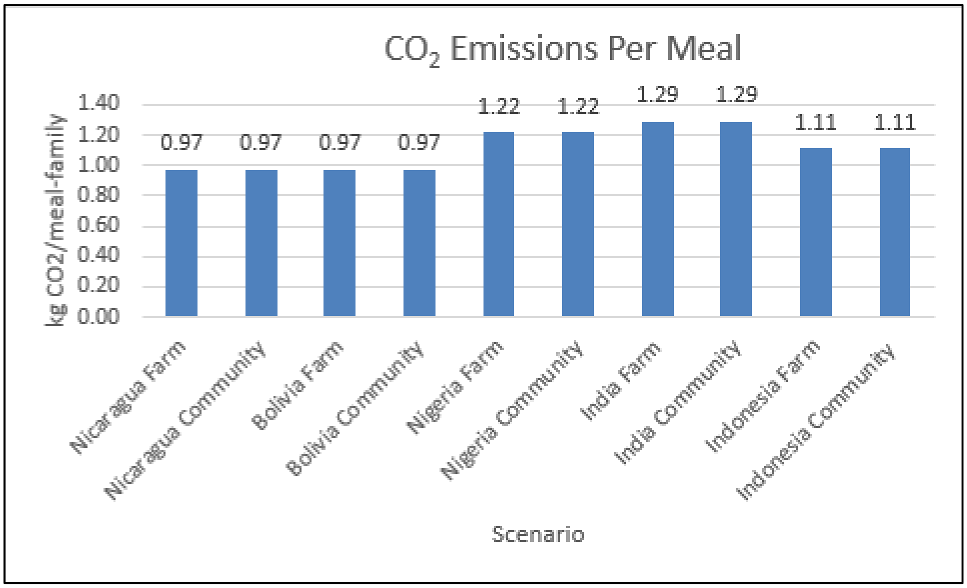


Figure 12. CO_2 emissions per meal.

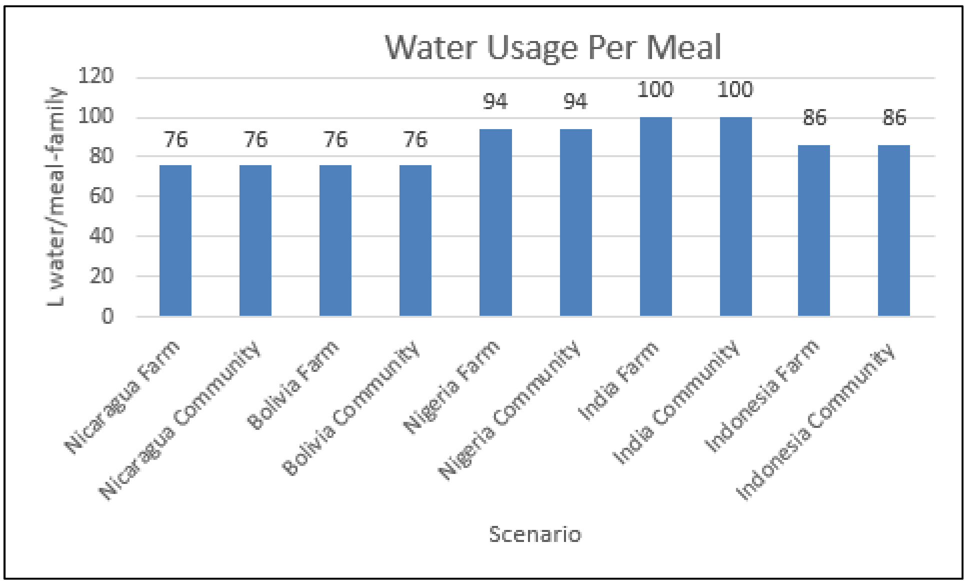


Figure 13. Water usage per meal.

Conclusions

Economic Analysis

The TEA results indicate that the tube digester design is the most economical in each of the scenarios. Looking at the results of the other two designs, it is clear that it would not be a viable option for the community scale. It does not make sense to construct multiple units of the flow-thru digester and the Deenbandhu biogas plant. It is more feasible to construct one unit like the tube digester and size the unit longer to accommodate for more biogas production needs.

Environmental Analysis

The implementation of a low-cost polyethylene tube digester would satisfy three of the four criteria of an appropriate technology. A tube digester is a suitable design for its intended purpose and therefore it is apt. It is small and would be manageable by the family or community. It can be constructed from local materials and the labor used to construct it can be local people. It does not take extensive training or specialized personnel to operate or construct. However, we do not feel like the system is sustainable due to the high water demands. Further research needs to be done on how the water usage can be decreased. The people in these countries already struggle to find adequate water supply and this would add to that issue.

Recommendations

Our group recommends implementing a low-cost polyethylene tube digester design in areas that have easy access to water. Since the water does not have to be purified, fresh river water would be sufficient. If water sources are scarce, a tube digester is not recommended to install. It is recommended that more research be done at different designs or optimizing this design to minimize water consumption in order to make this technology more sustainable.

Summary

The issue of wood burning stoves is growing concern in many developing countries. Negative health effects, air pollution, and deforestation are pushing society to find alternative methods of cooking food. Since many of these developing countries already have livestock, anaerobic digestion is an option to consider. Through the findings of our life cycle assessment and techno-economic analysis, it is difficult to determine whether or not it is a viable option. Economically, the implementation of a low-cost tube digester is a good option. It provides a cheap source of energy comparable to that of natural gas. It also benefits the local community by providing part time construction jobs, deterring local deforestation, and providing a healthier alternative to wood burning stoves. These low-cost digesters are very easy to maintain and can easily be done by anyone in the target countries. The system does however introduce a different problem. The high water demands found in the target countries are an area of concern. In many of the scenarios, these numbers were in the hundreds of liters per day. Low-cost anaerobic digesters have potential to be an appropriate technology, but more work needs to be done in optimizing the design.

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Appendix A: Model Assumptions

General Assumptions

- 10 families per community
- Each biodigester has 30% conversion of manure to biogas
- Costs were in U.S. Dollars
- Loan term of 5 years
- 3 meals per person per day for $/meal calculation
- Maintenance labor was 2 hours per day per family which accounted for gathering the manure and mixing the slurry (365 days x 2 hours per day = 730 hours per family)
    - Used in each operational cost
- For community scale maintenance labor was assumed to be 10% more efficient due to economies of scale
    - Used in each operational cost
- Repair costs 5% of total design cost
- Add $14.99 to each capital cost for cost of biogas burner
- Add $50 to each design for various repair tools
- Anything without a cost in a parts list could be used from a recycled part
- Interest rates and minimum wages for the countries were used

Table 9. Interest rate and minimum wage of target countries.

Country	Minimum Wage (USD/hr)	Interest Rate
Nicaragua	$0.52	10.54%
Bolivia	$.90	10.90%
Nigeria	$0.66	9.50%
India	$0.28	7.50%
Indonesia	$0.52	5.75%

Animal Assumptions

- Manure production fluctuation 10% daily accounted for in calculation (Hamilton, 2011)
- Assumed animals weighed average body mass found online
- Assumed animals were healthy

Flow-Thru Design Assumptions

- Steel drum cost $15
- Assumed access to welder to construct units
- Building labor per unit: 4 people x 8 hours each = 32 hours per unit (Doerr, 2008)
- Had access to all the supplies

Deenbandhu Design Assumptions

- Mud bricks were $0.25 each
- Sand and stone aggregates used in construction were collected locally
- $3m^3$ building labor requirements per unit: 4 people x 13 working days x 8 hours day= 416 hours
- $4m^3$ building labor requirements per unit: 4 people x 15 working days x 8 hours day = 480 hours

Tube Digester Design Assumptions

- Building for protection costs were $1/square foot and were made from local materials (Garnett, 2009)
- Basic fence around the biodigester cost $0.25/ foot (Rodriguez, 2009)
- Construction labor costs varied on the length of the biodigester (Rodriguez, 2009) (Luer, 2010)
    - Tube Digester Installation Constant: 10 hours x 4 people = 40 hours
    - Farm Scale Building Construction Costs: 4 people x 3 work days x 8 hour day = 96 hours
    - Community Scale Building Construction Costs: 4 people x 5 work days x 8 hour day = 160 hours

Life Cycle Assessment Assumptions

- Assumed each of the digesters had the same conversion rate

    - Each design had the same life cycle assessment due to the same conversion rates
- The farm was the control volume for the LCA
- 1 kg manure requires 4 kg water (Lansing, 2010)
- Biogas is 40 % carbon dioxide (Martin II, 2008)
- Biogas is 60% methane
- Density of methane is 0.66 kg/m^3
- Density of CO_2 is 1.842 kg/m^3
- Byproduct was 70% of manure weight due to 30% conversion rate of biodigesters designs
- Combustion of biogas releases 6500 kcal of energy (Homan, 2008)
- Carbon dioxide molar mass of 44.01 g/mol
- Methane molar mass of 16.01 g/mol

Appendix B: Model Calculations

Equation 1. Annuity equation.

$$A = \frac{P(I(1+I)^N)}{(1+I)^N - 1}$$

A= Annuity, P=Principal, I=Interest Rate, N=Loan Term

Animal Requirements Calculations

Manure production information per 1000kg live weight was available (Hamilton, 2011). Average body mass of each of the animals were used (Warrington, 2001).

Table 10. Average manure production.

Manure Type	Manure Production kg/(1000 kg live weight-day)	Average Body Mass (kg)	Average Manure Production (kg/animal-day)
Cattle	86	500	43
Dairy Cattle	58	650	37.7
Pigs	84	200	16.8
Poultry, Layers	64	2.7	0.17
Poultry, Broilers	85	1.9	0.16

With these numbers, the equation below depicts how the average manure production was found.

Equation 2. Average daily manure production.

$$Average\ Manure\ Production\ (\frac{kg}{animal * day}) = Manure\ Production\ (kg\frac{manure}{1000\ kg\ liveweight * day}) * Average\ Body\ Mass(kg)$$

The conversion into biogas depends on the volatile solid composition of the different types of manure. The volatile solid composition on a dry basis along with the moisture content of the manure allowed us to calculate how much volatile solids were available from the each of the animals manure content (Livestock Waste Facilities Handbook, 1993). Volatile solid content can be used to find the daily methane conversion potential of each animal. For the calculation, it was assumed that each of the biodigesters had a 30% conversion to methane and that manure production fluctuated 10%. Methane production per kg of volatile solids was found to be 1.1m^3 biogas/kg volatile solid (Hamilton, 2011). The equations below shows how daily methane production per animal was found.

Equation 3. Volatile solid content.

$$Volatile\ Solid\ \left(\frac{kg}{animal * day}\right) = Manure\ Production\ \left(\frac{kg}{animal * day}\right) * VS\ \% * Manure\ Dry\ Basis\%$$

Equation 4. Daily animal methane production.

$$Daily\ Methane\ Production\ \left(\frac{m^3}{animal}\right) = VS\ (\frac{kg}{animal * day}) * 0.3(Methane\ Conversion) * \frac{1.1m^3 biogas}{kg\ VS} * 0.9(Manure\ Productin\ Changes)$$

Table 11. Manure composition and daily methane production.

Manure	Manure Production (kg/animal-day)	% Dry Basis	% Volatile Solid (dry basis)	Volatile Solid (kg/animal-day)	Daily Methane Production (m^3/animal)
Cattle	43	12%	82%	4.090	1.215
Dairy Cattle	37.7	13%	84%	4.022	1.194
Pigs	16.8	9%	77%	1.190	0.353
Poultry, Layers	0.17	25%	61%	0.027	0.008
Poultry, Broilers	0.16	25%	61%	0.025	0.007

With the daily methane production per animal, the number of animals can be calculated to produce the daily biogas requirements. The animal requirements will vary from country to country depending on the biogas requirements. Also, the number of animals were rounded up to the nearest whole animal.

Equation 5. Number of animals required.

$$Number\ of\ animals = Daily\ Biogas\ Requirements\ \left(\frac{m^3}{day}\right) / Daily\ Methane\ Producion\ \left(\frac{m^3}{animal}\right)$$

Flow-Thru Digester TEA Calculations

Sizing Calculations

The first step in the techno-economic analysis was sizing the digester based off the biogas requirements in each country. One unit produced 27ft^3 biogas/day. Since each unit was made up of three 55 gallon drums, it was assumed that one drum produced 7 ft^3 of biogas/day. In each country, it was calculated how many 55 gallon drums were needed. Dividing the number of drums by three, we got the number of units each scenario needed. The number of units was rounded up to the nearest whole number. As you can see, the number of drums or units needed at a community scale is not a feasible option.

Table 12. Number of flow-thru units per country.

Scenario	Daily Biogas Requirements (m^3/day)	Daily Biogas Requirements (ft^3/day)	Number of 55-Gallon Drums Needed	Number of Units Needed
Nicaragua Farm	1.6	57	8.1	3
Bolivia Farm	1.6	57	8.1	3
Nigeria Farm	2.00	71	10.1	4
India Farm	2.12	75	10.7	4
Indonesia Farm	1.83	65	9.2	4
Nicaragua Community	16	565	80.7	27
Bolivia Community	16	565	80.7	27
Nigeria Community	20	706	100.9	34
India Community	21.2	749	107	36
Indonesia Community	18.28	646	92.2	31

Costs

The table below shows a list of materials needed to construct the flow-thru digester. The majority of the part prices were found at Lowe's website. The figures are for one flow-thru unit. These numbers were multiplied by the number of units needed in each country. The parts list and construction labor made up the capital costs for the flow-thru design. The capital costs were annualized. The operational costs included the maintenance labor and yearly repair costs. Any assumptions used are laid out in Appendix A.

Table 13. Flow-thru digester parts list.

Materials	Unit Cost (USD)	Quantity	Total Cost (USD)
PVC tube bend 1/2"	$ 1.56	4	$ 6.24
PVC T-fitting 1/2"	$ 1.96	4	$ 7.84
PVC lock valve 1/2"	$ 2.65	5	$ 13.25
PVC universal coupler 1/2"	$ 0.76	2	$ 1.52
PVC Adapter flange 1/2"	$ 0.90	4	$ 3.60
PVC Tube	$ 1.18	25 m	$ 10.62
Teflon Tape	$ 3.99	2	$ 7.98
Steel Wool (SH_4) filter	$ 3.97	1	$ 3.97
PVC plug for T-tube 1/2"	$ 0.87	1	$ 0.87
Metal Wire	$ 3.99	1 roll	$ 3.99
Nails	$ 5.00	2 box	$ 10.00
2 L plastic bottle	$ -	0	$ -
Transparent Flexible Tube	$ 2.63	12 (m)	$ 5.26
Steel Drum	$ 15.00	3	$ 45.00
Various Tools	$ 50.00		$ 50.00
Wood for Stand			
2x4	$ 3.57	20	$ 71.40
4x4	$ 7.57	4	$ 30.28
Plywood	$ 14.49	2	$ 28.98
Biogas Reservoir Polyethylene	12.88/m2	7.5 m^2	$ 96.60
		Total	$ 397.40

Table 14. Flow-thru cost analysis.

Scenario	Annualized Capital Costs (USD)	Yearly Operational Costs (USD)	Yearly Total Costs (USD)
Nicaragua Farm	$153.04	$436.05	$589.09
Nicaragua Community	$1512.12	$3974.17	$5486.29
Bolivia Farm	$160.67	$715.09	$875.7
Bolivia Community	$1588.01	$6487.13	$8075.14
Nigeria Farm	$181.73	$522.93	$734.66
Nigeria Community	$1800.05	$5040.75	$6840.80
India Farm	$165.82	$277.59	$443.40
India Community	$1642.91	$2564.91	$4207.61
Indonesia Farm	$130.44	$443.99	$574.42
Indonesia Community	$1290.69	$4053.54	$5344.23

Deenbandhu Digester TEA Calculations

Sizing Calculations

There are two possible sizes available for Deenbandhu Biogas Plans. One of them is a 3m^3, and the other is a 4m^3 design. Deenbandhu biodigesters produce 0.63 m^3 biogas per 1m^3 of biogas plant. The equation below depicts how large of volume of a biogas plant each scenario would need. From there, a 3m^3 or 4m^3 design can be chosen based off of the volume requirement. On the community scale, multiple units are required. This is not a reasonable solution to construction multiple of these designs.

Equation 6. Deenbandhu plant sizing equation.

$$Size\ Needed\ (m^3) = Daily\ Biogas\ Requirement\ (\frac{m^3}{day})/(Daily\ Production\ of\ 1m^3 Deenbandhu\ Plant)$$

Table 15. Deenbandhu plant size and quantity needed.

Scenario	Size Needed (m^3)	Plant Size Needed (m^3)	Number of Plants Needed
Nicaragua Farm	2.53	3	1
Nicaragua Community	25.28	4	7
Bolivia Farm	2.53	3	1
Bolivia Community	25.28	4	7
Nigeria Farm	3.16	3	1
Nigeria Community	31.60	4	8
India Farm	3.35	4	1
India Community	33.49	4	9
Indonesia Farm	2.89	3	1
Indonesia Community	28.88	4	8

Costs

The table below shows a parts list for a 3-m^3 and 4-m^3 Deenbandhu biogas plant (K.S.K. 2013). The figures are for one unit and will be multiplied by the number of each units in the scenarios. The parts with no costs were assumed to be used from recycled parts. Costs of the parts were found at Lowe's. Assumptions are laid out in Appendix A. Operational costs were the maintenance costs and the repair costs. Capital costs were building materials and construction labor. The capital costs were annualized.

Table 16. Deenbandhu biogas plant parts list.

3 m^3 Design			
Mud Bricks	$ 0.25	1250	$ 312.50
50kg Cement Bag 42.5 Grade	$ 3.46	27	$ 93.42
Coarse Sand	$ -	2	$ -
Fine Sand	$ -	2	$ -
Stone Aggregates	$ -	1.5	$ -
6 mm iron wire in kilograms	$ 3.30	10	$ 33.00
Binding iron wire in kilograms	$ 3.30	0.1	$ 0.33
150 mm diameter PVC pipe	$ 1.18	1.75	$ 2.07
Brackets welded with gas nipple	$ 10.00	1	$ 10.00
PVC gate valve 20 mm diamter	$ 2.65	1	$ 2.65
Biogas burner	$ 14.99	1	$ 14.99
100 mm long galvanized iron nipples	$ 5.00	2	$ 10.00
Female Threaded brass metal pipe nipple	$ 10.00	1	$ 10.00
Rubber hose in meters	$ -	1	$ -
Various Tools			$ 100.00
HDFE pipe in meters	$ 1.78	50	$ 89.00
		Total	$ 677.96
4 m^3 Design			
Mud Bricks	$ 0.25	1850	$ 462.50
50kg Cement Bag 42.5 Grade	$ 3.46	34	$ 117.64
Coarse Sand	$ -	2.5	$ -
Fine Sand	$ -	2.5	$ -
Stone Aggregates	$ -	2.5	$ -
6 mm iron wire in kilograms	$ 3.30	20	$ 66.00
Binding iron wire in kilograms	$ 3.30	0.2	$ 0.66
150 mm diameter PVC pipe	$ 1.18	1.9	$ 2.24
Brackets welded with gas nipple	$ 10.00	1	$ 10.00
PVC gate valve 20 mm diamter	$ 2.65	1	$ 2.65
Biogas burner	$ 14.99	1	$ 14.99
100 mm long galvanized iron nipples	$ 5.00	2	$ 10.00
Female Threaded brass metal pipe nipple	$ 10.00	1	$ 10.00
Rubber hose in meters	$ -	1	$ -
Various Tools			$ 100.00
HDFE pipe in meters	$ 1.78	50	$ 89.00
		Total	$ 885.68

Table 17. Deenbandhu cost analysis.

Scenario	Annualized Capital Costs (USD)	Yearly Operational Costs (USD)	Yearly Total Costs (USD)
Nicaragua Farm	$123.25	$425.06	$548.32
Nicaragua Community	$894.54	$3746.36	$4640.91
Bolivia Farm	$147.61	$710.37	$857.98
Bolivia Community	$937.89	$6252.08	$7189.98
Nigeria Farm	$123.59	$530.18	$653.77
Nigeria Community	$964.74	$4713.81	$5678.55
India Farm	$92.10	$244.87	$336.97
India Community	$316.08	$2252.37	$2568.45
Indonesia Farm	$92.10	$425.06	$517.16
Indonesia Community	$327.75	$3790.65	$4118.40

Tube Digester TEA Calculations

Sizing Calculations

To size this design, the total volume of the biodigester is found. Gas accounts for 25% of the volume, so the daily biogas requirement multiplied by four results in the volume of the biodigester. After the volume is calculated, the length can be calculated with the equation below (Luer, 2010). Note that 2.5 meters are added to the length to account for the inlet and outlet. A tube radius of 0.9 meters is used for farm scale and 1.9 meters for community scale (Ciotola, 2011).

Equation 7. Tube digester length equation.

$$Length\ of\ Biodigester = \left(Volume\,\frac{Biodigester}{pi * radius^2}\right) + 2.5m$$

Table 18. Tube digester sizing information.

Scenario	Volume of Biodigester (m^3)	Tube Radius (m)	Length of Biodigester (m)
Nicaragua Farm	6.4	0.9	4.8
Nicaragua Community	64	1.9	8.2
Bolivia Farm	6.4	0.9	4.8
Bolivia Community	64	1.9	8.2
Nigeria Farm	8.0	0.9	5.4
Nigeria Community	80	1.9	9.6
India Farm	8.5	0.9	5.5
India Community	84.8	1.9	10.1
Indonesia Farm	7.3	0.9	5.1
Indonesia Community	73.1	1.9	9.0

Costs

The table below is a parts list for a tube digester. Assumptions are laid out in Appendix A. Operational costs included the maintenance costs and the repair costs. Capital costs included the parts list, building for protection, tube digester construction labor, and building construction labor. The capital costs were annualized.

Table 19. Tube digester parts list.

Materials	Unit Cost (USD)	Quantity	Total Cost (USD)
Rubber Strap	$ -	1	$ -
PVC Drainpipe	$ 26.29	1	$ 26.29
PVC tube bend 1/2"	$ 1.56	4	$ 6.24
PVC T-fitting 1/2"	$ 1.96	4	$ 7.84
PVC lock valve 1/2"	$ 2.65	5	$ 13.25
PVC universal coupler 1/2"	$ 0.76	2	$ 1.52
PVC Adapter flange 1/2"	$ 0.90	4	$ 3.60
PVC Tube	$ 1.18	25 m	$ 10.62
Teflon Tape	$ 3.99	2	$ 7.98
Steel Wool (SH_4) filter	$ 3.97	1	$ 3.97
Biogas Burner	$ 14.99	1	$ 14.99
PVC plug for T-tube 1/2"	$ 0.87	1	$ 0.87
Straw or Fine Sand	$ -		$ -
Sacks of jute or old plastics	$ -		$ -
Metal Wire	$ 3.99	1 roll	$ 3.99
Nails	$ 5.00	1 box	$ 5.00
2 L plastic bottle	$ -	0	$ -
Transparent Flexible Tube	$ 2.63	12 (m)	$ 5.26
Various Tools	$ 50.00		$ 50.00
Biogas Reservoir Polyethylene	12.88/m2	7.5 m^2	$ 96.60
		Total	$ 258.02

Table 20. Tube digester cost analysis.

Scenario	Annualized Capital Costs (USD)	Yearly Operational Costs (USD)	Yearly Total Costs (USD)
Nicaragua Farm	$109.67	$412.53	$522.20
Nicaragua Community	$639.57	$3608.42	$4247.99
Bolivia Farm	$117.5	$691.76	$809.32
Bolivia Community	$614.41	$6094.68	$6709.09
Nigeria Farm	$111.90	$516.93	$628.33
Nigeria Community	$616.46	$4529.73	$5146.19
India Farm	$94.10	$236.70	$330.79
India Community	$544.08	$2026.33	$2570.41
Indonesia Farm	$91.10	$413.53	$504.63
Indonesia Community	$500.48	$3602.78	$4103.26

Life Cycle Assessment Calculations

The water usage was calculated straightforward. For every 1 kg of manure used 4 kg of water were used. Therefore, the amount of manure required in each scenario was simply multiplied by four. Carbon dioxide was found from the amount produced from anaerobic digestion, and the carbon dioxide emitted from burning biogas. The CO_2 emissions from burning biogas were found using the chemical formula for combusting methane and the density of biogas. All the assumptions are laid out in Appendix A.

Equation 8. CO_2 emissions from anaerobic digestion.

$$CO_2\ from\ Anaerobic\ Digestion\ \left(\frac{kg}{year}\right) = 0.4 * 1.842\ \left(\frac{kg}{m^3}\right) * Net\ Biogas\ \left(\frac{m^3}{year}\right)$$

Equation 9. CO_2 emissions from burning biogas.

$$CO_2\ from\ Burning\ Biogas = Net\ Methane\ \left(\frac{m^3}{year}\right) * 0.66\frac{kg}{m^3} * \left(\frac{44.01}{16.04}\right)$$

Table 21. Life cycle assessment summary table.

Scenario	Net Water (L/yr)	Net CO_2 (kg/year)	Net Energy (GJ/year)	CO2 Emissions Per Meal (kg CO2/meal)	Water Impacts Per Meal (L/meal)	Water Impacts Per Day (L/day)	Byproduct (kg/yr)
Nicaragua Farm	82688	1065	158.93	0.97	76	227	14470
Nicaragua Community	826884	10648	1589.31	0.97	76	2265	144705
Bolivia Farm	82688	1065	158.93	0.97	76	227	14470
Bolivia Community	826884	10648	1589.31	0.97	76	2265	144705
Nigeria Farm	103360	1331	198.66	1.22	94	283	18088
Nigeria Community	1033605	13310	1986.64	1.22	94	2832	180881
India Farm	109562	1411	210.58	1.29	100	300	19173
India Community	1095621	14109	2105.83	1.29	100	3002	191734
Indonesia Farm	94471	1217	181.58	1.11	86	259	16533
Indonesia Community	944715	12166	1815.79	1.11	86	2588	165325