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Assessing the Biogas Production Potential of Human Faecal Waste from Ecological Ventilated Improved Pit Toilets in Limpopo Province South Africa

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Abstract

The global imperative for sustainable energy solutions is underscored by escalating energy demands driven by population growth and economic development. Predominant reliance on fossil fuels for energy generation across various nations, including South Africa, poses significant environmental, climate and human health challenges. This research explores the potential of renewable energy derived from an unconventional source—human faeces, specifically collected from Ecological Ventilated Improved Pit toilets (EVIP), within schools in the Limpopo Province, South Africa. The implementation of EVIP toilets in schools throughout the Limpopo province was aimed at improving access to sanitation. However, the effectiveness and sustainability of using human waste collected from these toilets for energy production is still largely unexamined. The biochemical methane potential (BMP) assay was conducted to evaluate the bioenergy yield of faecal matter through anaerobic digestion. Preliminary findings indicate a volatile solid-to-total solids ratio (VS/TS) of 82. 7 %, a total solids content of 28.5 % (% w/w), a moisture content of 71.5 %, and a pH of 6.4. Following anaerobic digestion, the volatile solids content decreased to 48.4%, accompanied by a slight reduction in pH to 6.2. The experiment resulted in a total biogas volume of 0.00528 m^3 from a 25-gram wet mass of faecal matter. The maximum biogas production rate reached 0.000346 m^3/day, with a methane concentration of 54 % during the retention period. The system achieved its Asymptotic Cumulative Yield after 69 days. This study demonstrates that schools, such as the case study institution with 483 students, have significant potential to generate up to 66.62 m^3 of biogas per day from faecal matter, offering a practical and sustainable energy source to support national nutrition programs. The conversion of school-based waste management systems into resource recovery pathways facilitates the integration of energy recovery processes. This represents a significant advancement toward sustainable energy practices and reinforces the role of educational institutions in national green energy initiatives.

Key words: BMP, Energy, Environment, EVIP, Human Faeces

Introduction

South Africa's ongoing electricity crisis, marked by persistent load shedding, signals the need to explore alternative energy sources. Alongside efforts to advance renewable energy, increasing attention is being directed toward energy recovery from waste as a complementary strategy. This is being done with the goal of reaching the 2030 target of 17.8 GW to bolster the existing energy supply (Ferry & Giljova, 2015:1). To achieve the 2030 target, South Africa has considered to generate renewable energy from sewage sludge and agricultural wastes (Ferry & Giljova, 2015: 2). Burton *et al.* (2009:5) conducted a feasibility study in South Africa, to evaluate the energy recovery potential from wastewater. The study estimated that approximately 10,000 MW could be recovered from all wastewater treatment plants nationwide; equivalent to 7 % of the country's electricity supply from Eskom. Similarly, Ferry and Giljova (2015:17) assessed biogas production potential in nine South African municipalities. Their findings indicated that wastewater treatment plants in the Western Cape, specifically Outeniqua (5 ML/d) and Gwaing (12 ML/d), could generate up to 0.3 MW of electricity. In 2022, the South African Breweries (SAB) signed a power purchase agreement (PPA) with Bio2Watt where livestock waste is used to generate energy from a biogas plant with a capacity of 4.8 MW which is converted to electrical power (Bio2Watt, 2022).

The use of human faeces for energy generation is an environmentally friendly approach that can help reduce deforestation by providing an alternative to traditional fuelwood. Damm and Triebel (2008:32) reported that South African households consume approximately 11.2 million tons of fuelwood annually, a practice that significantly contributes to the depletion of natural forests. By converting faecal waste into biogas, communities can mitigate reliance on fuelwood, thereby preserving forest resources and reducing greenhouse gas emissions associated with wood burning. Moreover, the on-site treatment of human waste mitigates the risk of water contamination, thereby safeguarding aquatic ecosystems and enhancing environmental health. Studies by AfriForum (2018) and Herbig and Meissner (2019) revealed that 80 % of South Africa’s freshwater resources are polluted by effluent from wastewater treatment plants. The increasing demand for clean and affordable energy, coupled with the critical need to reduce environmental pollutant emissions, has accelerated the research into sustainable and renewable energy generation technologies. Similar to most countries, South Africa depends largely on coal (72.1 %) as the main source of energy (ESKOM 2021).

The use of coal to produce energy results into greenhouse gases emissions and leaves large quantities of fly ash, usually stored in ash ponds or landfills, which have a high concentration of heavy metals (Edokpayi *et al*. 2018). This consequently pollutes water sources and impacts on human health through water pollution and water borne diseases.

In a circular economy (CE), waste is considered a valuable resource for various economic applications, particularly as urban areas face increasing resource constraints (Miezah *et al*. 2015; Moya *et al*. 2017). The CE is a sustainable development strategy designed to address environmental degradation and resource scarcity, centered on the 3R principles namely: waste reduction, reuse, and recycling (Heshmati, 2017; Ekins *et al*. 2019). Recycling waste includes generating energy through Waste-to-Energy (WtE) conversion, a technology increasingly adopted worldwide. WtE can play a crucial role in reducing regional energy poverty by providing alternative modern energy services, aligning with the domesticated Sustainable Energy for All (SE4ALL) objectives, while simultaneously addressing waste management challenges (Deloitte, 2017; Drożyner, Rejmer, Starowicz, Klasa, & Skibniewska, 2013).

Investing in waste management technologies, particularly for human feaces, is environmentally sustainable, reduces communities' ecological footprints, and promotes overall environmental well-being. Previous studies have shown that biogas technologies effectively reduce groundwater contamination caused by the disposal of untreated or improperly treated waste (Zeng, *et al.* 2022). Biogas is regarded as a clean and renewable form of energy available through anaerobic digestion of organic waste. The anaerobic digestion of human feces offers significant public health benefits by effectively inactivating various pathogenic microorganisms (Ma *et al.* 2022), while also contributing to environmental sustainability through waste reduction and providing a cost-effective source of energy (Singh *et al.* 2021). Although numerous studies have explored the use of animal waste, food waste, and municipal waste for biogas generation to enhance energy security, human waste remains an underutilized resource in this context (Kell, 2019; Manyi-Loh *et al*. 2015; Yi *et al*. 2015).

However, several studies have found that human feaces can be used for different purposes such as biogas production, combustion as fuel, bio-char production, building materials (e.g. eco-cement) and as a fertiliser for farmland (Chang *et al.* 2020; Emetere *et al.* 2022; Harder, *et al.* 2019; Singh *et al.* 2021; Xu, *et al.* 2023). XI *et al* (2022:1) evaluated the plasma electrolytic faeces liquefaction and concluded that the method offers a sustainable approach for recovering resources from human waste. This study noted that the highest liquefaction yield was 85.67 %

with a heating value of 28.10 MJ/kg. Emetere and Pindar (2019:6) investigated the optimization of biogas generation from human waste and recommended replacing water with pressurized air in toilet systems to enhance biogas production. Their study demonstrated that using pressurized air increased methane output from 180 to 230 ppm. Andriani *et al*. (2015:223) investigated the current human waste collection system in Indonesia to investigate the potential recovery of energy and nutrients from human faeces. The study reported a biogas production of 106.85 m^3, which could be used at household level to augment the country's existing supply. Singh *et al* (2021) compared the rate and amount of biogas produced from co-digestion of human faeces (HF) with poultry litter (PL) and cow dung (CD) under anaerobic conditions. Results revealed that a total of 7.62 x10^3 ml, 9.85 x 10^3 ml and 12.96 x 10^3 ml of biogas were produced from HF, HF+PL and HF+CD, respectively. Thus, the co-digestion of human faeces with cow dung (HF+CD) gave a better biogas production. Onojo *et al.* (2013) conducted a similar study at the Federal University of Technology, Owerri, Nigeria, aimed at supplementing the university's energy supply. The biogas produced was sufficient to power a 5 kW biogas generator for six days.

Within the Limpopo province, pit latrines have been replaced by ecological ventilated improved pit (EVIP) toilets (Figure 1). This research notes that the effective implementation of Ecological VIP will assist in scaling up the recovery of energy from human faeces. This eco practice within the schools will ultimately assist South Africa to move closer to its 2030 target of reaching 17.8 GW energy generation, by simultaneously reducing the electricity consumption of 3.5 TWh a year by South African schools (Booysen *et al.* 2021:1). As such, human faeces collected from the EVIP toilets offer alternative renewable energy source to supplement the energy produced by ESKOM. Furthermore, the pursuit of sustainable ecological sanitation management, aimed at promoting optimal resource utilization, directly supports the achievement of Sustainable Development Goal (SDG) 7 - ensuring access to affordable, reliable, sustainable, and modern energy for all, and SDG 13, which calls for urgent action to combat climate change by reducing reliance on fossil fuels. Therefore, the purpose of this study was to estimate the potential of human faeces collected from the EVIP toilets to generate sustainable energy for lighting and cooking within the schools.

Specifically, the study sought to establish the optimal biogas required to cook a meal for learners and lighting in a school setting. The study argues that biogas production from human faeces offers many social, economic, and environmental advantages. Establishing optimum

biogas for cooking and lighting is critical to ensure sustainability of investing in such technologies. Ultimately, this study contributes to the WtE literature focusing on resource recovery from untreated human faeces, while ensuring the provision of sustainable energy to school settings and beyond. The first section of the paper provides a background to renewable energy and environmental and economic benefits of clean energy. This is followed by a descriptive explanation of the Biochemical Methane Potential test which determines the volume of biogas and methane produced from human faeces. The paper ends with a discussion and conclusion on the utilisation of the energy generated for lighting and cooking within the schools using EVIP toilets.

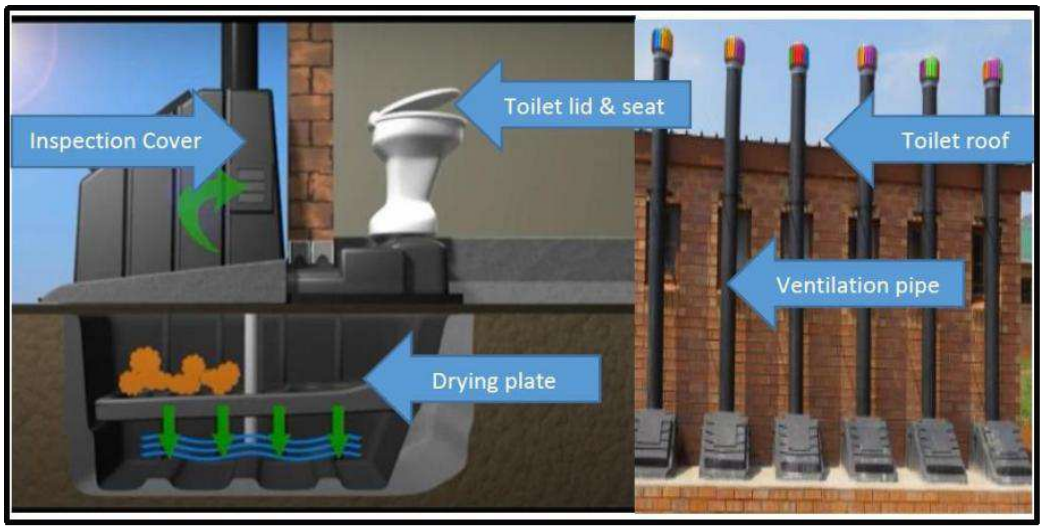


Figure 1: Schematic diagram of the Ecological Ventilated Improved Pit (EVIP) Toilet

Material and methods

In this study, an empirical approach was employed to estimate the potential of human faeces collected from Ecological VIP (EVIP) toilets to generate sustainable energy for cooking and lighting, using the Biochemical Methane Potential (BMP) procedure (Figure 2). Remigi & Buckley (2006) noted that the BMP test is valuable in evaluating organic materials' energy potential and efficiency for biogas production. The study adopted the daily average of 400 g of faeces, which a human produces in a day (Weisberger, 2018) and the experiment was tested at a school that has a total of 483 learners.

The estimated biogas output from human faeces was compared with the biogas usability benchmarks and energy equivalents provided by Kristoferson and Bokalders (2013) (see Table

1). Additionally, the sustainability of the biogas for cooking applications was assessed in relation to the requirements of the Limpopo School Nutrition Programme.

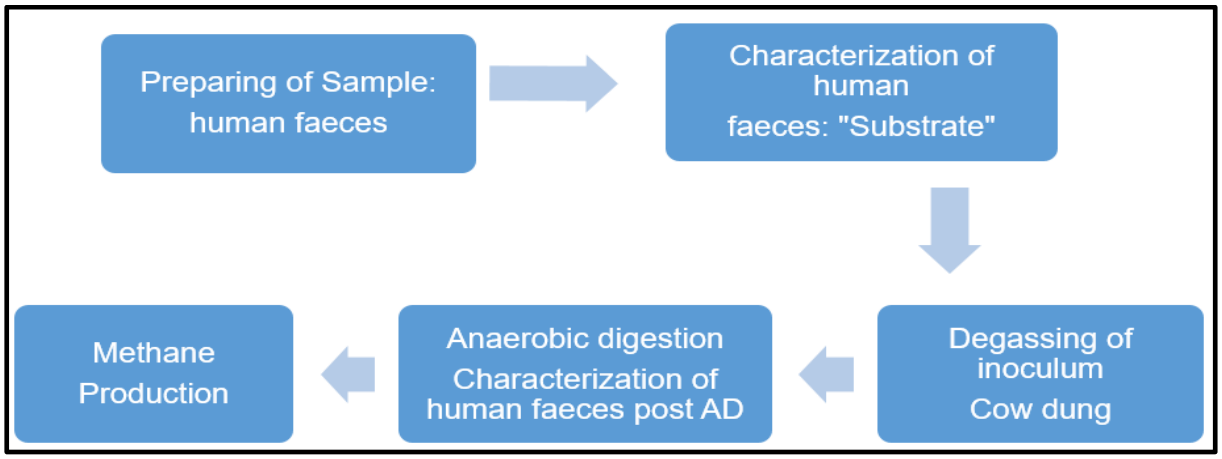


Figure 2: BMP test steps for estimating energy produced from human faeces

Table 1: Biogas usability and its equivalent

Application	1 m^3 biogas equivalent
Lighting	Equal to 60-100 watt bulb for 6 hours
Cooking	Can cook 3 meals for a family of 5-6
Fuel Replacement	0.7 kg of petroleum
Shaft Power	Can run a one horsepower motor for 2 hours
Electricity generation	Can generate 1.25 Kilowatt hours of electricity

Source: Kristoferson and Bokalders, 2013

Sample collection and preparation

Samples of human feaces from the EVIP toilets were collected while still moist using a laboratory beaker clip. The samples were stored in six specimen jars (250 g) with leak-proof screw lids designed to preserve the samples. The jars containing the collected human feaces were placed in resealable plastic bags to prevent external contamination and stored at 4 °C for short-term and -20 °C for long-term preservation. According to Holliger (2016:2515), the substrate composition changes due to water loss and the changes in volatile solids content are minimal at 4 °C for shorter storage periods (less than 7 days) and at -20 °C for longer periods (greater than one month).

Determination of pH, moisture content, total solids, and volatile solids in human faeces

The pH of the substrate was tested using laboratory pH meter. To determine total solids (TS) content and volatile solids (VS), three sets of human faeces (10 g each) were weighed into pre-dried crucibles using a weighing balance scale. The three sets were placed in a laboratory oven (ProLab Oven: manufactured by: FMH instruments, Cape Town, South Africa) at 105 °C for a 24 h period (15h30-15h30). The crucibles were labelled using a pencil. The dried samples were removed from the oven after 24 hrs and placed in a desiccator container for 20 minutes to cool down. The dried samples were weighed using a precision balance scale and incinerated in a muffle furnace (CNW Model SXL, Manufactured in China) at 550 °C for 240 minutes. After the specified time, the crucibles were removed from the furnace and cooled for 120 minutes. Equations 1, 2, and 3 were used to determine moisture content (MC), total solids (TS) and the volatile solid (VS) content, respectively.

$$\mathrm{MC} = \frac{(M3-M1)}{M3-M2} \times 100 \qquad \text{Equation 1}$$

$$TS = \frac{(M1-M2)}{M3-M2} \times 100 \qquad \text{Equation 2}$$

$$VS = \frac{(M1-M4)}{M1-M2} \times 100 \qquad \text{Equation 3}$$

where:

M1 = mass (g) of the dried sample + crucible

M2 = mass (g) of the crucible

M3 = mass (g) of the wet sample + crucible and

M4 = mass (g) of the residue + crucible after ignition

Degassing of the inoculum "Cow dung slurry"

In this study, cow dung slurry was used as an inoculum. Filer (2019) highlighted that inoculum is a significant factor for BMP test as it supplies microorganism during the anaerobic digestion process. The inoculum acts as a catalyst and does not influence the biogas produced by the substrate during the anaerobic digestion process. For the degassing process, the water bath (manufactured by: FMH instruments, Cape Town, South Africa) was prepared at 37 °C (mesophilic temperature) and filled with water. The water in the water bath, along with the pre-incubated inoculum, was monitored for 12 days at 37 °C (mesophilic temperature) to facilitate degassing and minimize methane production during the anaerobic digestion process. Anaerobic sludge "cow dung" was stored at ambient temperature for a shorter period at 25 °C as suggested by Elbeshbishy *et al.* (2012). Pinto *et al.* (2025) highlighted cow dung is a waste material with high bioenergy potential for use as inoculum. It has a rich content of organic matter and nutrients. Cow dung also contains a diverse community of anaerobic microorganisms essential for organic matter degradation and biogas production. Furthermore, cow dung poses minimal environmental risks compared to industrial sludge and chemical inoculants.

Anaerobic digestion

The process of anaerobic digestion was carried out using the water bath which was prepared at 37 °C (mesophilic temperature) and filled with water. The experiment was carried out in triplicate. Duran glass vessels (reactor) were filled with 268. 85 (g) degassed inoculum and 25 (g) of substrate "human waste", both weighed using a scale. The mass of the inoculum was calculated according to Equation 4. The reactor bottles were shaken daily to prevent sedimentation and to promote the uniform distribution of the substrate, microorganisms, nutrients, and alkalinity. The volume of biogas was monitored daily for 69 days and measured at 15h00 using a gas analyser (manufactured by: Envirotech, UK: Biogas 5000 series) (Figure 3). The substrate was further characterised for pH, volatile solids reduction and total solids after the 69 days of the anaerobic digestion.



Figure 3: Anaerobic digestion process and the collection of biogas produced

$$M_{ino} = \frac{M_{sub} * VS_{sub} \times 2}{VS_{ino}}$$ Equation 4 (Angelidaki *et al*. 2003)

where:

Mino = mass (g) of the inoculum,

Msub = mass (g) of the substrate,

VSino = the volatile solids content (%) in the inoculum

VSsub = volatile solids content (%) in the substrate.

Results and discussion

The feasibility of biogas production from human feces is contingent upon the substrate variables being well-characterized and maintained within optimal ranges, as unidentified or suboptimal conditions can lead to instability in the anaerobic digestion process (Telo, 2024) . According to Kelif Ibro *et al*. (2024), although any combustible organic waste holds potential for energy generation through anaerobic digestion, only those substrates exhibiting optimal pH, total solids, moisture content, and volatile solids in appropriate proportions are considered suitable for efficient and stable biogas production. Wang (2020) reported that a substrate for biogas production should be analysed for total and volatile solids, alkalinity, and moisture content to mitigate any potential inhibition problems.

Characterization of the substrate "human faeces"

(i) *pH*

In this study, results of the BMP test revealed that the average pH value of human faeces was 6.4, which is within the limits of biogas production as proposed by other researchers. Singh *et al.* (2021:4) indicated that human faeces with a pH value of 7 provides the highest biogas yield. Appels *et al.* (2008:755) as well as Chen *et al.* (2014:1523) also noted that the accumulation of inhibitory compounds such as ammonia and hydrogen affects the pH of the substrate, which prevents biogas production and indicated that the optimal pH range for biogas production is between 6.0 and 8.5. However, Parkin and Owen (1986:867) recommends a range from 6.5-7.6, otherwise, when the pH level increases beyond 9, toxic ammonia (NH3) is formed, preventing methanogenesis during anaerobic digestion (Appels *et al.* 2008:755).

(ii) *Moisture content*

Results of the characterisation of the substrate revealed that the moisture content ranged from 70-72 % with an average of 71.5 %. Singh *et al.* (2021:4) reported that moisture content of human faeces was 84 %, which is higher than cow dung (66 %) and poultry litter (29 %). Adjama *et al*. (2022:2) found the moisture content of human faeces sampled in Sunyani-Ghana to be 79.5 % and Woolley *et al*. (2014:276) reported 78.3 % from the samples collected in Durban, South Africa.

It is important to note that previous studies have identified age and dietary habits as significant factors influencing the moisture content of human feaces. Adjama *et al*. (2022:3) noted that human faeces collected from adults contain more moisture than younger people as they drink more water, while Forsum *et al*. (1990) cited diet as an indicator impacting the moisture content composition of human faeces. This study did not look at the diet of certain age groups, however, it is worth noting that the age of the learners at the sampled schools falls in the range of 6 to 13 years old. Thus, the lower moisture content of the faeces obtained in this study in comparison to other studies (average 71.5 %) could be attributed to the younger age group. Sandra *et al*. (2016:47) stated that high moisture content is a supportive agent of biodegradation and is essential for bacteria to survive. Therefore, the average of the moisture content (71.5 %) recorded in this study suggests a positive indicator of biodegradation for biogas production.

(iii) *Volatile solids*

Volatile solids content is an indicator of potential methane production whereby increased gas generation is directly proportional to the amount of volatile solids found in the raw substrate, which is highly biodegradable (Wang *et al*.2020: 96). Onojo (2013:199) cited that faecal matter is highly biodegradable. Similarly, Singh *et al*. (2021:4) recorded that human faeces recorded 81% wet volatile solids while Rose *et al.* (2015) recorded 92 %. This study reported that the substrate has an average volatile solid value of 82.7 % as supported by Mattocks (Wang *et al.* 2020: 98), the value of (82.7 %) suggests increased gas generation.

(iv) *Total solids*

The total solids content of feedstocks has a significant impact on anaerobic digestion because the higher the total solids content, the more difficult it is to breakdown the organic matter resulting to less production of biogas (Yi, 2014:2). The substrate characterized in this study exhibited a total solids (TS) content of 28.5%, a value considered optimal for anaerobic digestion processes. This measurement also falls within the range of total solids reported in human feaces, as documented by Adjama *et al*. (2022 : 3); Sunyani-Ghana (20.5 %), Forsum *et al*. (1990:177) reported 32.2 % and Rose *et al*. (2015) reported 25–54 %.

Degassing of inoculum "Cow dung slurry"

Although Elbeshbishy *et al*. (2012:18) studied the impact of inoculum pre-incubation and reported no significant difference in methane generation or biodegradability compared to non-incubated inoculum, other researchers have noted the significance of incubated inoculum. Incubation of the inoculum is broadly recommended in literature, since it is a significant variable that impacts the production of methane (Li *et al*. 2013:127; Raposo, 2012:861; Qamaruz-Zaman & Milke, 2008:1). Filer *et al*. (2019:4) recommended the incubation of inoculum for one to five days at mesophilic temperature to degas and decrease the impact of its methane production as outlined in the German guideline for fermentation tests (VDI-Handbuch, 2006). Raposo *et al*. (2012:1444) supported that degassing should be prolonged until there is no significant methane production, with an incubation period of 2-5 days.

However, Li *et al*. (117:2013) reported that pre-incubation of the inoculum can go up to 21 days depending on the inoculum source, especially if the reactor is fed with high content of fats or oils. Angelidaki *et al.* (2009 : 927) observed that extending the incubation period can

facilitate the degradation of residual substrate, thereby enhancing biogas yield. Consistent with this observation, the current study concluded the experiment after 12 days, at which point a plateau in biogas production was achieved, indicating the exhaustion of readily biodegradable material (Figure 4). In addition, Holliger *et al*. (2016:2515) and Abudi *et al.* (2020:887) stated that the recommended optimal inoculum range for pH should be between 7.0- 8.5. Chandra *et al*. (2012:1462) studied the impacts of pH value during anaerobic digestion and found that pH value higher than 8.5 has toxicity effects on the anaerobic digestion. In the present study, the average pH was 7.9, which falls within the optimal range for anaerobic digestion, suggesting that the inoculum used can effectively function as a catalyst in the process.

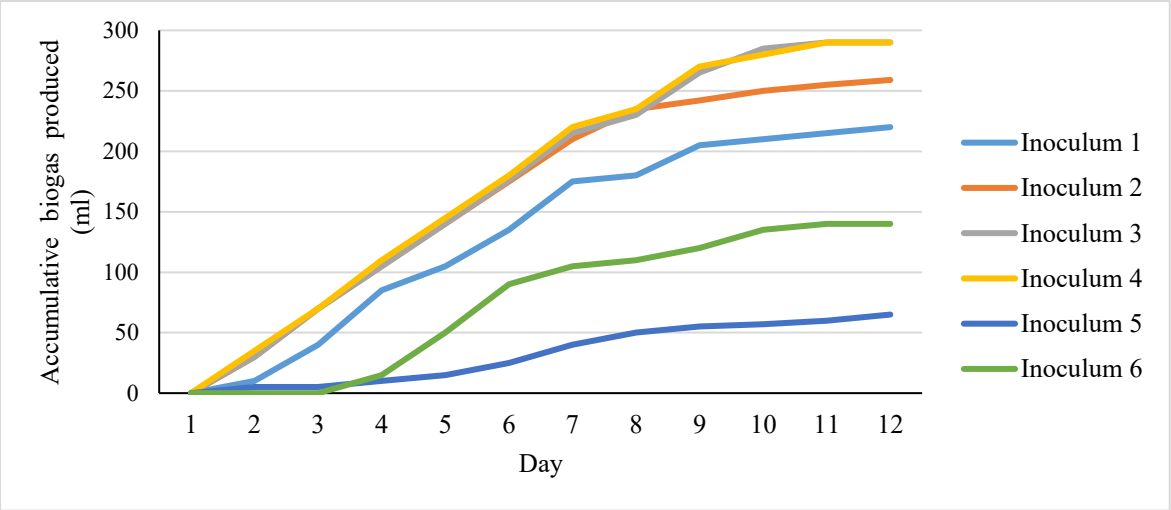


Figure 4: Cumulative biogas production from inoculum "cow dug" slurry

Anaerobic digestion

Dahunsi and Oranusi (2013: 489:492) noted that the anaerobic digestion of human faeces lasted for 60 days, and generated biogas composition containing 58 % methane (CH_4). Poocheera *et al.* (2014: 1105) reported that the methane produced from human faeces was 67.6 % within a 40-day cycle experiment. Raposo *et al.* (2012: 861) argued that the incubation time ranges from 30 to over 100 days, which is highly dependent on the biodegradability of the material. In this study, the experiment was conducted over a period of 69 days, with a substantial volume of biogas (1, 720 mL) produced between days 3 and 10.

However, methane production gradually declined from day 11 to day 17, decreasing from 1, 780 mL to 946 mL and a steady decline in biogas production was observed starting from day 20, with minimal to no biogas generated between days 62 and 69 (Figure 5). These results are similar to the findings by Adjama *et al.* (2022:3) which reported an increase in methane

production from day one to five (2, 296 ml) and a decrease from day six to ten with methane production from 2, 296 mL to 1 749 mL. From day 11 to 20 a slight similarity of biogas production was reported (1 500 mL) and a gradual decrease up to day 30.

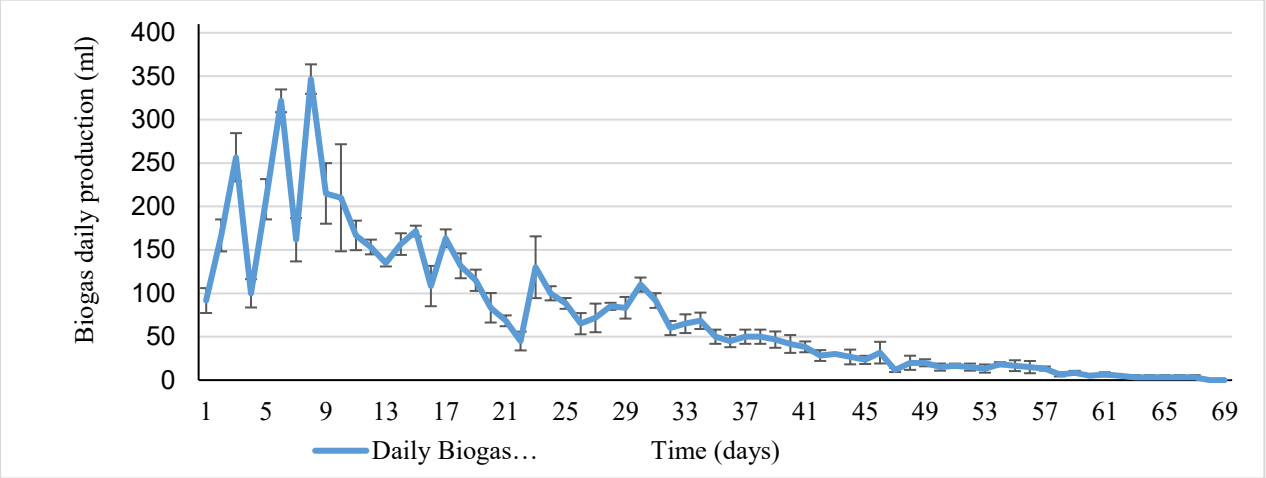


Figure 5: Daily biogas production from the "human faeces" substrate

The continuous decrease of biogas from the 20th day could be explained by the decrease in volatile solids (48.4 %) and the decrease of nutrients contained in the faecal matter over time. This decline corresponds to a reduction in the population of methanogenic bacteria, which consequently leads to decreased methane production (Andriani *et al*., 2015:219; Azman *et al.,* 2015:2523; Nopharatana *et al*., 2007:595). Notably, the volatile solids of the human faeces in this study were recorded at 82.7 % before anaerobic digestion (AD) and had reduced to 48. 4 % after the process, which is within the acceptable range as suggested in other studies, for example, Novak *et al.* (2011:618) reported 50 % of volatile solids reduction while Grűbel *et al.* (2013:349) reported 44 % of volatile solids reduction. The acceptable range of volatile solid reduction after the AD process is between 45-50 %, which is a metric used to assess the effectiveness of the process. The biogas generated was monitored and collected up to its minimal point (Figure 5). Therefore, the observations from this study align with previous research indicating that a portion of the organic material in the final phase of biogas production is microbiologically non-degradable, resulting in cessation of biogas generation (Tyagi & Lo, 2011:215*;* Weiland, 2010:846; Chen *et al.,* 2007:683). This explains the gradual decline in biogas production observed from day 62 onward.

Cumulative biogas

The daily biogas production was monitored and recorded to calculate the corresponding cumulative biogas volume (mL). Comparatively, this study observed cumulative biogas of

5, 280 mL during the 69-day cycle, while the study by Singh *et al (*2021:5) observed 6,720 mL for a period of 52 days and Poocheera *et al.* (2014:1103) reported 1865 mL over a period of 40 days. Figure 6 illustrates that the pre-incubation successfully minimized gas production from the inoculum, which served as a catalyst in the process. This step is crucial to ensure that subsequent biogas measurements primarily reflect substrate degradation rather than inoculum activity (Figure 4). This observation is further supported by the degassing results, which show that a plateau in biogas generation was reached, indicating the stabilization of the anaerobic digestion process. Therefore, the inoculum did not contribute to the daily biogas production.

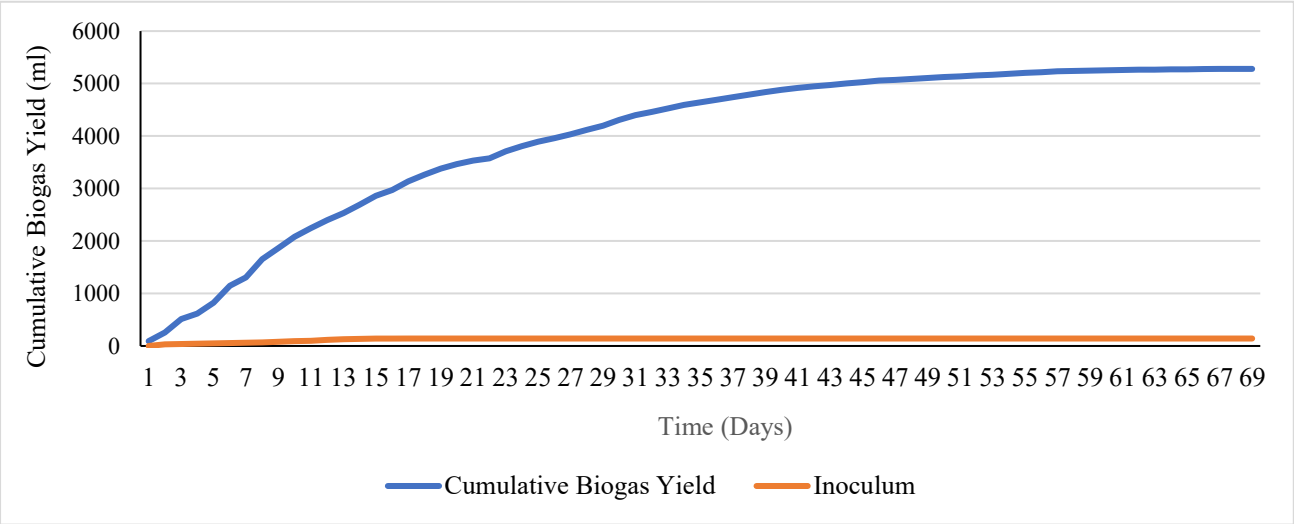


Figure 6: Cumulative biogas production from substrate "human faeces"

Methane content

As noted in literature, the composition of methane in biogas ranges between 50-70 %, (Li *et al*. 2019: 11567; Yadav & Hesse1981) while Ezekoye *et al.* (2011:53) suggest 40-70 %. Several empirical studies have reported different methane content produced from human faeces. Cook (2010) studied the generation of biogas from human faeces and reported 60 %, Jha (2005) reported 60 %, Duan *et al*. (2020:1) observed 50 % and Khanto and Banjerdkij (2013: 236) recorded 48 % of methane (CH_4) composition.

In this study, from the three sets of substrates, an average methane count of 54 % was recorded. Several studies have highlighted factors that have been attributed to the variations in methane composition. Duan *et al*. (2020:1) reported that a methane content reduction to 50 % was linked to elevated ammonia concentrations resulting from high pH levels, which inhibited reactor performance. Similarly, Khanto and Banjerdkij (2013: 236) and Rose *et al.* (2015:1827) highlighted that the presence of non-biodegradable material, largely influenced by an

individual's diet, also adversely affects reactor efficiency. In this study, the pH level after the AD not attributed to the pH level cannot be attributed to pH-related inhibition.

In addition, Emetere *et al.* (2022: 4) reported that the microbial populations responsible for methanogenesis in human faeces are influenced by the individual's diet. Vanderhaeghen *et al*. (2015:1) examined faecal samples from eight individuals and found that only five harbored methanogens. Their study also revealed that 65 % of children and 89 % of adults carry methanobacteriales, highlighting age-related differences in methanogenic microbial colonization. Notably, this study collected faecal samples at a school with learners between the ages of 6-13 years. As reported by Vanderhaeghen *et al.* (2015:1), only a fraction of children (i.e., 65 %) carry methanobacteriales in their faeces which is responsible for methane generation, and this explains the 54 % methane content reported in this study.

Potential biogas produced from human faeces

From the study experiment, the cumulated biogas produced from 25 g of faeces was 0,00528 m^3 in 69 days and the maximum production rate per day was 0,000346 m^3. To calculate the sustainability usage of the cumulated biogas produced from the human faeces substrate collected from the school, the following assumptions were adopted:

(i) Previous studies have reported individual faeces production to be an average of 400 g (Weisberger, 2018), 520 g (Torondel, 2010), and 796 g which includes adults above 18 years of age (Rose *et al*. 2015:1833). This study adopted the daily average of 400 g of faeces reported by Weisberger (2018).

(ii) Based on the study population, one learner is likely to produce 0, 129 m^3 of gas per day and the total learners (483) from the sampled school are likely to produce 62,66 m^3.

(iii) Considering the calorific value of 22 MJ/m^3 and the mega joules unit of 3.60 MJ, the energy yield of 62,66 m^3 gas produced from human faeces is 1,378.52 MJ/day or 382,92 kWh/day. Therefore, a biogas generator using 382.92 kWh can run for approximately three days.

The Limpopo primary schools' nutritional planned menu for the learners is depicted in table 3. For cooking, a normal gas burner uses 2 kWh in one hour when operating at maximum output (Electric Ireland: 2023). For lighting, Kristofferson and Bokalders (2013) noted that 1 m^3 can operate a 60–100 W bulb for six hours and generate 1.25 Kilowatt hours of electricity. Therefore, the above-mentioned nutritional meals can be prepared by the daily amount of biogas produced by the learners (62.66 m^3) as 2 m^3 can burn for approximately 1 hour. Tables 2 and 3 indicate the amount of biogas required to prepare the nutritional meals and the energy which could be used for lighting. From the daily production of 62, 66 m^3 the maximum energy needed for cooking is 9 m^3 on Tuesday and the minimum being 2 m^3 on Wednesday.

Table 2: Biogas usability and its equivalent within the school

Menu prepared	**Duration for preparing**	**Biogas needed (m^3)**	**Duration of combustion**
Beans	2 hours	4	2 hours
Fish	30 minutes	1	30 minutes
Samp	2 hours	4	2 hours
Butter nut	30 minutes	1	30 minutes
Cabbage	30 minutes	1	30 minutes
Thick maize porridge	1 hour	2	1 hour
Rice	1 hour	2	1 hour
Soya mince	30 minutes	1	30 minutes

Table 3: Biogas required (m^3) for preparing the nutritional meals and lighting

Day	**Biogas for cooking**	**Biogas for lighting**	**Total**	**Daily energy surplus**
Monday	4	40	44	18.66
Tuesday	9	40	49	13.66
Wednesday	2	40	42	20.66
Thursday	4	40	44	18.66
Friday	4	40	44	18.66

The school has 40 (32W) fluorescent tube lights which require 40 m^3 and are selectively used, primarily on overcast days or when required. The school does not illuminate the school during the night because it relies on the community Apollo lights for lighting.

After cooking and lighting needs are met, the daily surplus biogas is estimated to range from approximately 13.66 m^3 to 20.66 m^3. This surplus can be diverted to meet other energy demands within the school or sold to local communities, thereby generating additional revenue for the

institution. Furthermore, the school stands to benefit economically from reduced operational expenses, as significant costs are currently allocated to electricity and cooking fuels such as firewood or gas. On-site energy production through biogas generation can lead to substantial cost savings over time. In addition to energy benefits, the anaerobic digestion process produces a nutrient-rich byproduct known as digestate. This digestate can be utilized as fertilizer for school gardens, promoting food security while reducing departmental expenditures related to sourcing vegetables for the school feeding program. The practice of biogas generation from human faeces collected from the EVIP toilets can be regarded as sustainable based on the biogas produced per day (66.62 m^3). Notably, for a continuous biogas generation process, it is critical that the human faeces feedstock is introduced to the anaerobic digestion process daily, as reported in this study, that the significant amount of biogas is produced between the 3rd and the 10th day.

Conclusion

The utilization of human faeces for biogas production presents a dual benefit: it generates renewable energy while simultaneously mitigating significant environmental challenges associated with unmanaged human waste disposal. In South Africa, where dysfunctional sewage treatment plants contribute to the pollution of approximately 80 % of freshwater resources, this approach offers a sustainable solution to pressing ecological concerns. Moreover, biogas generation from human waste aligns with national efforts to address the ongoing energy crisis and reduce dependence on fossil fuels, particularly in the context of persistent load shedding and increasing energy demand.

The findings of this study demonstrate that human faecal matter is a viable substrate for biogas production, capable of generating substantial energy for cooking and lighting through the anaerobic biodegradation of organic material by methanogenic bacteria. To fully realize this potential, it is imperative to foster strong awareness and behavioural change among potential users, thereby facilitating the adoption of biogas technology as a sustainable energy alternative. Therefore, harnessing human faeces through anaerobic digestion not only contributes to energy security and environmental protection but also offers socioeconomic benefits, making it a strategic component of South Africa's sustainable development agenda.

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Consent and Ethics

Consent was given by the human participants

The ethical guidelines of North-West University's Mafikeng Campus were followed in conducting this study. Ethical clearance was obtained from the Faculty of Natural and Agricultural Sciences Research Committee with the ethics number **01783-20-A9**

Consent to publish

Not applicable

References

Abudi, Z.N. Hu, Z. Abood, A.R. Liu, D. & Gao, A. 2020. Effects of alkali pre-treatment, total solid content, substrate to inoculum ratio, and pH on biogas production from anaerobic digestion of mango leaves. *Waste and Biomass Valorization*, 11: 887-897.

Adjama, I. Derkyi, N.S.A. Uba, F. Akolgo, G.A. & Opuko, R. 2022. Anaerobic Co-Digestion of Human Feces with Rice Straw for Biogas Production: A Case Study in Sunyani. *Modelling and Simulation in Engineering*, 2022(1): 2-3. https://doi.org/10.1155/2022/2608045

AfriForum. (2018). AfriForum releases reports on drinking water, sewage and landfill sites. Accessed 16 May 2020.

Andriani, D. Wresta, A. Saepudin, A. & Prawara, B. 2015. A review of recycling of human excreta to energy through biogas generation: Indonesia case. *Energy Procedia*, 68: 219-225.

Angelidaki, I. Alves, M. Bolzonella, D. Borzacconi, L. Campos, J.L. Guwy, A.J. Kalyuzhnyi, S. Jenicek, P. & Van Lier, J.B. 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. *Water Science and Technology*, 59(5):927-934.

Appels, L. Baeyens, J. Degrève, J. & Dewil, R. 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science*, 34(6):755-781.

Azman, S. Khadem, A.F. Van Lier, J.B. Zeeman, G. & Plugge, C.M. 2015. Presence and role of anaerobic hydrolytic microbes in conversion of lignocellulosic biomass for biogas production. *Critical Reviews in Environmental Science and Technology*, 45(23): 2523-2564.

Booysen, M.J. Samuels, J.A. & Grobbelaar, S.S. 2021. LED there be light: The impact of replacing lights at schools in South Africa. *Energy and Buildings*, 235:110736.

Chandra, R. Takeuchi, H. & Hasegawa, T. 2012. Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. *Renewable and Sustainable Energy Reviews*, 16(3): 1462-1476.

Chang, Z., Long, G., Zhou, J.L., & Ma, C. 2020. Valorization of sewage sludge in the fabrication of construction and building materials: A review. *Resources, Conservation and Recycling*, 154,104606. https://doi.org/10.1016/j.resconrec.2019.104606

Chen, Y. Jiang, S. Yuan, H. Zhou, Q. & Gu, G. 2007. Hydrolysis & acidification of waste activated sludge at different pHs. *Water Research*, 41(3): 683-689.

Cook, P.A. 2010. Design of a Household Human Waste Bioreactor. *Journal of American Society of Research Institute*, 69(99): 1

Dahunsi, S.O. & Oranusi, S.U. 2013. Co-digestion of food waste and human excreta for biogas production. *British Biotechnology Journal* 3(4): 485-499.

Damm, O. & Triebel, R. 2008. A synthesis report on biomass energy consumption and availability in South Africa. *GTZ (Gesellschaft für Technische Zusammenarbeid) Programme for basic energy and conservation (ProBEC).* ProBEC and LHA Management Consultants, Pretoria, South Africa: 32

Duan, G.Y. Ren, Y. Tang, Y. Sun, Y.Z. Chen, Y.M. Wan, P.Y. & Yang, X.J. 2020. Improving the Reliability and Accuracy of Ammonia Quantification in Electro-and Photochemical Synthesis. *ChemSusChem*, 13(1): 88-96. doi: 10.1002/cssc.201901623.

Edokpayi, J.N. Durowoju, O.S. & Odiyo, J.O. 2018. Assessment of heavy metals in landfill leachate: a case study of Thohoyandou landfill, Limpopo Province, South Africa. *Heavy Metals*, 16: 214-227.

Elbeshbishy, E. Nakhla, G. & Hafez, H. 2012. Biochemical methane potential (BMP) of food waste and primary sludge: influence of inoculum pre-incubation and inoculum source. *Bioresource Technology Journal, 110*:18-25.

Emetere, M.E. Chikwendu, L. & Afolalu, S.A. 2022. Improved biogas production from human excreta using chicken feather powder: a sustainable option to eradicating poverty. *Global Challenges*, 6(6): 2100117.

Emetere, M.E. & Pindar, H., 2019, September. Human waste biogas production: Processes and Utilization. In *IOP Conference Series: Earth and Environmental Science*, 331(1): 012049.

Ezekoye, V.A. Ezekoye, B.A. & Offor, P.O. 2011. Effect of retention time on biogas production from poultry droppings and cassava peels. *Nigerian Journal of Biotechnology*, 22: 53-59.

Ferry, A. & Giljova, S. 2015. Biogas potential in selected wastewater treatment plants. *South African Local Government Association and German Cooperation:* Deutshe Zusammenarbeit. South Africa: p. 1-38

Filer, J.; Ding, H.H.; & Chang, S. 2019. Biochemical Methane Potential (BMP) Assay Method for Anaerobic Digestion Research. *Water* 11, 921. https://doi.org/10.3390/w11050921

Forsum, E. Eriksson, C. Göranzon, H. & Sohlström, A. 1990. Composition of faeces from human subjects consuming diets based on conventional foods containing different kinds and amounts of dietary fibre. *British Journal of Nutrition (BJN)*, 64(1):171-186.

Grűbel, K. Machnicka, A. & Wacławek, S. 2013. Impact of alkalization of surplus activated sludge on biogas production. *Ecological Chemistry and Engineering*, 20(2):343-351.

Harder R., Wielemaker R., Larsen T.A., Zeeman G., & Öberg G. 2019. Recycling nutrients contained in human excreta to agriculture: pathways, processes, and products. *Critical Reviews in Environmental Science and Technology*, 49:695–743. doi: 10.1080/10643389.2018.1558889.

Herbig, F. J. W., & Meissner, R. 2019. Talking dirty - effluent and sewage irreverence in South Africa: A conservation crime perspective. *Cogent Social Sciences*, 5(1). https://doi.org/10.1080/23311886.2019.1701359

Khanto, A. & Banjerdkij, P. 2013. Methane fermentation of night soil and food waste mixture. *Journal of Clean Energy Technologies*, *1*(3): 234-37.

Kell, C.J.K. 2019. *Anaerobic co-digestion of fruit juice industry wastes with lignocellulosic biomass* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Kristoferson, L.A. & Bokalders, V. 2013. Renewable energy technologies: their applications in developing countries. Great Britain, British Library: pp1-338

Li, Y. Feng, L. Zhang, R. He, Y. Liu, X. Xiao, X. Ma, X. Chen, C. & Liu, G. 2013. Influence of inoculum source and pre-incubation on bio-methane potential of chicken manure and corn stover. *Applied Biochemistry and Biotechnology*, 171 :117-127.

Ma, G., Chen, Y., & Ndegwa, P. 2022. Anaerobic digestion process deactivates major pathogens in biowaste: A meta-analysis. *Renewable and Sustainable Energy Reviews*, 153, 111752 https://doi.org/10.1016/j.rser.2021.111752

Manyi-Loh, C.E. Mamphweli, S.N. Meyer, E.L. Okoh, A.I. Makaka, G. & Simon, M. 2015. Investigation into the biogas production potential of dairy cattle manure. *Journal of Clean Energy Technologies*, 3(5): 326-331

Mattocks, R. 1984. Understanding biogas generation. *Volunteers in Technical Assistance,* 6(84) :1-23

Nopharatana, A. Pullammanappallil, P.C. & Clarke, W. P. 2007. Kinetics and dynamic modelling of batch anaerobic digestion of municipal solid waste in a stirred reactor. *Waste Management*, 27(5):595-603.

Parkin, G.F. & Owen, W.F. 1986. Fundamentals of anaerobic digestion of wastewater sludges. *Journal of Environmental Engineering*, 112(5):867-920

Pinto, C.C., Paes, J.L., Gomes, A.D.S., Cecchin, D., Oliva, I.F., Valadão, R.C. and Sant'Anna, V.R.D.S., 2025. Anaerobic Co-Digestion of Cattle Manure and Sewage Sludge Using Different Inoculum Proportions. *Fermentation*, *11*(7), p.373.

Qamaruz-Zaman, N. & Milke, M. 2008. Digested sewage sludge as seed for batch test of anaerobic biodegradability. University of Canterbury:1-11.

Raposo, F. De la Rubia, M.A. Fernández-Cegrí, V. & Borja, R. 2012. Anaerobic digestion of solid organic substrates in batch mode: an overview relating to methane yields and experimental procedures. *Renewable and Sustainable Energy Reviews*, 16(1):861-877.

Remigi, E.U. & Buckley, C.A. 2006, Co-Digestion of High-Strength/Toxic Organic Effluents in Anaerobic Digesters at Wastewater Treatment Works. Pretoria, South Africa: *Water Research Commission*, 1-387

Rose, C. Parker, A. Jefferson, B. & Cartmell, E. 2015. The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Critical Reviews in Environmental Science and Technology*, 45(17):1827-1879.

Sandra,K. Namasaka.K. Muthoni,K.M. & Siteti.M.C. 2016. Physicochemical characteristics and Biodegradability of organic fraction of solid wastes generated in Eldoret Municipality, Kenya. *Research Journal of Environmental and Earth Sciences* 8(3):1-

Singh, S. Hariteja, N. Sharma, S. Raju, N.J. & Prasad, T.R. 2021. Production of biogas from human faeces mixed with the co-substrate poultry litter & cow dung. *Environmental Technology and Innovation*, 23:1-5

Telo, D. K., Yigezu, Z. D. (2025). Production and Characterization of Biogas from Cow Dung, Poultry Manure and Their Co-digestion. *American Journal of Environmental and Resource Economics*, *10*(3), 82-96. https://doi.org/10.11648/j.ajere.20251003.11

Torondel, B. 2010. Sanitation Ventures Literature Review: on-site sanitation waste characteristics. *London, UK: London School of Hygiene and Tropical Medicine*,1-30

Tyagi, V.K. & Lo, S.L. 2011. Application of physico-chemical pretreatment methods to enhance the sludge disintegration and subsequent anaerobic digestion: an up to date review. *Reviews in Environmental Science and Bio/Technology*, 10:215-242.

Vanderhaeghen, S. Lacroix, C. and Schwab, C. 2015. Methanogen communities in stools of humans of different age and health status and co-occurrence with bacteria. *Federation of European Microbiological Societies* (*FEMS) Microbiology Letters*, 362(13):1-92

Wang, Z. Jiang, Y. Wang, S. Zhang, Y. Hu, Y. Hu, Z.H. Wu, G. & Zhan, X. 2020. Impact of total solids content on anaerobic co-digestion of pig manure and food waste: Insights into shifting of the methanogenic pathway. *Waste Management*, 114:96-106.

Weisberger, M. 2018 How Much Do You Poop in Your Lifetime? https://www.livescience.com/61966-how-much-you-poop-in-lifetime.html Accessed 3 April 2020

Weiland, P. 2010. Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology*, 85:849-860.

Woolley, S.M. Cottingham, R.S. Pocock, J. & Buckley, C.A. 2014. Shear rheological properties of fresh human faeces with different moisture content. *Water SA*, 40(2):273-276.

Yi, J. Dong, B. Jin, J. & Dai, X. 2014. Effect of increasing total solids contents on anaerobic digestion of food waste under mesophilic conditions: performance and microbial characteristics analysis. *PloS one*, 9(7):2548.

Miezah, K., Obiri-Danso, K., Kádár, Z., Fei-Baffoe, B., & Mensah, M. Y. 2015. Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. *Waste Management*, 46, 15–27. https://doi.org/10.1016/j.wasman.2015.09.009

Moya, D., Aldás, C., Jaramillo, D., Játiva, E., & Kaparaju, P. 2017. Waste-To-Energy Technologies: An opportunity of energy recovery from Municipal Solid Waste, using Quito - Ecuador as case study. *Energy Procedia*, 134, 327–336. https://doi.org/10.1016/j.egypro.2017.09.537

Heshmati, A. 2017. A review of the circular economy and its implementation. *International Journal of Green Economics*, 11(3/4), 251. https://doi.org/10.1504/ijge.2017.10010876

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., & Lotti, L. 2019. The Circular Economy: What, Why, How and Where. Managing environmental and energy transitions for regions and cities. Managing Environmental and Energy Transitions for Regions and Cities, 1–89. Retrieved from https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf. Accessed on 16 August 2024

Deloitte. 2017. SE4ALL Action Agenda. Government of Malawi.

Drożyner, P., Rejmer, W., Starowicz, P., Klasa, A., & Skibniewska, K. A. 2013. Biomass as a renewable source of energy, *Technical Sciences,* 16(3), 211–220.

Xu, P-P., Sun, K., Du, J., Xie, G., Xing, D., & Liu, B-F. 2023. Biochar prepared from human feces (HFBC) as a promoter in biohydrogen production using simulated feces as substrate, *Chemical Engineering Journal*, 461, 142074. https://doi.org/10.1016/j.cej.2023.142074

Zeng, W., Qiu, J., Wang, D., Wu, Z., & Lintong He, .L. 2022. Ultrafiltration concentrated biogas slurry can reduce the organic pollution of groundwater in fertigation, *Science of the Total Environment*, 810, 151294. https://doi.org/10.1016/j.scitotenv.2021.151294.