Optimizing biogas recovery from pit latrine faecal sludge

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Abstract

The study investigated the potential of recovering biogas from pit latrine faecal sludge through anaerobic digestion. Pit latrine faecal sludge was obtained from the ventilated improved pit latrines of Hlalani Township in Grahamstown, South Africa, based on accessibility and less rubbish for the ease of extraction. Initially, a hollow steel corer was used for manually extracting faecal sludge from the pit latrines but, this method of sampling was not repeated because it was laborious and only permitted the recovery of limited amount of the faecal sludge and thus a vacuum truck was used. Anaerobic digestion was conducted under mesophilic temperature conditions (29±2°C) in a controlled environment room. The initial anaerobic digestion experiment was run using a tall Perspex digester with an electric stirrer attached to the top and the inner tube of a car tyre (18 litres) was used for gas collection. Pit latrine faecal sludge without a co-feed was used. Biogas recovery was not successful as the car tyre tube remained deflated throughout the digestion period (60 days). A second anaerobic digestion experiment was run using three modified 200 litres plastic drums. A co-feed was added in two drums which was an effluent from an anaerobic digester at Belmont Valley Wastewater Treatment Works. The mixing proportions in the two drum digesters were 1:2 pit latrine faecal sludge and the effluent from an anaerobic digester at Belmont Valley Wastewater Treatment Works, 2:1 pit latrine faecal sludge and the effluent from an anaerobic digester at Belmont Valley Wastewater Treatment Works. One anaerobic digester had 100% of pit latrine faecal sludge. The lids of each digester were sealed using silicone glue. Within 48 hours of initiating the anaerobic digestion run, the inner car tyre tube attached to the 1:2 mixture of pit latrine faecal sludge and the effluent from an anaerobic digester at Belmont Valley Wastewater Treatment Works started filling up while the other tubes from the other digesters remained deflated. The smell of hydrogen sulphide from the lids of the digester with a 2:1 mixture of pit latrine faecal sludge and the effluent from the anaerobic digester suggested that there was a gas leak. To show that the gas that had filled the other inner car tyre tube was flammable, a Fisher burner was connected to the gas outlet of the car tyre tube and then ignited successfully. This experiment was repeated but the sealant was changed to acrylic glue and PTFE Teflon plumbing glue was also used at the threads of the neck of the drums to improve the sealing when the lids were screwed on. Cow paunch manure was also added in all the reactors to enrich the anaerobic microorganisms in the reactors and to also improve biogas production. The digester with the a 2:1 mixture of pit latrine faecal sludge and the effluent from the anaerobic digester filled up four inner car tyre tubes, one inner tractor tyre tube (142 litres) and partially filled (half the total volume) one more inner tractor tyre tube with biogas. Thus, from this anaerobic digestion experiment, a total of 285 litres of biogas was recovered. In conclusion, the study showed that biogas can be recovered from pit latrine faecal sludge, however, a co-feed is necessary for anaerobic digestion to improve the quantity of biogas recovery.

Keywords: Anaerobic digestion, faecal sludge, biogas, recovery

Introduction

Pit latrines are the common cost effective sanitation facilities that are used for the collection, storage and treatment of excreta mostly in developing countries. Over time, these facilities fill up and the faecal sludge requires emptying, a task which is achieved by applying manual methods or mechanical methods [1-2] . The manual methods involve the use of shovels, spades or a gulper whereas the mechanical methods mostly involve

the use of vacuum trucks [2]. Faecal sludge is the partially digested slurry generated from the storage of human excrement in the presence or the absence of grey water [2]. After the pit emptying, faecal sludge is usually disposed in wastewater treatment plants, water bodies or in open fields. The disposal in open fields and water bodies poses a risk to human health and the environment due to the presence of high concentrations of pathogenic microorganisms in the faecal sludge including other contaminants such as heavy metals [3].

Human excrement is made up of 65-85% of water with 15-30% being particulate organic and inorganic matter [4-5]. The high content of organic matter in human excrement makes it valuable source for reuse as a soil amender or a fertilizer. However, the presence of high concentrations of microorganisms requires that the excreta be treated before use [4, 6]. Various techniques are available for treating faecal sludge and converting the organic content into a valuable resource and these include composting, anaerobic and aerobic digestion, vermicomposting, deep row entrenchment and solar drying [7-10]. From the mentioned faecal sludge treatment techniques, anaerobic digestion is of interest because this particular treatment process leads to the production of biogas and the sludge which could be used as a fertilizer or a soil amender.

Anaerobic digestion (AD) degrades complex organic matter to simpler organic molecules with simultaneous production of biogas and sludge by anaerobic microorganisms [11-12]. The produced biogas consists mainly of methane (>60%), carbon dioxide (29%) and a small percentage of other gases such as hydrogen sulphide [13]. The AD process which leads to the formation of biogas and sludge follows a series of steps which include hydrolysis, acidogenesis, acetogenesis and methanogenesis [11,14-15]. Proteins, polysaccharides and phospholipids are the molecules that are broken down into soluble organic compounds in a process called hydrolysis [11,14-15]. The energy output from hydrolysis is used to produce organic acids, hydrogen and carbon dioxide through the process called acidogenesis [14-15]. Propionic acid (CH_3CH_2COOH) and butyric acid ($CH_3CH_2CH_2COOH$) are the organic acids that are formed. These are reduced by acetogenic microbes forming acetic acid (CH_3COOH), hydrogen and water in a process called acetogenesis [11,14-15].

For acetogenesis to be thermodynamically favourable and the forward reaction to occur within the system, the partial pressure of hydrogen has to be 10-3 atm [11,14-15]. Hydrogen scavenging by methanogenic archaea lowers the partial pressure and keeps a thermodynamically favourably process of acetogenesis [11, 14- 16]. Two processes catalyse methane production via methanogenesis. One process utilizes hydrogen and carbon dioxide to form methane through hydrogenotrophic methanogenesis [16]. In the other process, acetate is formed from the conversion of hydrogen and carbon dioxide through homoacetogenesis [15-16]. Thereafter, acetotrophic methanogens convert acetate into methane and carbon In summary, that is how biogas is produced through AD [11, 14- 16].

Depending on the active anaerobic microorganisms present in the digester, AD is carried out at specific pH's and temperatures [11, 17]. A pH range of 6.8 to 7.8 is the recommended optimum range for AD, but the final pH varies depending on the digestion technique and the substrate [17]. For the optimum operation of the digester the ratio of carbon to nitrogen has to range between 20 to 30:1 [17]. A wide range of temperatures is used for optimum AD which range from psychrophilic, mesophilic, thermophilic and hyper-thermophilic however, the mesophilic and the thermophilic temperatures are the commonly used ranges for organic matter digestion [11,17]. At these temperatures the metabolic rates of the active microorganisms is activated and there is a possibility of the die off of pathogenic microbes. In mesophilic temperatures, the content of ammonia and the formation of long chain fatty acids that inhibit AD is reduced [11, 15]. High moisture content (90%) in sludges is known to increase methane production [10]. In cases where methane production is low, pre-composting or thermal treatment is used to improve biogas yields [11,15].

Extracellular commercial enzymes such as proteinases, peptidases, carbohydrates and lipases are used by some researchers to enhance the breakdown of organic matter thereby improving methane production during AD [18-19]. On the process cost of AD, the inclusion of these enzymes has huge implications [20]. There can be reduced anaerobic biodegradation of organic matter due to the presence of refractory compounds or inhibitory soluble molecules such as chlorinated benzene and polychlorinated biphenyls [12,21]. The decrease in biodegradability of organic matter and toxicity could result from the high molecular weight compounds [22]. At

high temperatures and pressures organic matter could be split into smaller molecules that are biodegradable [11, 15].

Factors such as reactor configuration, temperature, pH, alkalinity, temperature, organic loading rate, hydraulic retention time, solid retention time and mixing affect the performance of the anaerobic digesters [16]. The removal of specific constituents by the biomass in the digester depends on the contact time [11, 14- 16]. Solid retention time dictates the effectiveness of the microorganisms that have optimal growth conditions in the reactor and also changes the ecology of microorganisms within the system. If the solid retention time is too low, the microorganisms will be washed out and, if too high, then the system will be nutrient deficient and fail [11, 14- 16]. The organic loading rate inhibits two methanogenesis processes namely, acetotrophic methanogenesis and hygrogenotrophic methanogenesis [11, 14- 16]. Methane production is negatively affected during early start up if the produced organic acids are in high concentrations [11, 14- 16]. Temperature is a vital component for the optimal operation of the digesters because the efficiency of AD is regulated by microorganisms [11, 14- 16]. Organic matter solubilisation could be improved by prior physiochemical treatment since the rate limiting step of AD is hydrolysis [16].

There is a positive impact on the livelihood of community dwellers and individual households in rural communities upon implementation of small scale anaerobic digesters [26-27]. Small scale digesters are implemented to treat human waste in community healthcare centres, prisons, boarding schools and hospitals [15- 16, 23-24]. A significant reduction in the amount of biosolids produced, nutrient rich effluent and sludges which could be used as soil amender or fertilizer, reduced indoor pollution from cooking fires, energy recovery through biogas that can be used as a cooking fuel and the empowerment of women by eliminating the time used to collect firewood from the forest are the positive social and economic benefits of using anaerobic digesters [26-27]. The use of biogas as a fuel in developing countries could potentially reduce deforestation, indoor pollution and also give women more time to partake in other activities other than collecting firewood for cooking [28]. In South Africa, biogas is mostly produced from agricultural waste by farmers to generate electricity [29]. Considering the wide use of ventilated improved pit latrines in the rural communities of South Africa, there is a potential to recover biogas from the faecal sludge. However, the low level of literacy in such communities requires awareness campaigns about the risks of handling faecal sludge and, the reactors for generating biogas should be user friendly. This study focused on optimizing the recovery of biogas from pit latrine faecal sludge with or without a co-feed using a simple anaerobic digester.

Methodology

Three consecutive AD experiments were run at mesophilic temperatures (29 ± 2 degrees Celsius) in a controlled environment room. The pit latrine faecal sludge used as a feedstock was obtained from the ventilated improved pit latrines of Hlalani Location, Grahamstown, South Africa. The potential sampling ventilated improved pit latrines were selected based on accessibility of the contents through the extraction port behind the toilet structure or that the pedestal could be removed and that there was the least rubbish present in the pit to facilitate extraction of the pit contents without interference from rags, hair, braids and plastics. A coarse nylon mesh bag (mesh size ~ 1 centimetres) was used for the screening the pit latrine faecal sludge material prior anaerobic digestion. Initially, a 2 metre long hollow steel (2 millimetres thick and 80 millimetres external diameter) corer was used to recover the contents of the pit latrine (see Figure I). The manual extraction process of the contents of the pit latrine required two people. In this instance, the toilet pedestal was removed from the concrete plinth to provide access to the faecal sludge in the pit. Recovery of pit material was achieved by constantly rotating the corer until the bottom of the pit was reached. After reaching the bottom of the pit, the corer was retrieved carefully to prevent the recovered pit contents form sliding out. Then the collected material was transferred into 25 litre plastic buckets and transported to the laboratory. The initial AD experiment was run using a tall Perspex digester with an electric stirrer attached to the top and the inner car tyre tube (18 litres) was used for gas collection (see Figure II). The pit latrine faecal sludge (20 litres) collected from a single pit latrine using a core sampler was used as a feed stock without an inoculum based on the assumption that the microbial community responsible for AD would be present in the sludge. In subsequent experiments, the used faecal sludge recovery method was not repeated because it was very laborious and only permitted a recovery of limited amount of the

faecal sludge. As a result, a vacuum truck from the Makana Municipality was used to collect faecal sludge from multiple pit latrines in subsequent recovery events.

Figure I: The hollow sampler that was used to collect the pit latrine faecal sludge on the first sampling expedition with the plastic cover sleeve next to it.

Figure II: The Perspex digester used for anaerobically digesting pit latrine faecal sludge. An inner tube of a car tyre (white arrow) was attached to the top of the digester collected biogas.

Prior to the commencement of the AD run, the sludge was homogenised using an electrical stirrer. The mass of the inner car tyre tube used for biogas recovery was determined before and after the AD experiment using an UWE OFW-B60 scale (UWE Scales, Johannesburg, South Africa, minimum weight of the scale- 0.10 kilograms) to determine if gas recovery was successful. The experiment was run for 60 days to improve biogas recovery. A second AD experiment was run using three modified 200 L plastic drums (see Figure III). The changes in the anaerobic digester design were to mitigate energy inputs into operating the AD and to improve biogas recovery. Pit latrine faecal sludge from multiple pit latrines using a municipal vacuum truck was used as a feed stock. A co-feed was added to two digesters which was sourced from an anaerobic digester at Belmont Valley Wastewater Works. The mixing proportions in the two digesters were 1:2 pit latrine faecal sludge and the effluent from the anaerobic digester, 2:1 pit latrine faecal sludge and the effluent from the anaerobic digester. One digester had 100% of pit latrine faecal sludge and this served as a control. Each digester was filled to 180 L leaving 20 L headspace for gas collection. The screwed-on lids of each digester were sealed with silicone glue to minimize gas leaks. This experiment was run for 45 days, as this was considered sufficient time for biogas recovery (17). A third AD experiment was conducted after the completion of this digestion experiment. The experimental set up was identical to the one outlined above. To improve gas production in the third AD experiment, each digester was additionally inoculated with 2 kg of bovine paunch manure obtained from an abattoir near Grahamstown, to provide the microbial consortium required for AD. The physicochemical and microbiological property of the sludge is attached in appendix I.

Figure III a: The second type of anaerobic digesters with the attached inner car tyre tube. **Figure III b**: The crank handle with the stirrer attached to the lid of the anaerobic digester. This was to permit stirring of the anaerobic digester contents.

Results and discussion

Organic content is degraded from complex to simple organic molecules by a consortia of microorganisms during AD and each of the microorganisms are distinct metabolically, with each having their unique operating conditions [16]. These microorganisms have a syntrophic relationship with each other [30]. The consortia of microorganisms exchange low concentrations of metabolites that accumulate leading to feedback mechanisms which influence the activities upstream of the metabolite accumulation [30]. In the initial AD experiment, before anaerobic digestion, the inner car tyre tube was weighed and the mass was recorded as 0.85 kg. The same mass was recorded after the AD period suggesting that biogas recovery was not successful. Visual observations of the tyre tube also confirmed as the car tyre tube remained deflated throughout the AD period. This was due to the quantity of the faecal sludge in relation to the volume of the reactor which was too small (refer to Figure II). The

headspace was estimated to have made up 75% of the digester volume. In an anaerobic digester, a particular percentage of the total volume of the digester should be reserved as a headspace to allow biogas to accumulate, generating enough pressure to allow the gas to diffuse into the gas collection chamber [25]. Inoculating a consortium of microorganisms responsible for the breakdown of biodegradable matter under anaerobic conditions is recommended in literature as a way of improving biogas recovery [18-19]. In this study, a co-feed was not used because of the assumption that the microorganisms responsible for anaerobic digestion were already present in sufficient concentrations in the sludge. However, the presence of microorganisms is not the only factor that affects biogas production, the low concentrations of biodegradable organics also plays a significant role [10]. The experience from this study led to a decision to include a co-feed as means of enriching the organic content of faecal sludge to improve biogas recovery in the subsequent studies. In addition, the headspace was reduced to 10% of the total reactor volume.

These changes did have an impact on biogas recovery in the second AD experiment. Approximately 48 hours after the commencement of the AD experiment, the inner car tyre tube that was attached to the 1:2 pit latrine faecal sludge and the effluent of the anaerobic digester started expanding until in filled up. That was an indication of biogas production within the digester which was estimated to be 18 litres (see equation 1). The tubes on the other reactors, however, remained deflated. Poor gas collection from the other digesters was attributed to gas leakage from the manifold accommodating the crank handle as hydrogen sulphide gas could be smelt despite the use of silicone sealant. A study conducted by Zhang (2006) suggested that gases such as carbon dioxide, nitrogen, oxygen and methane can permeate silicone [31]. The volume of gas recovered was calculated using the following formula:

$$V(m^3) = 2\pi^2 \times Rr^2 \qquad (1)$$

In this equation, V is the volume of the tyre, R is the centre of the torus (average of internal diameter and external diameter of the tyre) and r is the thickness of the tyre divided by 2. The inner car tyre tube was detached from the digester, connected to a Fisher burner and the gas was ignited to show that there was flammable gas inside the tube. Although biogas was produced, the quantity produced was insufficient as only one inner car tyre tube was filled.

In the third AD experiment, the sealant used on the AD was changed from silicone to an acrylic glue and acrylic paint to reinforce the sealing and to also provide a thick, low gas permeable layer to minimize the leakage of gas [32-33]. Furthermore, PTFE Teflon plumbing tape was used to improve the sealing between the digesters and their lids. As means of further improving biogas recovery, each digester was seeded with cow paunch manure to enrich the microbial community responsible for AD. The 2:1 pit latrine faecal sludge and effluent from the anaerobic digester filled up 4 inner car tyres, one inner tractor tyre tube and partially filled (half of the total volume) of one more inner tractor tyre tube with biogas. An estimated volume of 72 litres of biogas was produced by the 4 inner car tyre tubes. The volume of the inner tractor tyre tube was 142 litres, therefore 142 litres of biogas was produced by a full inner tractor tyre tube while the half-filled inner tube produced an estimated volume of 71 litres. Thus, an estimated volume of 213 litres of biogas was produced by the inner tractor tyre tubes. The recovery of biogas was poor from the 100% pit latrine faecal sludge digester and from the 1:2 pit latrine faecal sludge and effluent from the anaerobic digester despite the sealants being changed and the ADs being inoculated. Additionally, the rubber material of the inner car tyre tube appeared to be permeable to some biogas components. This observation suggested that the properties of biogas retention of the inner car tyre tube were poor and an alternative collection vessel needs to be investigated using either flexoil opaque material with 4 ply construction, a gas canister or a tedlar bag. Moreover, this observation suggested that the produced biogas, if a car tyre tube is used for collection, needs to be used while being collected to minimize the biogas loss. The flammability of the recovered gas was successfully confirmed from each inflated inner car tyre tube by using a Fisher Burner as mentioned previously.

Conclusion

The study demonstrated that it is possible to recover biogas from pit latrine faecal sludge through anaerobic digestion, provided a co-feed is added. However, recovering biogas from 100% pit latrine faecal sludge was not successful, possibly due to the stabilized nature of the bulk of the pit latrine faecal sludge, where the remaining organic content was less accessible to the anaerobic microbial consortia. In recovering faecal sludge from pit latrines, fresher material in the upper part of the pit is mixed with stabilized material lower down, further reducing the amount of digestible organic material available to the microbial consortium. This could lead to less organic material being available to contribute to methane production [34].

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Appendix I

Table I. The physicochemical properties of the pit latrine faecal sludge before the first anaerobic digestion experiment.

Parameter	Measurements (n=3)
Dry weight % of wet weight (g/g)	92.8 ± 0.3
Moisture content (%) (g/g of dry weight)	7.2 ± 0.3
LOI % (g/g of dry weight)	96.1 ± 0.2
COD (mg/l)	1 406 ± 0.4
PO_4^{3-} (mg/l)	48.1 ± 3
NH_4^+ (mg/l)	10.9 ± 5
NO_3^- (mg/l)	26 ± 2
Cl^- (mg/l)	2 293 ± 95

Table II. The physicochemical and microbiological properties of the pit latrine faecal sludge mixed with the effluent from the anaerobic digester of Belmont Valley WWTW at different ratios [2:1 pit latrine faecal sludge to effluent (66% FS), 1:2 pit latrine faecal sludge to effluent (33% FS) and 100 % pit latrine faecal sludge (100% FS)] before anaerobic digestion.

Parameter	33% FS	66% FS	100% FS
Dry weight % of wet weight (g/g)	1.30 ± 0.30	2.79 ± 0.61	2.77 ± 0.30
Moisture content (%) of dry weight (g/g)	98.7 ± 0.3	97.2 ± 0.6	97.2 ± 0.3
LOI (%)of dry weight (g/g)	61.1 ± 10.1	77.1 ± 5.0	64.4 ± 0.1
COD (mg/l)	46 317 ± 12 872	43 580 ± 10 763	35 780 ± 3 935
PO_4^{3-} (mg/l)	103 ± 6	133 ± 23	137 ± 15
NH_4^+ (mg/l)	8 537 ± 3 575	7 600 ± 990	10 080 ± 439
NO_3^- (mg/l)	15 600 ± 3 524	24 277 ± 7 588	24 017 ± 6 985
K (mg/l)	670 ± 375	1 267 ± 35	553 ± 12
Cl^- (mg/l)	297 ± 91	350 ± 46	393 ± 86
pH	7.50	7.57	7.00
***E.coli* (cfu/g of dry weight)**	$7.5x10^2$	$3.7x10^3$	$6.6x10^2$
***Salmonella* spp. (cfu/g of dry weight)**	$7.5x10^2$	$3.7x10^2$	$3.3x10^2$
Total helminths/ g of dry weight	0	0	1

Table III. The physicochemical and microbiological properties of the different proportions of pit latrine faecal sludge and the effluent from the WWTW mixed with cow paunch before the third anaerobic digestion experiment.

Parameter	**33% FS**	**66% FS**	**100% FS**
Dry weight % of wet weight (g/g)	2.12 ± 0.60	1.64 ± 0.60	0.82 ± 0.60
Moisture content (%) of dry weight (g/g)	97.9 ± 0.6	98.4 ± 0.6	99.2 ± 0.6
LOI (%)of dry weight (g/g)	57 ± 14	33 ± 29	0
COD (mg/l)	3 639 ± 87	3 216 ± 70	2 993 ± 66
PO_4^{3-} (mg/l)	82 ± 1	95 ± 7	99 ± 3
NH_4^+ (mg/l)	21 067 ± 5 041	18 673 ± 5 065	19 187 ± 1 123
NO_3^- (mg/l)	5 943 ± 178	5 533 ± 806	5 443 ± 525
K (mg/l)	313 ± 6	340 ± 10	427 ± 21
Cl^- (mg/l)	583 ± 11	590 ± 6	712 ± 22
pH	7.32	7.51	7.79
***E.coli* (cfu/g of dry weight)**	$1.4x10^5$	$1.3x10^5$	$1.5x10^4$
***Salmonella* spp. (cfu/g of dry weight)**	0	0	0
Total helminths/ g of dry weight	0	0	0