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Experimental evaluation of fresh human feces biogas and compost potential: Evidence for circular economy from waste streams in Ethiopia

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ABSTRACT

Biogas toilets are one of the most resource-efficient sanitation technologies. The technology has dual purposes of generating energy and stabilizing waste-producing biofertilizers. In Ethiopia, knowledge of human feces' energy potential is limited to optimize the development of biogas toilet facilities. Therefore, this study was aimed to evaluate the biogas and biofertilizer potential of human feces in Jimma City, Ethiopia, which may contribute to the development of sustainable sanitation technologies. The study was lab-based experimental design. In the lab-scale batch experiment, fresh human excreta samples were collected using a urine diversion raised toilet. Using ultimate and proximate laboratory analyses, the theoretical yield of biogas was predicted. Then a series of anaerobic digestion batch experiments were conducted to determine the practical energy yield. The bio-fertilizer potential of human feces was determined by analyzing the nutrient contents of human feces. The findings of this study showed that the bio-methane yield from the experimental results has a mean of 0.393 $m^3\ kg^{-1}$, which is 14.16 MJ kg^{-1}. The *bio-methane* meter cube per capita per head per year were 28.71 (28.03–29.27) from the experimental result and 45.26 for the theoretical yield of methane. In this study, the bio-fertilizer potential of human feces was evaluated using nutrient analysis, specifically the NPK (nitrogen, phosphorus, and potassium). Accordingly, human feces contain potassium (2.29 mg kg^{-1}), phosphorus (1.12 mg kg^{-1}), and nitrogen (3.71 mg kg^{-1}). This finding suggests the bio-methane potential of human feces can be used for energy recovery and alternative sanitation options, providing a positive remedy for the sanitation crisis in urban settings.

1. Introduction

Lack of safe sanitation is attributed to the transmission of many diseases, including those caused by human excreta (fecal-oral diseases) [1]. Untreated human excreta are the main cause of environmental degradation, such as surface and groundwater contamination, soil contamination, and insect nuisances, particularly in cities [2,3]. Despite the importance of sanitation in disease prevention and poverty reduction, large proportion of the world's population lacks access to sanitation services. According to 2019

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United Nations report, an estimated 775,000 people die each year as a result of poor water, sanitation, and hygiene worldwide [4]. Investing in sanitation reduces ill health-related poverty and mortality significantly, with a USD 1 investment resulting in 5.5 USD reduction in health-care costs and a reduction in premature death [5].

In 2020, 46 % of the global population (3.5 billion people) did not have access to safely managed sanitation services; over 1.7 billion people did not have basic sanitation services; and 494 million people practice open field defecation, which increases the risk of fecal contamination in the environment [6]. Urban environment is more vulnerable to contamination resulting in poor sanitation access in less developed countries [7]. This lack of access has created a huge gap in less developed countries, particularly among the urban poor, and with the urban population expected to rise to 6.7 billion by 2050 [8], life in urban Africa is becoming increasingly precarious in terms of sanitation. Furthermore, almost one-third of urban people live in urban slum areas, and more than 90 % of urban slums are found in low-income countries [9].

According to various studies, Ethiopia is one of the sub-Saharan African countries with the lowest sanitation coverage [4,10]. The primary source of contamination in the urban environment is poor management of human excreta [11]. Human excrement from uncontained household sanitation facilities in urban areas frequently ends up in open drains. The majority of excreta in drains goes untreated, presenting a high-risk fecal exposure pathway [7].

In areas with low sanitation access in low-income countries, adopting new sanitation platforms is emerging as a solution [12,13]. The view is that human waste can be turned into a resource as a sustainable sanitation alternative. It involves resource recovery from human excrement using acceptable, sustainable technology and environmentally appropriate waste recycling to conserve natural resources and human health [14]. Sanitation options such as compost toilets and biogas toilets have recently received attention as viable alternatives to sustainable sanitation in African cities [15–18]. However, the use of such alternatives as sanitation options in Africa is not at an advanced stage, and there is still a large potential for its development.

Biogas technology is a renewable energy source with numerous application [15,19,20]. It includes anaerobic digestion (AD) of any kind of organic waste, including human excreta [21]. AD is the process of decomposing organic matter and producing CH_4, CO_2, and other gases in the absence of oxygen [22]. AD biogas can be used for cooking, heating, or energy generation [23]. In urban areas, biogas toilets are thought to be the best option. The rationale is that large areas of land are not required, nutrient requirements are minimal, and methane and carbon dioxide are obtained as end products [24].

Human feces are byproducts of body processes and contain water, protein, undigested lipids, polysaccharides, bacterial biomass, ash, and other organic material [22,25]. Co-digestion or co-composting allows for higher-quality biogas or compost production while also helping with long-term waste management [26,27]. Excreta has been shown to have good fertilizing potential, providing essential plant nutrients and organic matter [28,29]. Digested sludge can be used as fertilizer on farmland without further treatment. This is due to the microbial decomposition of the waste matter in the biogas reactors that act as treatment. In biogas reactors, acetic acid-forming (acetogenins) and methane-forming (methanogens) bacteria are among the microorganisms that affect anaerobic digestion. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four biological and chemical steps of anaerobic digestion [30].

The efficiency of biogas production from waste depends on the feedstock's holding temperature as well as the pH and chemical composition of waste. The temperature in the biogas reactor influences the growth of microorganisms that aid in waste digestion. There are three temperature ranges to consider: psychrophilic, mesophilic, and thermophilic [31]. Higher temperatures give a faster rate over a shorter period, resulting in a higher gas yield. Between 25 °C and 45 °C, the solubilization rate is quite high, ranging between 62.2% and 72.7% [32,33]. The other important factor is the pH of the digester as an operational parameter [34,35]. It has direct impact on the growth and metabolism of microorganisms [36]. The activity of methane bacteria is inhibited at pH levels below 6.5 [37]. Additionally, the chemical composition of waste has a significant impact on the amount of methane produced. Different studies suggest estimating the biogas potential of waste using different methods. One of the methods using theoretical yield estimation is the stoichiometric calculation of the products from the anaerobic breakdown of a generic organic material's chemical composition [38]. The other is based on experimental measurements of the gas yield. In the theoretical yield estimation, the ultimate (elemental) analysis is the chemical properties, which consist of carbon content, oxygen content, hydrogen content, nitrogen content, and sulfur content. The proximate analysis (physical parameters) is based on moisture content, ash content, volatile matter, and fixed carbon [39]. The amount of CH_4 that can be created from organic material during the anaerobic digestion process is related to the amount of converted COD in the substrate [40]. According to *stoichiometry*, CH_4 has a COD of 2 mol (=64 g of COD) of oxygen per mole. Since no oxidation by atmospheric O_2 can occur, the biodegradable COD from the substrate can be preserved in the end products [41].

Literature has shown how to treat various organic solid wastes with anaerobic digestion as well as to forecast the bio-methane potential of food waste, municipal solid waste, and cow dung. Few studies have been carried out on the characterization of human excrement [42,43]. In the case of waste treatment, biogas production is the most practical, feasible, and cost-effective way for society to treat waste [27,44]. Additionally, it helps with better nutrient management, which also includes the recirculation of nutrients from human excreta to agricultural inputs for food production [45]. Furthermore, accurate estimates of biogas potential aid in the development of anaerobic digestion technologies for waste treatment, including human excreta. However, there is limited information that shows the biogas potential of human feces specific to the Ethiopian context. Therefore, this study aimed to evaluate biogas (bio methane) and compost potential of human feces in the case of Jimma town, which aids in the design of alternative sanitation technology in urban Ethiopia. Jimma town is located 352 km from Addis Ababa. The town has an estimated total population of 195,228 residing in 17 kebeles (small administrative villages) with an estimated 40,450 households. The town is located at 7° 40′ 24.47″ N latitude and 36° 50′ 4.95″ E longitude [46]. Safely managed sanitation is available to only 13 % of households in the town, and this access level was much lower in the town's urban slums [47]. Recent findings show that sanitation technology options are limited to pit latrines, which are not supported by the current urban expansion and land use [48]. The evidence from this study may contribute to the urban sanitation sector and stakeholders pooling evidence of alternative circular economies in the sanitation sector to develop biogas toilets as an alternative sanitation technology.

2. Materials and methods

2.1. Study design and period

Laboratory-based experimental (batch experiment) study was conducted. The sample analysis was conducted in four laboratories in Ethiopia. The sampled human feces were characterized using ultimate and proximate analysis at Jimma University's Environmental Health Science & Technology Laboratory. The bio-methane AD batch experiment was done at Jimma University's Animal Nutrition and Soil Laboratories. Finally, the nutrient content of human feces was measured at the Ethiopian Conformity Assessment Enterprise laboratory in Addis Ababa. The study was conducted from May 20, 2022, to August 15, 2022.

2.2. Experimental setup

In this study, urine-diversion, raised-dry toilet was constructed (supplementary material S1). It was installed in a public place in Bossa Addis Kebele in Jimma town. The technology was designed to allow easy handling of human feces, separated using urine divert slab as a user interface. The human feces were collected in a collection box, and the urine was collected in a separate jar. It was developed in such a way as not to expose the users and researchers during handling. It was protected against fly exposure and odor reduction, and cleaned regularly by the research team to attract the users to drop their feces for the experiment. The toilet was designed to be comfortable for both males and females considering the socio-cultural and economic conditions, free from odor and fly nuisance, and installed with eco-friendly waste recycling technology. The feces collected using these technologies was used in this study's experimental work.

The anaerobic digestion of excreta (feces) was performed using the biochemical methane potential (BMP) test. The total volume of methane produced during the digestion period, per amount of feces added, was recorded (supplementary material S2). The BMP protocol was used, in which known amount of feces was added to 250-mL serum bottles (supplementary material S1). The bottles were gassed with N_2 for 3 min to eliminate the oxygen and sealed immediately using rubber septa and aluminum crimp caps. Once sealed, the bottles were placed in an incubator and maintained at a constant mesophilic temperature of 35 °C. Throughout the incubation period, the bottles were manually shaked every day. The duration of the BMP assay was determined when the cumulative biogas curve reached the area of stability (estimated to be 28–30 days). Testing the amount of methane was done every other day for 28 days, or until the amount of methane produced was 1 % of the total methane obtained. The concentration of gas was measured using a multi-gas monitor type 1302 (*Bruel & Kjaer multi-gas monitor type 1302*). The proximate and ultimate analyses were determined using APHA Standard Methods (APHA, 2005). The proximate analysis includes moisture content, volatile matter, ash content, and fixed carbon. An ultimate analysis includes total nitrogen, total sulfur, organic carbon, COD, and BOD. The microwave plasma-atomic emission spectrometer (MP-AES method: BCTL/100 MP-AES) was used to determine the nutrient composition of the sample.

2.3. Sample collection, preparation, and storage

The samples were collected from urine-diversion-raised-dry toilet. During one day of feces sample collection, 30 community members from Bossa Addis kebele in Jimma town used the test toilet. Before the study, the participants signed written informed consent. Information about the participants' diets was assessed using lists of questions. Since the toilet was placed in an area that lacks a toilet (usually, open defecation is practiced), participants were invited to use the test toilet and voluntarily participated in the study. Adults (aged 18 and more) used the test toilet just to get an easy understanding of how to use the new slab. The majority of participants ate grains: 'enjera and wot'; bread, pasta, and macaroni; 'bula' ; potato (dinch beduqo); tomato; meat in a few respondents; milk and milk products; vegetables; fruits; kolo (bokolo xibsi); coffee; and few participants used khat.

The collected sample was quickly deposited in a container after mixing with sticks in the test toilet storage tank, and the proximity analysis was conducted over the collection days, within two days. The collected feces were dried at 105 °C for 24 h in a dry oven. Then the dry fecal matter was stored at −20 °C for a maximum of two weeks until the laboratory analysis was performed. At the same time, the work for the AD batch experiment was performed. These samples were properly and carefully labelled, sealed, and transported to the laboratory of Department of Environmental Health Sciences and Technology at Jimma University.

2.4. Proximate and ultimate analysis

The proximate analysis provides the weight percent of moisture, combustibles (composed entirely of volatile matter and fixed carbon), and ash in the biomass sample [49]. Herein, the fixed carbon is the portion of combustible residue left after the removal of moisture, ash, and volatile materials from feces. Thus, 5 g of the sampled feces were prepared in three replicates after homogenizing. The determination of moisture content, volatile, ash, and fixed carbon content of the sample was done using ASTM standard methods for chemical analysis of wood charcoal (D1762–84, 2007). The precision of the measurement was evaluated by repeating each of the three triplicate samples. It was conducted using an elemental analyzer (Model: Vario EL III Element Analyzer; Elementary Co., Germany). Similarly, to evaluate the precision of measurement, each sample was carried out in triplicate.

2.5. Theoretical methane yield estimation

In this study,the Buswell equation (Equation (1)) was used, which provides a stoichiometric calculation on the products from the anaerobic breakdown of a generic organic material of chemical composition $C_cH_hO_oN_nS_s$ [38]

$$BMP = \frac{22.4\left(\frac{c}{2}+\frac{h}{8}-\frac{o}{4}-\frac{3n}{8}\right)}{12c+h+16o+14n}......\&hellip \qquad 1$$

Equation (1): Buswell equation for theoretical maximum gas production estimation.

BMP is the normalized volume of methane (ml/g). The molar proportion of carbon (c), hydrogen (h), oxygen (o), nitrogen (n), and sulfur (s) in biomass's organic fraction is determined using the molar proportion of its elements. The Buswell equation is used to estimate the theoretical maximum CH_4 production (as it assumes 100 % organic biomass breakdown) and related CH_4 and CO_2 proportions, as well as H_2S and NH_3 production. CH_4 calculated using the Buswell equation is always higher than what can be obtained in the AD process, as only a small portion of biomass is consumed in the anabolic metabolic pathways and therefore converted to microorganisms. The other estimation used in this study was the estimation of methane potential using chemical oxygen demand (COD) (Equation (2)). COD is commonly used in water and wastewater management to measure the organic strength of influent and effluent. The COD test is a wet chemistry analysis using a strong oxidizing reagent under acidic conditions and high temperatures. The strength is expressed in "oxygen equivalents." The main benefit of the COD test is that when we measure the quantity of oxygen consumed by a sample, we are also measuring the number of electrons transported from organic compounds to the terminal electron acceptor, which is O_2 [50]. In this theoretical determination of methane production from chemical oxygen demand, the CH_4 produced during incubation (0.4 m^3 CH_4 per 1 kg COD removed) is divided by the samples' initial COD. This gives an estimate of the amount of organic matter that will be converted to CH_4 during digestion.

Equation (2) Theoretical maximum methane production based on chemical oxygen demand (Ultimate methane yield)

$$1\mathit{kg\ of\ COD}= 0.4\mathit{m3of\ CH}4\mathit{produced\ during\ the\ digestion\ process} \qquad 2$$

Methane yield estimation methods: Methane yield in theory is known by the carbon component in the substrate (Banks & Heaven, 2013) using the following equation:

Equation (3)*: Methane yield estimation*

$$Y_{CH_4}\left[m^3Kg^{-1}\right] = \frac{CH_{4-out\ put}}{VS_{-in\ put}} \qquad 3$$

Based on the value of the VS samples that were tested and measuring the volume of methane gas every week, every variation of methane yield samples was evaluated. The calorific value of 1 m^3 is about 36 MJ.

2.6. Nutrient content of human feces

The micro- and macronutrient constituents of feces ash were determined using an MP-AES (A200-MP-AES). The determination of micronutrient analyses was done for manganese (Mn), iron (Fe), copper (Cu), and zinc (Z). The macronutrient analysis was done for sulfur (S), potassium (K), calcium (Ca), and boron (B). All samples were analyzed in triplicate.

2.7. Data management and analysis

In all procedures of the experiments, standard methodologies were used. All of the chemical reagents utilized were of analytical grade, and their expiry date was checked. To ensure accuracy, each test was performed in triplicates. Experiments using a blank and a control group were conducted. The collected data were entered, organized, and summarized using the mean values and standard deviation using Statistical Package for Social Sciences version 20 software (SPSS). The results were presented in tables and graphs.

2.8. Ethical clearance

The study was conducted after ethical clearance was obtained from the institutional review board (IRB) of Jimma University with reference number *IHRPG/756/2019*. Official letter was written for Jimma Town Health Department, and permission was secured at all

Table 1
Proximate analysis of raw human feces result from the batch experiment, Jimma town, Ethiopia, 2022.

Properties	Unit	Mean Value (SD)
Moisture content	(%w/w)	24.80 (±8.49)
Volatile Matter	(%w/w)	27.02 (±2.04)
Ash content	(%w/w)	3.90 (±0.29)
Fixed carbon	(%w/w)	44.46 (±7.09)

levels. Each participant provided written informed consent prior to the data collection.

3. Results

3.1. Proximate and ultimate composition of human feces

For the experimental work, fresh human feces were collected using a properly designed urine diversion toilet. The collected raw feces were analyzed, and the key properties (proximate and ultimate analysis) were examined. Table 1 shows the proximate composition of human feces in percent weight/weight (% w/w) with the standard deviation. The proximate analysis (the physical parameters) is the analysis of the physical properties of the waste, which consists of moisture content, ash content, volatile matter, and fixed carbon. Accordingly, the mean moisture content of human feces was 24.80 (SD = 8.49), the volatile matter was 27.02 (SD = 2.04), the ash content was 3.9 (SD = 0.29), and the fixed carbon was 44.46 (SD = 7.09) [Table 1].

The ultimate analysis results of total nitrogen (mg kg^{-1}), total phosphorus (mg k^{-1}), potassium (mg kg^{-1}), total sulfur (mg kg^{-1}), and total organic carbon matter (mg kg^{-1}), are shown in Table 2. Accordingly, the feces sample contains total organic carbon (74.00), total nitrogen (3.70), potassium (2.29), total phosphorus (1.12), and total sulfur (0.20).

3.2. Biogas potential (experimental yield) of human feces

In the current experiment, the AD biogas generated was measured every other day using the standard methods described in the method section above. The sample was prepared in triplicate in three AD bottles, and the total methane volumes generated in the 28 days of incubation were summed. Each day's generation vs. volume is presented below in Fig. 1. Accordingly, experiment 1 was 0.39 m^3 kg^{-1}; experiment 2 was 0.38 m^3 kg^{-1}; and experiment 3 was 0.40 m^3 kg^{-1}. Based on the energy conversion of methane to MJ by multiplying the values, experiment 1 had 14.24 MJ kg^{-1}, experiment 2 had 13.81 MJ kg^{-1}, and experiment 3 had 14.43 MJ kg^{-1} [Table 3].

3.3. Biogas potential (theoretical yield) of human feces

The theoretical gas yield of human feces was calculated based on two equations (Eq (1) and Eq (2)). In the current experiment, carbon (74), hydrogen (5.5), oxygen (15), and nitrogen (3.70) were measured. Using the above formula based on the conversion factor, human feces generate 22.14 MJ kg^{-1}. The BMP is based on the COD value of feces sample from the experiment. It was done in triplicate. The COD mg L^{-1} of the sample was calculated using the relationship between COD and methane production using the following formula: 1 kg of COD is equal to 0.40 m^3 of CH_4. On the other hand, 1 m^3 of methane generates 36 MJ of energy. Therefore, the mean MJ per kg of human feces was 11.69. A comparison of the experimental results of methane yield and the theoretical yield shows the experimental yield was lower than the theoretical yield, as presented below in Table 4.

3.4. Compost potential of human feces AD slurry (resources recovery)

In this experiment, the fertilizer potential of human feces was measuredusing standard laboratory methods. The chemical composition of feces was analyzed. The two categories of nutrients measured were micronutrients and macronutrients. Table 5 provides the nutrient content of human feces after energy is recovered. Fecal sludge is very rich in nutrients and organic matter. Human feces after energy recovery provide those nutrients: nitrogen, phosphorus, and potassium, which are fundamental nutrients for plant growth. Nitrogen (3.71 g kg^{-1}), potassium (2.29 g kg^{-1}), total phosphorus (1.12 mg kg^{-1}), and sulfur (0.20 %) were detected.

4. Discussion

This laboratory-based experimental study evaluated the biogas and compost potential of human feces, predicting their theoretical yield and practical biomethane potential. Additionally, nutrient analysis was conducted to determine the fertilizer potential. This study

Table 2
Ultimate analysis of raw human feces, Jimma town, Ethiopia, 2022.

Parameters		Mean	(SD)
Total Nitrogen		3.71	0.56
Total phosphorus		1.12	0.18
Potassium (K), mg kg^{-1}		2.29	0.32
Total Sulfur		0.20	0.00
Total Organic carbon		74.00	8.5
Ratio	Carbon to Nitrogen (C: N)	20.01	0.74
	Nitrogen to Sulfur (N:S)	18.55	2.53
	Carbon to Sulfur (C:S)	370.02	37.69
COD mg L^{-1}		1088.00	64
BOD mg L^{-1}		668.65	24.7

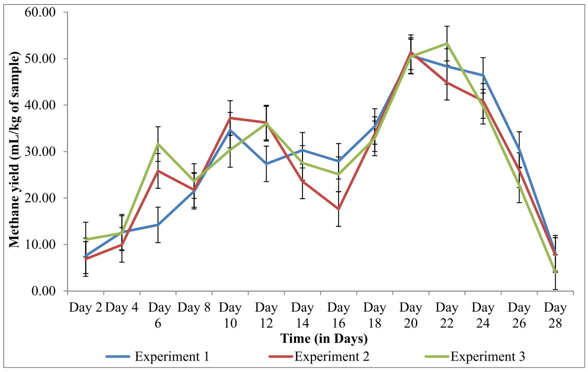

Fig. 1. Bio-methane yield of human feces during 28 days of incubation: batch experiment results, Jimma town, Ethiopia, 2022.

Table 3
Bio-methane potential (experimental yield) of human feces: batch experiment results, Jimma town, Ethiopia, 2022.

Experiment	CH_4 (m^3 kg^{-1})	MJ kg^{-1}
Experiment 1	0.39	14.22
Experiment 2	0.38	13.82
Experiment 3	0.40	14.44
Mean Yield	0.39	14.16

Table 4
Comparison of experimental results of methane yield and the theoretical yield.

Estimation method	Methane yield m^3 kg^{-1}	Thermal value MJ kg^{-1}	[a] CH_4 yield m^3 cap^{-1} $year^{-1}$	[b] Thermal value MJ Cap^{-1} $Year^{-1}$
Equation 1	0.62	22.32	45.26	1629.36
Equation 2	0.32	11.69	23.73	853.37
BMP Experiment 1	0.39	14.22	28.83	1038.06
BMP Experiment 2	0.38	13.82	28.03	1008.86
BMP Experiment 3	0.40	14.44	29.27	1054.12

Key: a: Assuming an average adult person produces 200 g of feces per day, b: The thermal value of human feces calculated using the conversion of 1 m^3 of methane generates 36 MJ of energy.

Table 5
Micronutrient and macronutrient contents of human feces: results from a batch experiment, Jimma town Ethiopia, 2022.

Nutrient Type		Mean (mg kg^{-1} dry matter)	SD
Micronutrient	Manganese (as Mn)	0.049	0.01
	Iron (as Fe)	0.13	0.02
	Copper (as Cu)	34.68	4.67
	Zink (as Zn)	0.03	0.00
Macronutrient	Sulfur (as S)	0.2	0.00
	Nitrogen (as N)	3.71	0.46
	Phosphorus (as P)	1.12	0.18
	Potassium (as K)	2.29	0.26
	Calcium (as Ca)	0.85	0.19
	Boron (as B)	2.1	0.36

examined the moisture content, volatile matter, fixed carbon, and ash content of human feces. The moisture content was 24.80 %, the ash content was 3.90 %, the volatile matter content was 27.02 %, and the fixed carbon content was 44.46 %. BOD and COD were 668.65 mg L^{-1} and 1088.00 mg L^{-1}, respectively. These findings suggest that the moisture content of urine is diverted to the toilets, which are so dry that they facilitate the reuse of human feces as compost. Evidence from other works suggests that low moisture contents (64 %) ensure aerobic degradation of feces, whereas higher moisture levels cause both aerobic and anaerobic decomposition [51]. Findings from similar studies shows that human feces have a 51 % ash content, 17 % volatile matter, a moisture content ranging from 53 % to 92 % [18], and 32 % fixed carbon [52]. The findings from the current study shows that total organic carbon was 74 %, total nitrogen was 3.71 %, potassium was 2.29 %, total phosphorus was 1.12 %, and total sulfur was 0.20 %.

The methane theoretical yield of human excreta was calculated based on two equations [53]. The methane generation potential of human feces was 22.14 MJ kg^{-1} for equation (1). The BMP is based on COD value of a feces sample from our experiment. COD mg L^{-1} of the sample was calculated using the relationship between COD and methane production using the following formula: 1 kg of COD is equal to 0.40 m^3 of CH_4, while 1 m^3 of methane generates 36 MJ of energy. Biogas production began on the second day of the test period, similar to the study conducted in Sokoto, Nigeria [54]. The AD process was slow during the first 14 days. This is due to the fact that the development of methanogenesis bacteria has resulted in low biogas generation [55]. The volume of biogas created increased from 18 days until 26 days later, due to a decrease in carbonic corrosive accumulation or an increase in pH [56]. At the end of the experiment, biogas production decreased and eventually came to zero due to a deficiency in supplements [57], smelling salts, or an alkali buildup within the digester [58].

In the current experiment, the AD biogas generated was measured every other day using the standard methods described in the method section above. Accordingly, the mean methane production in ml kg^{-1} of the sample was 393.30, and the energy conversion of methane to MJ by multiplying the values shows a mean of 14.16 MJ kg-1. This result is in line with the previous study findings about the outcomes of an aerobic digestion experiment employing human feces [59], feces gasification [53], and hydrothermal liquefaction [60], which reveal 26.80 kW h power from 35 kg, 15 MJ kg^{-1}, and 12.36 MJ kg^{-1}, respectively. The CH_4 recovered from anaerobic digestion systems is regularly of great quality and not only represents energy recovery but also avoids the discharge of CH_4 into the environment. Besides, in terms of pollution control, carbon change efficiencies in anaerobic digestion systems have been reported to range from 75 to 85 % when working at optimal conditions [61].

The sanitation implication of this study is that with the use of biogas toilets, human feces can be stabilized through AD digestion. AD digestion facilitates the treatment of human feces and helps the complete interruption of feco-oral diseases of feces origin. The process of AD digestion follows the containment approach that limits environmental contamination of human feces. Therefore, the use of biogas toilets as a sanitation solution can be an important alternative for future urban sanitation platforms in Ethiopia.

In this study, the biofertilization potential of human feces was assessed using nutrient analysis, specifically NPK. Human feces contain nutrients that are very important for plant growth. For instance, it contains potassium (2.29 mg kg^{-1}), phosphorus (1.12 mg kg^{-1}), and nitrogen (3.71 mg kg^{-1}). This finding is consistent with results from other studies [20,62]. Human feces are rich in phosphorus, potassium, and nitrogen, which are important plant nutrients. They also contain carbon, which can increase the fraction of organic matter in soils [63]. More organic matter in soils is especially important to improve the soil structure [64]. It is also known that increasing organic matter through compost use can make plants more salt-tolerant, as seen in Swiss chard, common beans [65], and apple trees [66]. This gives more predictable, quick-release natural fertilizer that can be applied to cropland for maximum plant nutrient take-up with minimal loss to the environment. AD fertilizer, with its diversified nutrients and slow-acting manure impact, promotes crop development and soil organism movement while protecting soil richness. It reduces agricultural costs, prevents soil structure damage, protects the soil's ecological environment, and promotes a sustained yield increase [13].

5. Conclusion

In conclusion, the study found that human feces' bio-methane potential can provide energy recovery and alternative sanitation options, addressing urban sanitation issues. Additionally, the biogas reactor's slurry's compost potential has positive nutrient values, significant fertilizer potential, and potentially can replace inorganic fertilizer. The current study can be evidence for the energy recovery and bio-fertilizer potential of human waste (human feces) in the study setting. However, community acceptance and cultural implications of using feces products may require further research. Therefore, future work needs to focus on technical feasibility, sanitation technologies, and local sanitation systems to connect this advanced waste treatment option to urban settings. Moreover, the study's results were based on a controlled environment, and hence a pilot study in a real environment is recommended to optimize the findings for specific study sites. This could help alleviate the sanitation crisis in Ethiopia's towns and cities.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable.

Author's contributions

DO and AD designed the study, trained the research team, and oversaw the fieldwork, and sample analysis. DO participate in drafting the manuscript. AB, HE, DD, and GT participated in the design of the study, approved the study, and oversaw the critical revision of the manuscript. All authors read and approved the final version of the manuscript.

Ethics declarations

The study was conducted after ethical approval was obtained from the institutional ethical review board (IRB) of Jimma University with reference number *IHRPG/756/2019*. An official letter was written for Jimma town Health Department, and permission was secured at all levels. Each participant provided written informed consent prior to the data collection.

Data availability statement

The datasets used during the current study are available in the manuscript and supplementary material.

CRediT authorship contribution statement

Dereje Oljira Donacho: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gudina Terefe Tucho:** Writing – review & editing, Supervision, Methodology. **Dessalegn Dadi Olani:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Hailu Endale:** kabtiyimer, Writing – review & editing, Supervision, Resources, Methodology. **Abebe Beyene Hailu:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Aysha Desalegn:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

AD	anaerobic digestion
ASTM	American Society for Testing and Materials
BMP	bio-methane potential
BOD	biological oxygen demand
CO_2	carbon dioxide
COD	chemical oxygen demand
pH	potential hydrogenation
NPK	nitrogen, phosphorus, and potassium
kg	kilogram
g	gram
mg	milligram
MJ	mega joule
Eco-san	ecological sanitation toilet.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22494.

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