Design and Construction of a Solar Mobile Anaerobic Digester for Rural Communities

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***Abstract*– An anaerobic digestion system that was completely operated on solar power (both photovoltaic and solar thermal energy), and mounted on a trailer to make it mobile, was designed and constructed. A 55-gallon batch digester was placed within a chamber that was heated by hot water pumped through a radiator. Hot water was produced by a solar thermal collector and photovoltaic panels charged a battery which operated pumps for recirculating water. It was found that the temperature in the heating chamber was maintained above ambient temperature but it follows the same trend as ambient temperature. The temperature difference between the chamber and ambient values was not constant but varied with time of day. Advantageously, the temperature difference was highest during night and early morning and lowest near noon. In winter when ambient temperature dipped to 2 °C during early morning hours, the chamber temperature did not drop below 10 °C. Model simulations showed that even if the digester is subjected to diurnal variations of temperature (as observed in winter of a subtropical region), about 63 % of the waste that would have been processed under constant digester temperature of 38 °C, can still be processed. The cost of the digester system without the trailer was $1,800**

***Keywords*—Anaerobic, digestion, solar-mobile, rural communities, solar, hybrid.**

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I. Introduction

Agricultural activity is responsible for using about 70% of the water worldwide [1] and agricultural waste contains about 80-90% moisture [2]. The degradation of this waste releases water with high amounts of dissolved organic carbon and nutrients [3,4]. Run off affect the nutrient balance of water bodies near agricultural operations. There are programs to incentivize the reduction of impacts of agricultural operations on the environment [5]. One method of reducing the environmental impact is to process agricultural residues in engineered systems that capture the emissions and subsequently disposes residues in a sound manner.

Anaerobic digestion (AD) is a widely used engineered process in which organic matter (biodegradable material) is converted into biogas (a mixture of methane and carbon dioxide gases) in the absence of oxygen and by the action of synergistic microbial populations under near ambient conditions [6]. Biogas can be utilized as a fuel for heating or electrical power generation. The residuals (also called digestate) after biogasification are still rich in nutrients and minerals, and can be land applied for soil fertilization. Various types of organic matter like food waste, municipal solid waste and agricultural residues can be anaerobically digested.
Anaerobic digestion can assist in managing the disposal of agricultural wastes and residues not only with minimal environmental impact but also with concomitant revenue generation in the form of biogas. Even though anaerobic digestion is a net producer of energy, it consumes energy for pumping and heating. It has been evaluated that the energy consumption for operation could range between 12 and 50% of the energy produced as biogas [7]. A challenge in deploying anaerobic digesters in rural areas is the availability of electrical power. Solar power has been proven to be a good alternative in areas that lack grid electricity [8]. Solar energy can be converted directly into electricity using photovoltaic (PV), or indirectly with concentrating solar power (CSP). PVs are scalable from small to large scale systems whereas CSP is applicable for large scale power generation. Solar thermal energy (STE) harnesses sunlight for generating thermal energy (heat). PVs can eliminate the need for purchased electricity (usually electricity gained from burning fossil fuels), however, in the absence of sunlight, PV systems also require expensive energy storage systems like batteries. Biogas on the other hand can be stored and utilized on demand for generating electrical and thermal energy. Commercial anaerobic digestion systems are often large and expensive and are not feasible for small scale operations. In this project, a small scale anaerobic digester system was designed and constructed to be operated completely off-the-grid using PV and STE. PV electrical power was used to operate the pumps for liquid recirculation and STE was used to heat water for maintaining digester temperature. The complete system was mounted on a trailer and can be hauled to different locations for testing different feedstocks.

Temperature is an important operating parameter that affects the rate of decomposition of organic matter in an anaerobic digester. Anaerobic digestion can be carried out at

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mesophilic (38 ± 2ºC) or thermophilic (55 ± 2ºC) temperatures [9]. Each temperature regime has a range within which microorganisms are active with an optimum value that maximizes microbial activity within this range. Therefore, an important variable to evaluate in the design of solar powered digester is the diurnal temperature variation that can be expected in the digester. The temperature variation can influence the volumetric throughput and the biogas production rate. In this paper, the design and construction of a mobile solar digester (MSD) is presented along with material and equipment costs. As a first step the temperature variations in the digester were monitored over the fall to winter periods of the subtropical climate of north-central Florida. Based on temperature measurements a mathematical model was used to assess the expected throughput and biogas production rate from the system. The results of this assessment are presented

II. Material and methods

A. Mobile Solar Digester (MSD)

A digestor is an air-tight vessel where anaerobic digestion takes place, it can be made of different materials, but it should be inert to the reaction that takes place inside it. Besides, it should guarantee the temperature and pH appropriated for the operation. In the developed model, at this stage, only temperature is automatically controlled, the pH control is still performed by the operator manually.

A picture and isometric view of the MSD is shown in Figures 1A and 1B. A solar thermal collector and PV panels are mounted atop the enclosed box. The completed unit is mounted on a trailer; dimensions of the entire assembly is given in Figure 1C. The core of the unit is the enclosed box section named "heating chamber", this chamber contains 2 reservoirs of water, 2 pumps, a car radiator and the digester. This chamber is made from 3.5 x 9.0 cm timber (2 x 4 studs) lined with 1.25 cm (0.5 inches) thick plywood sheets. One of the sides of the box is detachable, to serve as an access door (Figure 2). Rubber insulation was between the plywood sheets and gaps were taped with rubber-insulating tape.

Figure 1A. Assembled Mobile Solar Digester Unit

Figure 2 shows the top view cut-away of the heating chamber. For the thermal solar collector to work properly, pumps are required. It is not possible to have a natural (passive) thermo-syphon system, because the thermal collector is mounted higher than the water storage tanks.

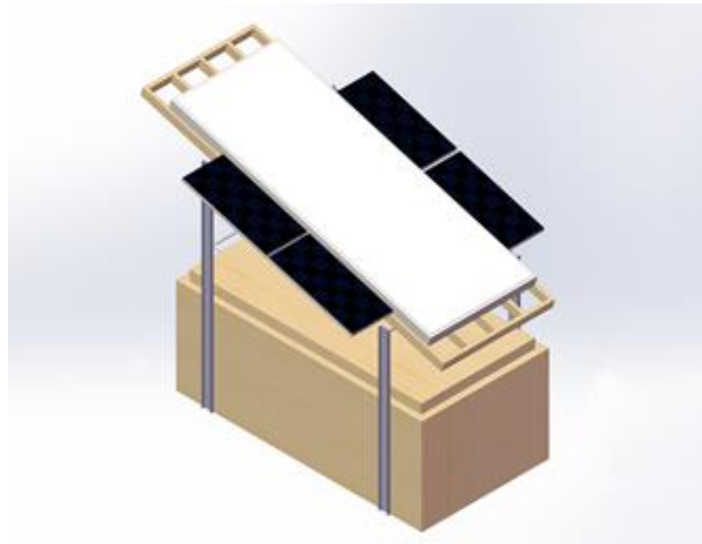

Figure 1B. Isometric view of the MSD showing the placement of solar thermal collector and photovoltaic panels

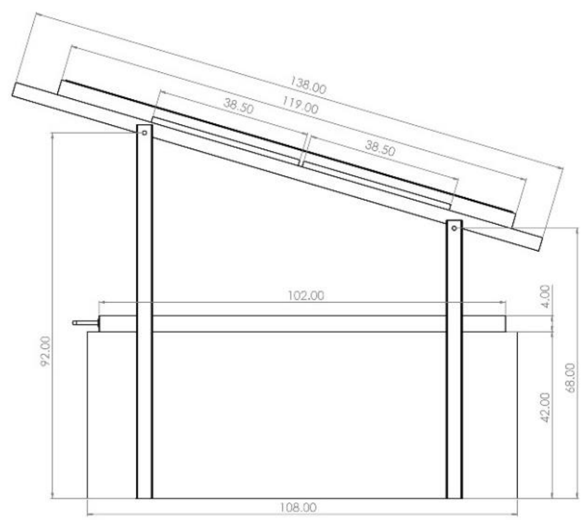

Figure 1C. Side view dimensions of MSD (dimensions in inches).

As it can be seen in figure 2, the water leaving from the panel goes to a reservoir (Tank 1) and then to the radiator. Thereafter, the water leaving from the radiator is accumulated in another reservoir (Tank 2) and then pumped back to the panel making in this way a closed loop. These pumps are operated on battery, recharged by the PV panels.

The heat collected by the solar heating system is transferred to the heating chamber by natural convection by means of a car radiator (heat exchanger); in case the digester reaches the desired temperature, the radiator can be bypassed and the water circulates between the collector and the water reservoirs. The hot water is circulated by two marine pumps at alternating intervals of 15 minutes per hour with a total pump run time of 30 minutes each hour during daylight hours. After sunset, the water re-circulates throughout the reservoirs and the heat exchanger to keep the chamber at the desired temperature. Time intervals can be determinate by regional climate.

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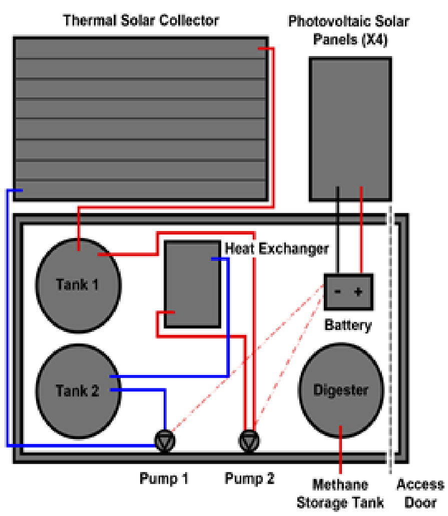

Figure 2 Top view cut-away of the heating chamber, solar collector and PV panels.

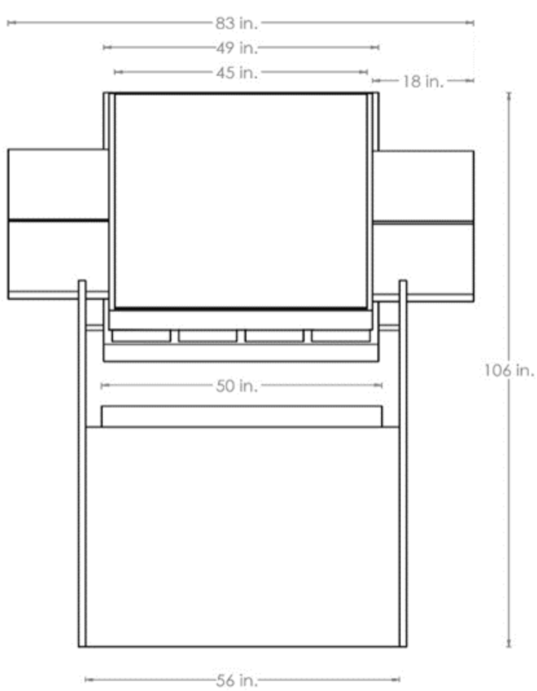

Figure 3A Assembly of the solar PV panels

The electrical assembly for MSD is a self-sustaining circuit and depends on four (PV) solar panels for energy, fixed to the sides of the solar thermal collector (Figure 1B and 3A) by lateral supports made from steel pipe, and placed at roughly ¼ of the total frame length from each end.

As is shown in Figure 3B, the energy obtained from the (PV) solar panels by the sun is transmitted to the solar charger controller that, in turn, charges a standard 12V DC car battery. The PV panels are connected in parallel, resulting in a generation of 19.6V (Figure 3C), which was over the 12V specified by the manufacturer, and 6 to 8 Amperes. The energy stored in the battery is used to power both pumps and timers. The voltage stored in the battery is displayed in real time in the solar charger controller (Figure 3D).

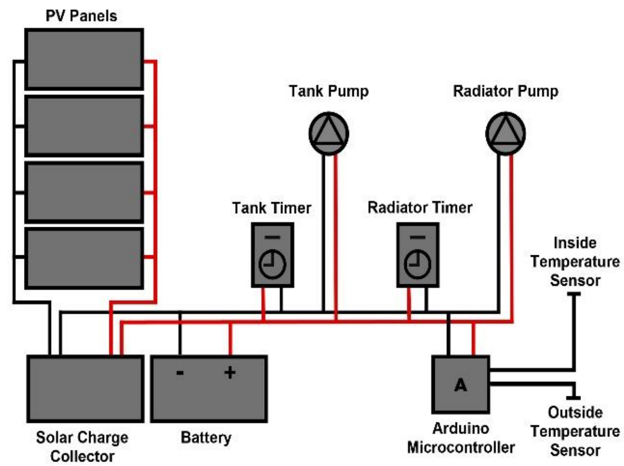

Figure 3B layout of the electrical circuitry of the MSD

Figure 3C Actual reading of the voltage generated by the four solar panels connected in parallel

Figure 3D Battery voltage in real time

The two timers and the solar charger controller are mounted on a control panel on the exterior of the heating chamber. This allows for data collection and maintenance to be done easily, without opening the heating chamber (Figure 3E).

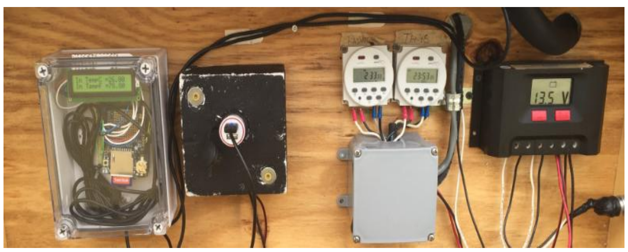

Figure 3E MSD unit controls and logging system

An Arduino UNO R3 microcontroller is used to control temperature in the reactor and water storage, and ADAFRUIT for Arduino is used as a data logger (Figure 4), the data is stored in an 8 GB memory SD card, which needs to be removed every month to download data. The temperature is measured by means of two sensors, one located outside of the unit and another located inside the heating chamber. Data is recorded every 5 minutes.

Figure 4 Arduino controller and ADAFRUIT data logging system

The anaerobic digester is an air-tight tank that assures an anaerobic environment for the bacteria. The unit can be operated as a batch digester. To facilitate easy loading of waste and unloading of residue, waste will be introduced in a heavy-duty laundry bag. Also, this unit was provided with two valves: one at the top to release the biogas and one at the bottom to release leachate if necessary.

Biogas is collected and stored by a water displacement system. The biogas storage unit is placed outside the MSD. The storage system consists of two tanks. The smaller diameter tank, is placed upside down into the open–top second tank which is filled with water (not shown). The top tank, in which biogas collects, has two valves: an inlet and an outlet line. The inlet line carries the biogas from the digester into the storage tank, while the outlet line is the user line. As biogas fills the tank it is pushed up. Guide posts made from 1.25 cm (½") PVC pipe are placed in the space between the bottom and top tank to prevent the top tank from toppling over. Crossbars made from the same dimensions PVC pipe are located at a defined height to stop the displacement of the top tank.

B. *Mathematical Model for Anaerobic Digestion*

At this stage only temperature measurements were taken inside the chamber and compared with ambient temperature. MSD has not yet been deployed for anaerobic digestion. Temperature was monitored over a period of six days in November and a further period of seven days in December. The effect of temperature variation on the decomposition of organic waste placed in the digester within the heating chamber was predicted using a mathematical model. The mathematical model developed by Lai et al. [10] was first adapted to predict anaerobic digestion of food waste in batch digesters at mesophilic (38 ˚C) and thermophilic (55 ˚C) temperature. The model was then validated on data collected at both temperatures by Hegde and Pullammanappallil. A temperature dependence was then incorporated for the maximum specific growth rates of microbial populations within the digester. This model was then simulated to predict the rate of decomposition and biogas production from a digester subjected to temperature fluctuations as would be expected in the MSD.

III RESULTS

A. *Temperature monitoring*

The temperature within the heating chamber was monitored for six days in November and over seven days in December. The temperature profile during each day of this monitoring period in shown in Figures 5 and 6. Figure 5 shows the profile for November and Figure 6 the profile for December. The x-axis scale starts at midnight. Temperature monitoring was initiated from around mid-day during each month. Hence the data for Day 1 starts at 15 hours past midnight (3:00 PM) during November and at 12 hours past midnight (12:00 PM) for December. Likewise, temperature monitoring was concluded around mid-day for both periods. In November, during Days 1 and 2 there was a greater difference between high and low ambient temperatures compared to Days 3 to 6 (Figure 5). Ambient temperatures dropped to 5 °C at night on Day 1 and below 5 °C on Day 2 with the highs being around 25 °C during these days. The chamber temperature was below ambient when monitoring was initiated on Day 1. This was primarily because the chamber was opened to set up the sensor. Once the access door was closed the chamber heated up within a couple of hours and temperatures reached 23 °C. Thereafter, the temperature in the chamber dropped as the ambient temperature dropped. The chamber temperature dropped only as low as 13 °C even though ambient temperature had dropped to 5 °C. On Day 2, the ambient temperature continued to decrease in the early hours of the morning and dropped to as low as 2 °C. The chamber temperature followed this trend dropping to 10 °C. This low value was reached 2 hours after the ambient temperature had reached its low value. On Day 3, ambient temperature varied between 12 and 22 °C whereas chamber temperature varied between 20 and 25 °C. On Day 4, the temperature difference between chamber and ambient was much smaller, sometimes chamber temperature being lower than ambient temperature.

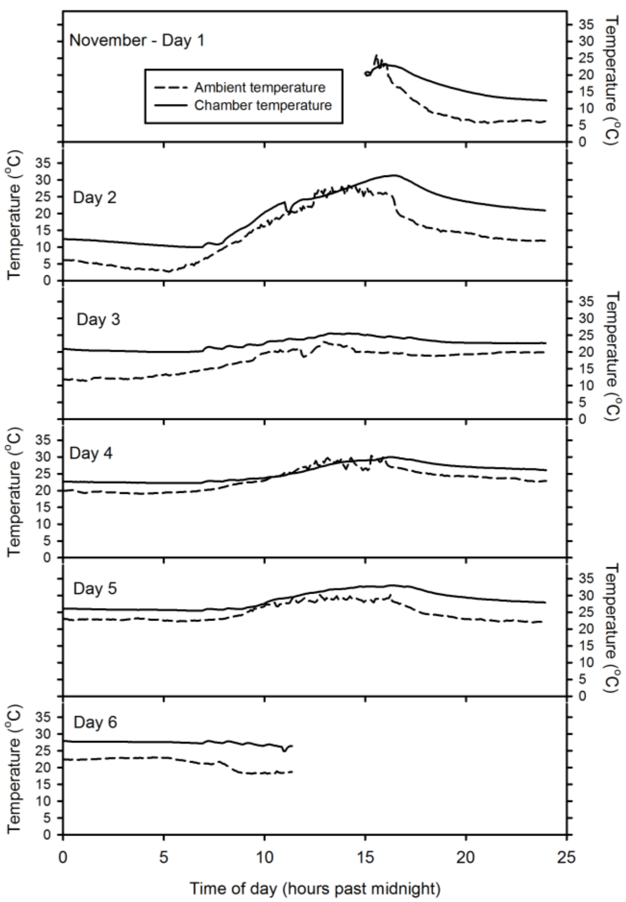

Figure 5. Ambient temperature and temperature inside the heating chamber during six days in November.

Temperature difference between chamber and the ambient was 3 °C higher in the chamber during majority of the monitoring period, reaching as high as 12 °C. The higher temperature differences occurred at night, which would be advantageous for operating the digester (Figure 6).

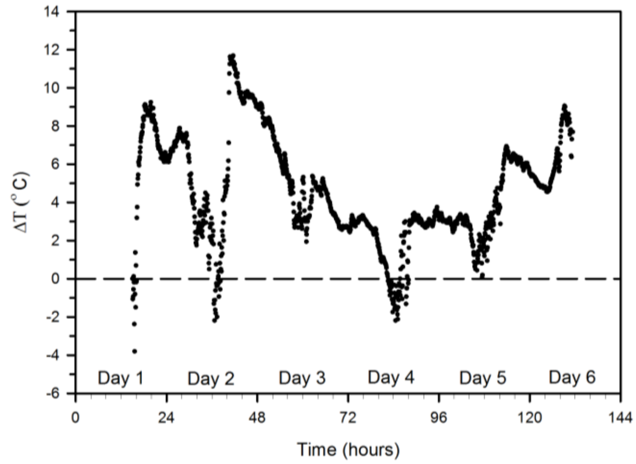

Figure 6. Temperature difference between chamber and ambient in November.

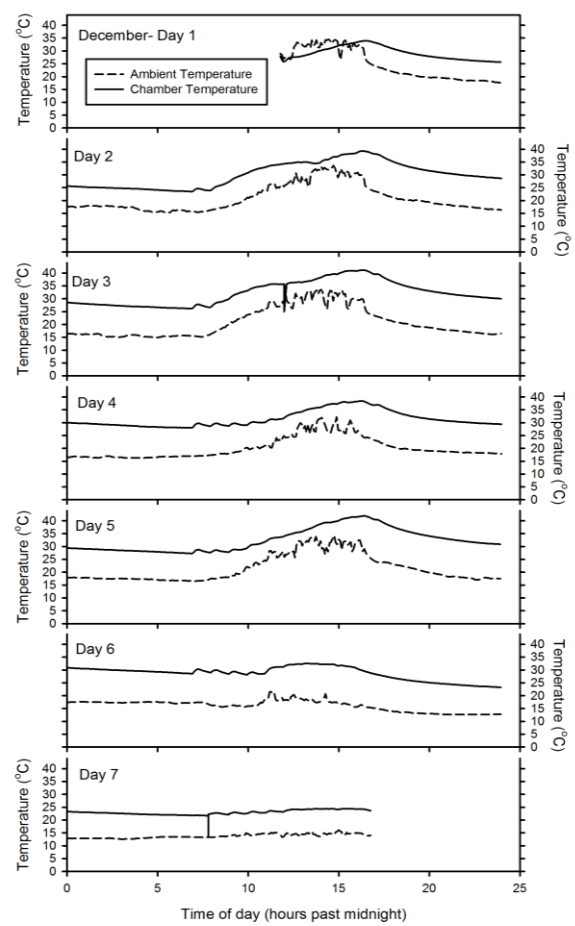

Figure 7. Ambient temperature and temperature inside the heating chamber during six days in December.

The monitoring periods in December were characterized by higher ambient temperatures, with temperatures reaching as high as 32 °C on Days 1-5. On Days 6 and 7, the high temperature was only 20 °C and 15 °C respectively (Figure 8).

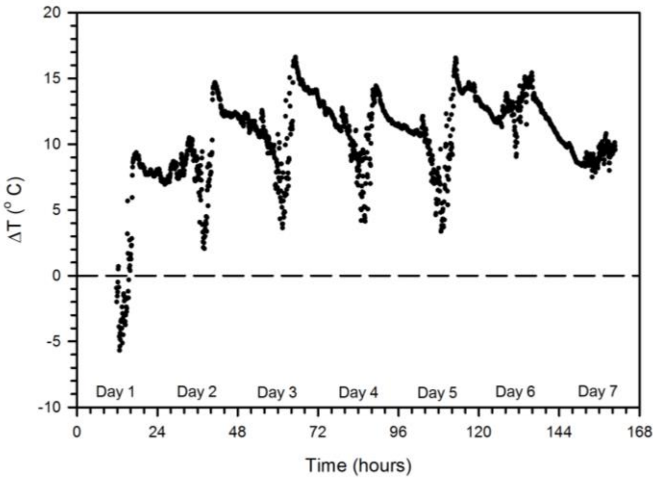

Figure 8. Ambient temperature and temperature inside the heating chamber during six days in December.

In response to this, the peak value of chamber temperature was around 40 °C on Days 1 to 5 and the highs dropped to 32 °C and 25 °C on Days 6 and 7 respectively. The chamber temperature did not drop below 25 °C for Days 1 to 5 and low values were around 22 °C the other two days. Figure 7 shows the temperature differences between chamber and ambient for December monitoring days. Four hours after the access door was closed, the temperature of the chamber remained above ambient during the rest of the duration of the monitoring period. Lower temperature differences were observed during the middle of the day, with the higher values at night or early morning (Figure 8)

Generally, the temperatures in the chamber of the MSD was maintained above ambient temperatures. Even when ambient temperature was 2 °C, chamber was maintained around 10 °C.

B. Anaerobic digestion in MSD

The next step was to assess performance of anaerobic digestion process in the MSD. This was carried out by using a mathematical model of the process. A mathematical model developed by Lai et al [10] was adapted to the digestion of food waste. Hegde and Pullammanappallil [9] carried out anaerobic digestion of fruit and vegetable waste under mesophilic (38 °C) and thermophilic (55 °C) temperature controlled conditions in pilot scale batch digesters. The temperatures chosen were optimal values in the mesophilic and thermophilic regimes respectively. Cumulative methane production data from the experiments is shown in Figure 9. Run 1 corresponded to a startup experiment when the digestion process was initiated at both temperatures by simply adding a buffer solution to the waste.

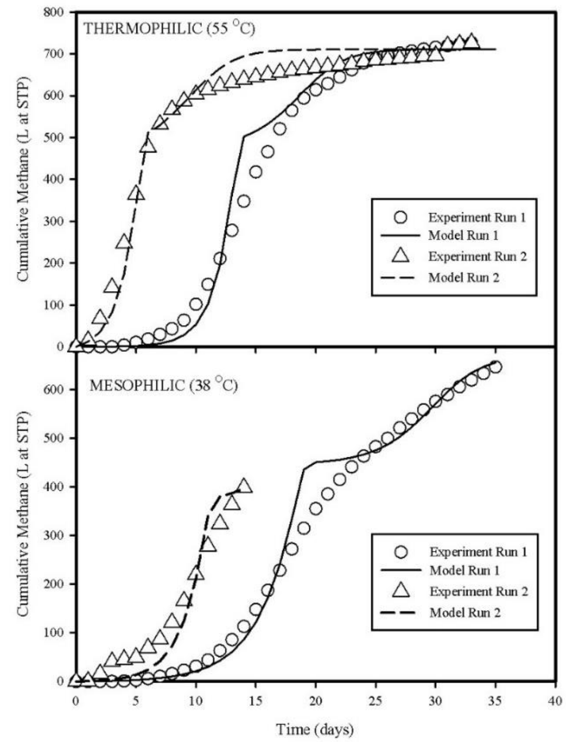

Figure 9. Comparison between model and experimental data for mesophilic and thermophilic digestion.

Run 2 was carried out by using mixed liquor produced at the end of Run 1 as inoculum. As expected, the methane generation was slower in Run 1 compared to Run 2. Also, as expected, the rate of methane generation at thermophilic temperatures was faster than at mesophilic temperatures. Comparing Run 2 most of the methane from food waste was released within 10 days at thermophilic temperature whereas only half this amount was released during the same period at mesophilic temperature. It was possible to adapt the mathematical model to predict these experimental results by only changing the maximum specific growth rate (μ_{max}) of the methanogenic bacteria. The μ_{max} value for methanogenic bacteria at mesophilic temperature was 0.58 day^{-1} and at thermophilic temperature was 0.7 day^{-1}. Differences between model Runs 1 and 2 was that in Run 1, only a very low concentration of initial microorganisms was used, whereas to simulate Run 2 the values of the final concentration from Run 1 was used as starting values.

Since temperature measurements in the MSD indicated the digestion process is likely to be in the mesophilic regime (below 40 °C), further simulations were done in this range. The kinetics of decomposition was adjusted as function of temperature by varying only the maximum specific growth rate of the methanogens if temperature was above 18 °C and varying maximum specific growth rates of all microbial population for temperatures below 18 °C. The well-known rule of thumb that microbial growth rate doubles for every 10 °C rise in temperature was used to estimate μ_{max} at different temperatures (μ_{max} at 38 °C was taken to be 0.58 day^{-1}).

Table 1 below shows the effect of temperature on the duration (batch residence time) required to produce 90% of the ultimate methane potential of food waste. It was assumed that the temperature was held constant at the tabulated values. As expected, decrease in temperature increases the time required to digest the waste. The batch time increases two-fold when temperature drops from 28 °C to 18 °C and more drastically for small drops in temperature below 18 °C.

Table 1
Effect of temperature on batch residence time

Temperature (°C)	Batch residence time to produce 90% of methane potential (days)
38	20
28	22
18	44
15	96
10	135

Further simulations were carried out to assess the effect of diurnal variations in temperature as observed with the MSD on batch residence time. It was assumed the temperature variation measured in the chamber on Day 1 and first 12 hours of Day 2 (i.e. from 12 noon Day 1 to 12 noon Day 2) of the November monitoring period was repeated every day during digestion. During this period the maximum temperature was 25 °C and minimum was 10 °C. Given this variability in temperature, Figure 10 shows the model predictions in methane production. As can be seen, there was a period of around 8 days of very low methane production. Then methane production rapidly increased, producing about 500 liters within 32 days. At this time, almost all the methane potential of waste was exhausted.
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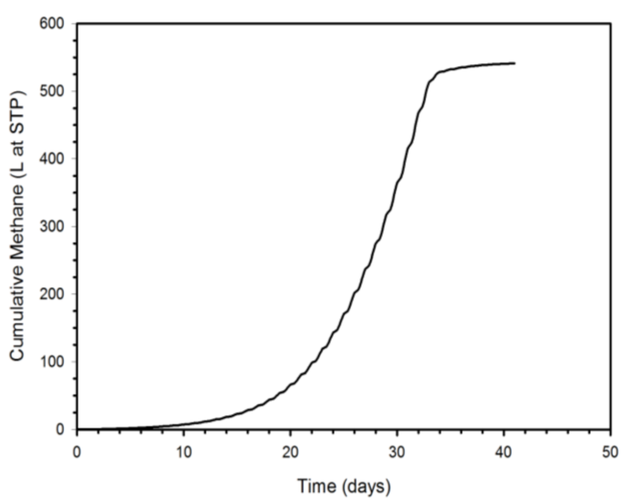

Figure 10. Model predictions of cumulative methane production when anaerobic digestion process is subjected to diurnal temperature variations.

The digestion duration under varying temperatures was between batch residence times simulated for a constant temperature of 28 °C (22 days) and 18 °C (44 days). A duration of 32 days is reasonable residence time in an anaerobic digester. During summer, when temperatures in MSD may reach 38 °C to 40 °C, the duration for digestion could be around 20 days. But this period increases to 32 days during the winter months of sub-tropical climate. This means that only about 63% of the waste processed in Summer can be processed in winter for a specified digester volume.

C. *MSD cost*

Table 2 lists the cost of materials, equipment and parts to build the MSD.

Table 2
MSD material and equipment cost

Quantity	Item	Cost (US$)	Total(US$)
1	Solar collector, thermal	700	700
4	PV panels	145	570
2	12V Timer Switch Relays	6.50	13
1	Solar charge controller VicTec Intelligent 30 A 12/24V	40	40
1	12V 120 Amperes battery	125	125
2	12V marine pumps	30	60
1	Car radiator (2ft length, 1.5ft. wide, 0.06 ft. thick)	45	45
50	ft. insulated cable #14	15	15
1	flatbed trailer 5 by 8 Ft	1,600	1,600
3	½" plywood sheets	15	45
1	Gallon black latex chalkboard paint	15	15
1	Arduino UNO R3	25	25
1	Adafruit logging shield for Arduino	15	15
1	8 GB Sandisk memory card	6	6
	Hardware (Miscellaneous)	125	125
	Total		3,399
	Total (without trailer)		1,799

The total cost of assembly of this MSD unit was approximately US$ 3,400.00. The major expenses are the cost of the PV solar panels, solar thermal collector and flatbed trailer. The flatbed trailer was purchased in this project only to make the digester mobile for demonstration purposes. If this is not required, the cost of solar digester decreases to $1,800

IV CONCLUSIONS

A low cost (about US$3,400.00) anaerobic digestion system operated on solar energy was successfully designed and constructed. After pilot testing, it was seen that the system temperature fluctuates depending on ambient temperatures. However, the MSD is capable to keep the temperature in the anaerobic digester up to 15°C hotter than the ambient temperature. A simulation based on a mathematical model showed that even during Florida's winter, the unit is able to perform anaerobic digestion of the waste loaded into the system.

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