Landscape Architecture and Regional Planning
2020; 5(2): 21-26
http://www.sciencepublishinggroup.com/j/larp
doi: 10.11648/j.larp.20200502.11
ISSN: 2637-4358 (Print); ISSN: 2637-4374 (Online)

Assessment of Energy Recovery Potential of Faecal Sludge

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To cite this article:

Mehejabin Chowdhury Ankan, Md. Murad Hasan, Md. Jobaer Howlader. Assessment of Energy Recovery Potential of Faecal Sludge. *Landscape Architecture and Regional Planning*. Vol. 5, No. 2, 2020, pp. 21-26. doi: 10.11648/j.larp.20200502.11

Received: December 16, 2019; **Accepted**: December 26, 2019; **Published**: May 28, 2020

Abstract: Faecal sludge generating from fixed-place defecation system has been an increasing concern in Bangladesh. In the city, this challenge is acute due to high population density, rapid and unplanned growth, and inadequate service provisions. Energy can be recovered from faecal sludge (FS) by converting the waste into usable heat, electricity, or fuel through pyrolization. Through Pyrolyzation biochar, biofuel, biogas can be obtained. Biochar can be produced by heating FS at high temperature. The burned portion of the sludge is the biochar, condensed steam is the biofuel and the uncondensed part is the biogas. This study shows that FS has volatile matter ranged between 39 to 50%, which qualify the FS as fuel. The ash residue of FS is between 34 to 45%. The rest of this is moisture. From Thermo Gravimetric Analysis (TGA) it was observed that major thermal events (mass loss rate) were found approximately between 150°C and 400°C which was considered as the ideal temperature range for pyrolysis process. Significant amount of biochar but negligible amount of biogas and biofuel were obtained from the samples by the pyrolysis process. 93.3% biochar, 2.8% biofuel and 3.8% biogas (at 200°C); 91.4% biochar, 3.5% biofuel and 5.1% biogas (at 300°C); 84.6% biochar, 9.3% biofuel and 6.1% biogas (at 400°C) were obtained. The result of pyrolysis analysis shows significant potential for energy recovery from FS.

Keywords: Faecal Sludge, Pyrolysis, Bio-char, Bio-oil, Bio-gas, TGA

1. Introduction

1.1. General

Faecal sludge (FS) comes from onsite sanitation technologies, and usually has not been transported through a sewer in Bangladesh. It is raw or partially digested, a slurry or semisolid, and results from the collection, storage or treatment of combinations of excreta and black water, with or without grey water. Examples of onsite technologies include pit latrines, unsewered public ablution blocks, septic tanks, aqua privies, and dry toilets.

Collection, transport, treatment and disposal of faecal sludge of onsite systems is correlated with suitable public health and environmental protection and management methodology, as it is highly variable in consistency, quantity, and concentration. Though there are lots of collections and transport companies are exist in West African cities, due to lack of adequate infrastructure huge volume of faecal sludge are disposed into the environment directly [14]. Exact data of FS properties, operational parameters, and proper selection of treatment method need to confirm before constructing FS treatment plant. Besides, the properties of wastewater is known, the presence of FS properties is very limited to unavailable. Findings of the experiment are extremely different, and are typically carried out for short time, not affected by climate throughout the year [16, 15].

Faecal sludge management (FSM) systems need lot of interlocution among various stakeholders such as household, collection and transport company, treatment plant, enduse or disposal, in comparison to one utility managing a sewer-based system. The financial liability of sanitation on households and governments can be transferred by building new value propositions from human waste [8].

The sanitation needs of 2.7 billion people across the globe are served by onsite sanitation methods, and that number is expected to grow to 5 billion by 2030. It is a general concept that onsite technologies fulfill sanitation demands for rural areas, but in reality, around one billion onsite facilities globally are in urban areas. In many cities, onsite technologies have much wider coverage than sewer systems. For example, in Sub-Saharan Africa, 65-100% of sanitation access in urban areas is provided through onsite methods [17].

In urban areas where the sanitation management system is comparatively in lower stage, the faecal sludge (FS) management methods have overall annualized capital and operation expenses that are five times less costly than traditional sewer based sludge treatment system. Therefore, households served by on-site sanitation method have to pay more amount than the households served by sewer based systems [9].

However, despite the fact that sanitation needs are met through onsite systems for a huge number of people in urban locations of low-income and middle-income countries, there is usually no management system in place for the resulting accumulation of FS. It is proved that the management of FS is an emergency demand that must be considered, and that it will continue to play an essential role in the management of world sanitation into the future [9].

Increasing amount of faecal sludge (FS) generation due to high pollution growth and its lack of management has become one of the major environmental concerns in rural areas of Bangladesh. Currently uncovered drains are the primary destination of faecal sludge. However, this practice of faecal sludge treatment has negative impacts on human health and the environment. For this, alternatives to disposal of faecal sludge can be considered as the FS has the potential resources. The sanitation problem in our country has been almost solved. But due to large use of onsite sanitary latrine, a large amount of untreated faecal sludge is generated. This sludge should be treated. The common methods of thermal treatment are incineration, gasification and pyrolysis. These methods are capable of producing energy and reducing the quantity of the sludge.

Recently there has been a regeneration of global interest in renewable energy resources from faecal sludge. Faecal sludge is taken on the planted drying bed for treatment, which is reputed as remarkable technology of faecal sludge recycling. The end product of this treatment is used as soil conditioner and compost [2].

Pyrolysis is a process by which this unwanted sludge can be converted into value added and useful products such as bio-char. Bio-char can be used as soil conditioner and due to the high porosity it may improve the water retention and aeration capacity by increasing surface area in soils [1]. There are few problems associated with the sewage sludge produce including discharge of toxic pollutant into the sewer, improvement of effluent quality lead to enhance sewage production, sludge treatment cost and possibility of environmental pollution that may affect the human health. Reuse and management of sludge mostly depend on the situation of surroundings. The treatment cost of sewage sludge is more than 50% of total wastewater treatment cost [3].

1.2. Objectives

The objectives of this study are as follows:

1. To determine the yielding of bio-char production.
2. To develop a pyrolysis equipment for thermal treatment of faecal sludge.
3. To investigate the ideal temperature range required for pyrolysis process.
4. To determine the physical properties (Moisture content, Volatile matter, Ash residue) of faecal sludge.

2. Literature Review

Faecal sludge (FS) sampling process affects the characterization results. During the construction of FS treatment plant, variety of onsite system needs to select. Improper design of onsite systems and climate change can be the liable for quantity of FS that is collected, transported and treated [4]. Recently energy recovery from sludge by incineration method becomes established scenario in a wide range globally. The quantities of energy that will be recovered fully depend on moisture content of sludge and the whole methodology and performance of incineration [3]. Government and private organizations and agencies take initiative on management of faecal sludge after overlooking long time. The enhancement of on-site sanitation system motivates poor people to maintain faecal sludge management carefully [5]. Onsite wastewater recycling is one of the tough jobs for engineers, as there are few vital issues to be maintained including congenial technology, complexity in operation, maintenance and monitoring [6]. The trade value and profit generation vary place to place depends on the property of the sludge, surroundings industrial sector, availability of materials. The end-product of sludge treatment is used as soil conditioner, it is the most common, but not profitable than any other end uses. These are the factor raised the concern about the viable management system of resource recovery from faecal sludge [7]. Enduring business programs could arise from designing faecal sludge management methods around resource recovery, which would in turn help to assure sustainable measures of enough sanitation facilities [8]. Application of faecal sludge as an influencer for rearing insect larvae for protein in animal feed is another effective treatment and resource recovery method. There are no full scale executions, however at the laboratory scale the application of faecal sludge as a feed origin for black soldier fly (BSF) larvae, Hermetiaillucens, has been experimented and revealed significant findings [10]. There are few studies have been done on possibilities of sludge. Conversion of sludge into fertilizer is one of the significant items of them. But the conversion process is becoming more restricted due to financial reasons. Several authors have experimented on sludge treatment to convert it into various forms; activated carbon is one of the fascinating items among these [11]. So far it is known that study on production of ethanol, butanol, or acetone from sewage sludge is very rare because the generation of ethanol, butanol, or acetone from sewage sludge is not so attractive due difficulties in the isolating process at the end of the treatment operation. But few researches have been done on production of hydrogen from sewage sludge [12, 13].

3. Research Method

The methodology is followed in the study are stated below:

a) Samples were collected and air dried for about a month.
b) Moisture content, Voc and ash residue using muffle furnace were determined.
c) Determination of appropriate temperature range for pyrolysis using Thermo Gravimetric Analysis (TGA).
d) Development of equipment used for pyrolysis process.
e) Pyrolyzed sample in the pressurized chamber was collected as bio-char.

4. Materials and Methods

4.1. Materials

To perform the study faecal sludge was used. This faecal sludge was collected from a house; location of the house is 22.896885^{o} N 89.502692 ^{o} S. The mass of faecal sludge collected for the study was about 9 kg. Then it was air dried.

The following procedure was maintained for sampling the faecal sludge for the required analysis:

a) A bucket was dumped in the septic tank
b) The bucket had a hole at the bottom so that water can pass through it
c) From the middle part of the sludge deposition the sample was collected
d) It was kept in a porous bag so that extra water can get out of it
e) The bag was kept in the sun for few days
f) When the sludge was medium dry it was put out of the bag and was spread on the floor
g) It was kept like that for 20 days
h) When the sample was dried enough it was crushed at was made in powder form
i) Then it was dried for 5 days more for the tests

4.2. Proximate Analysis

4.2.1. Moisture Content

Placing 25 to 30 gm FS sample in a tin can and the weight was measured. The can was placed in an oven at the temperature of 105°C for 24 hours. Dry weight was taken and from there moisture content was calculated from the following equation:

$$\text{Moisture content} = \frac{W_w - Wd}{W_w} \text{ x } 100\%$$

Where,
Ww = wet weight of sample
Wd = dry weight of sample

The process was repeated for three times and the average value of moisture content was measured.

4.2.2. Volatile Solid Compounds and Ash Residue

The dry sample from the moisture content test was taken as the initial sample for volatile solid content and ash residue test. The sample was taken in a ceramic pot and was kept in oven at 550°C for 30 minutes and then weight was measured. The percent of volatile solid content was calculated using following formula:

$$\text{Volatile solid content} = \frac{W_1 - W_2}{W_1} \text{ x } 100\%$$

Where,
W_1 = dry weight of sample at 105°C
W_2 = dry weight of sample at 550°C

The process was c repeated for three times and the average value of volatile solid content was calculated. The percent of ash residue were determined through the following formula:

Ash residue = (100-volatile solid content)%

4.3. TGA Analysis

The volatile matter content in the sample was determined using a thermo-gravimetric analyzer (TGA-50H) (Figure 1). A fixed amount of FS was taken and the instrument was purged with nitrogen. The temperature was increased from room temperature to 800°C @ 10°C/min and the weight loss was recorded. The flow rate was 10mL/min and the holding time was 0 min. The volatile matter content was calculated based on the percentage weight loss from the derivative curve.

Figure 1. *TGA 50-H.*

4.4. Pyrolysis

4.4.1. Experimental Equipment

A pressure cooker based setup was used for the test. The pressure cooker acted as the closed chamber and a bent copper pipe was used as the condenser. An electric heater was used for the heating and it was attached with a thermostat which controlled the temperature inside the pressure cooker. Figure 2, Figure 3 and Figure 4 shows the detail experimental equipment, installation of pyrolysis unit and raw sample & Biochar respectively are used in the study.

Figure 3. *Arrangement ofpyrolysis unit.*

Figure 4. *Raw sample (at the left) & Biochar (at the right).*

A pyrolysis setup (Figure 4) was developed for the study. The setup consists of a pressure cooker, electric heater, copper condenser, thermostat, gate valve. The flow diagram of the equipment is shown in Figure 5:

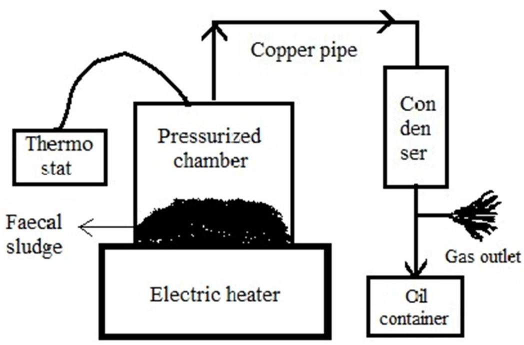

Figure 5. *Flow diagram of the pyrolysis setup*

4.4.2. Experimental Procedure of Pyrolysis

First 1.2 kg of the sample was taken in the pressure cooker and the lid was closed. Then all the apparatus were attached together. Then water was supplied and when the outflow started the heater was made on and the thermostat was fixed at a desired temperature. The first experiment was performed at 200°C. When the experiment started the gate valve was closed and when the temperature rose to 40°C it was opened. During the whole experiment a beaker was placed under the gate valve to collect the biofuel. Gradually the temperature reached at 200°C and the thermostat made the heater off. Due to this the temperature remained at 200°C. A little variation in temperature was happened. When the temperature reached at desired value it was kept for extra 20 minutes and then the heater was turned off. All the oil deposited in the beaker was collected in a bottle and used for further study.

4.5. Calorific Value of Biofuel

Using a bomb calorimeter in laboratory, higher calorific value of FS was determined. A certain amount of waste was burnt in a crucible, placed inside a strong container caleed bomb, submerged in a thermal calorimeter filled with water. Oxygen was also filled in the bomb. An electric spark was used to ignite the sample. Released heat was absorbed by all the components of the calorimeter and some heat was lost to the surrounding. at first put the waste sample (oven dry) in the crucible inside the bomb. Attach the fuse wire of known mass in such a way that it touches maximum surface of the sample. Drop 1 mL of distilled waterin the bomb by pipet. Now close the bomb and after charging oxygen in the bomb at a maximum pressure of 30 bar then immerse it in water in the calorimeter.

The water in the calorimeter was constantly stired before ignition of the sample and the temperature was recorded at an interval of one minute. As the temperature of the water becomes steady for exactly 5 minutes, the electric circuit was closed to make a spark in the persence of abundant oxygen. The temperature of water begins to rise and with the help of magnifying glass. precised temperature was read in every 30 seconds till the maximum temperature was reached. Afterwards, it can e recorded every minute till the drop in temperature for about 5 successive observations were uniform. After the experiment was completed, the unburned fuse wire was to be collected from the bomb and weighted. The higher calorific value was then determined by using the following formula:

$$Cx + C_1x_1 = (M+W)(\Delta\theta + 0.5\Delta tr^o)$$

Where,

C = Higher calorific value of the waste burnt (Kcal/kg)

x = Mass of the fuel burnt, gm

C_1 = Calorific value of the fuse wire burnt, (2.79 cal/cm)

x_1= Length of the fuse wire burnt, cm

M = Mass of water contained in the calorimeter, mL

θ_1 =Steady temperature before the combustion, °C

θ_2= Observed maximum temperature after the combustion, °C

$\Delta\theta = \theta_2 - \theta_1$ = Observed rise in temperature, °C

r^o = Time rate of the temperature drop after the maximum temperature was reached

Δt = Time elapsed for maximum temperature to reach

W = Water equivalent (206 gm/°C)

(Consistent unit must be used for each term)

5. Results and Discussion

5.1. Proximate Analysis

Table 1 shows the proximate analysis results of FS samples. Proximate analysis was performed in wet basis. The study obtained moisture content of 14% to 16% and volatile matter ranged between 39% to 50%. The volatile solid should be greater than 40% of the total mass of the solid waste to qualify the waste as fuel. The percentage of ash content of the samples ranged between 34% to 45%.

Table 1. *Experimental results of proximate analysis of FS.*

Physical parameters	Moisture content (%)	Volatile solid (%)	Ash residue (%)
Sample 1	16.0	49.1	34.9
Sample 2	14.3	45.3	40.4
Sample3	16.1	39.5	44.4

5.2. TGA Analysis

Figure 6 shows the TGA analysis of FS. Thermo Gravimetric Analysis experiment was carried out with 7.613 mg of FS sample at different rates with nitrogen flow maintained at 10 mL/min.

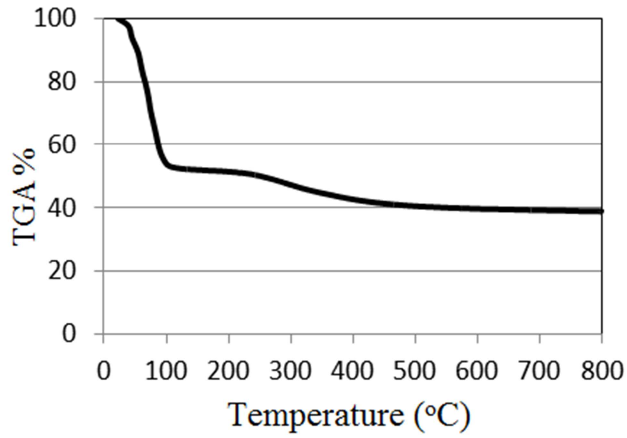

Figure 6. *Thermo Gravimetric Analysis of FS sample.*

In the graph ash residue at 800°C is just below 40% which is very close to the ash residue found in V°C test. Major mass reduction occurred between 150°C and 400°C. This temperature range was used in pyrolysis. Three pyrolysis have been conducted at 200°C, 300°C and 400°C. The raw material used for the experiment was the faecal sludge.

During experiment 1.2 kg of FS sample was taken in the reactor chamber for each experiment. The experiments were performed by varying the temperature within the range of 200°C to 400°C at every 100°C interval.

5.3. Mass Balance

The raw material used for the experiment was the faecal sludge. During experiment 1.2 kg of FS sample was taken in the reactor chamber for each experiment. The experiments were performed by varying the temperature within the range of 200°C to 400°C at every 100°C interval. The data collected during the experiment is shown in Table 2.

Table 2. *Experimental data of pyrolyzing 1.2 kg of FS at various temperatures.*

No of observation	Temperature In°C	Bio-Product			Experimental duration (min)
		Char (kg)	Oil (kg)	Gas (kg)	
01	200	1.120	0.034	0.046	55
02	300	1.097	0.042	0.061	70
03	400	1.015	0.112	0.073	90

5.4. Effect of Temperature on Product Yield

Temperature has effect on the yielding of products. At 200°C the biochar production was higher than the biochar production at 400°C. The effect of temperature on the pyrolysis products obtained from FS has been shown in Table 3. The results have been plotted in Figure 7.

Table 3. *Effect of temperature on Product Distribution of Pyrolysis of FS.*

No of observations	Temperature In°C	Weight (kg)	% of Bio-Product		
			Char	Oil	Gas
01	200		93.3	2.8	3.8
02	300	1.2	91.4	3.5	5.1
03	400		84.6	9.3	6.1

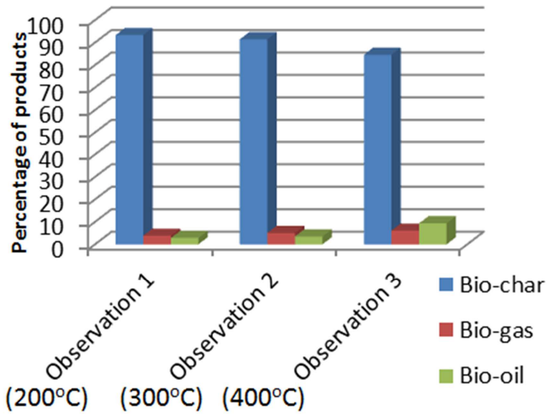

Figure 7. *Effect of temperature on product yield.*

In this case with the increase of temperature both biofuel and biogas increases but biochar decreases gradually. Biochar can be used as soil conditioner. It can be broadly used in agricultural field. Biogas can be used as a fuel. It can also be used in gas engine to convert the energy in the gas into electricity and heat. Biofuel can be used as a pure fuel or blended with petroleum.

A significant amount of bio-char was obtained from the pyrolysis but the bio-oil production was very low. The quality of bio-char was good at 400°C and the overall production was more than 80% of the total samples.

6. Conclusions

Based on the findings of this thesis, few conclusions can be summarized and we can perceive that Pyrolysis equipment was developed by which bio-char production was performed successfully. Ideal temperature range for faecal sludge was found (150-400)°C. Biochar yielding was more than 80%, so it can be commercialized.

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