PREDICTION OF BIOGAS POTENTIAL OF FRESH HUMAN FECES FOR THE DEVELOPMENT OF SUSTAINABLE URBAN SANITATION TECHNOLOGY IN JIMMA TOWN, SOUTHWEST ETHIOPIA

By

Aysha Desalegn (B.Sc.)

Thesis Report Submitted to the Department of Environmental Health Sciences and Technology, Faculty of Public Health, Institute of Health Sciences, Jimma University, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Environmental Science and Technology

December 2022

Jimma, Ethiopia

JIMMA UNIVERSITY

INSTITUTE OF HEALTH SCIENCE

FACULTY OF PUBLIC HEALTH

DEPARTMENT OF ENVIRONMENTAL HEALTH SCIENCES & TECHNOLOGY

Prediction of Bio-methane Potential of Fresh Human Feces for the Development of Sustainable Urban Sanitation Technology in Jimma Town, Southwest Ethiopia

BY: Aysha Desalegn (BSc.)

Advisors:

1. Abebe Beyene (PhD, Assoc. Prof.)
2. Hailu Endale (MSc, Ph.D. candidate)
3. Dereje Oljira (MSc, PhD candidate)

Thesis Report Submitted to the Department of Environmental Health Sciences and Technology, Faculty of Public Health, Institute of Health Sciences, Jimma University, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Environmental Science and Technology

December 2022

Jimma, Ethiopia

Approval sheet

Members of boar of the examiners

External examiner	Signature	Date
____________________	_______________	_______________
Internal examiner	Signature	Date
____________________	_______________	_______________
Chairperson	Signature	Date
____________________	_______________	_______________

Advisors Signature Date

Dr. Abebe Beyene_______________ _______________

Mr. Hailu Endale_______________ _______________

Mr. Dereje Oljira_______________ _______________

DECLARATION

Name: Aysha Desalegn Signature: _________________

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and that all sources of materials used for the report have been fully acknowledged.

Abstract

Background: *Recycling human excreta has become one of the alternatives for the prevention of communicable diseases related from lack of safe sanitation while generating revenue. In urban areas, sanitation-related health risks extend far beyond basic access to household sanitation. The problem is more serious in low-income countries, including Ethiopia, and particularly in urban slums where the majority of people live together. Biogas toilets are among the most resource-efficient sanitation technologies, generating energy and stabilizing waste-producing biofertilizers for agricultural input. In Ethiopia, knowledge of the energy potential of human excrement is limited to optimizing the development of biogas toilet facility Therefore, the prediction of the bio-methane potential of human excreta for the development of sustainable sanitation technology is one alternative way of reducing the environmental pollution.*

Objective: *This study aimed to evaluate the biogas and biofertilizer potential of human excreta in Jimma City, Ethiopia, which may contribute to the development of sustainable sanitation technologies.*

Methods and materials: *In this study, experimental and theoretical prediction methods were used. The lab-scale batch experiment was conducted by taking composite samples of fresh human feces using Eco-San technology. Using both ultimate and proximate laboratory analysis, the theoretical yield of biogas was predicted. Then a series of anaerobic digestion batch experiments were conducted to determine the practical energy yield. The biofertilizer potential of human feces was determined by analyzing the nutrient constituents of human feces.*

Results: *The findings of this study showed that the biogas yield from the experimental results of Experiment 1,2,&3 was, on average, 0.393* m^3*/kg. Based on the energy conversion of methane to MJ by multiplying the values, the mean was 14.16 MJ/kg. The biogas meter cubes per capita per head per year were 28.71 (28.03–29.27) in the experimental result and 45.26 for the theoretical yield of methane & C/N ratio was 20.11%. In our study, the biofertilizer potential of human feces was evaluated using nutrient analysis, specifically the NPK. Accordingly, human feces contain potassium (2.29 mg/kg), phosphorus (1.12 mg/kg), and nitrogen (4.29 g/kg). This finding suggests the bio-methane potential of human feces can satisfy energy recovery and alternative sanitation options, providing a positive remedy for the sanitation crisis in urban settings.*

Keywords: *Bio-methane, human excreta, Sustainable Sanitation, Anaerobic Digestion*

Acknowledgments

First and foremost, I thank the Almighty God who led me through all the times and gave me time, peaceful life, and the strength to complete this research thesis.

Next, I would like to forward my heartfelt gratitude to my advisors, Dr. Abebe Beyene, Mr. Hailu Endale, and Mr. Dereje Oljira for their scientific guidance, endless constructive comments; help in correcting, and unconditional assistance in this thesis writing.

My special acknowledgment also goes to Mr. Siyum Derib for his unreserved support during laboratory work and for sharing his experience of laboratory work. My special thanks also go to Jimma University Environmental Health Science and Technology Department, for their willingness and support to laboratory activities, and provision of laboratory materials, and facilities. I would also like to offer thanks to Bless Agri-a campus of Veterinary medicine laboratory, soil laboratory, animal science laboratory, and post-harvest laboratory for allowing me to use their laboratory and provided with the necessary materials during sample analysis.

A special appreciation and thanks go to Mr. Eshetu (veterinary medicine laboratory assistant) and Mr. Abiyot Hundesa (animal nutrition laboratory assistant) helped me with every move in the laboratory.

I would also like to offer thanks to the Ethiopian Conformity Assessment Enterprise (ECAE) of Addis Ababa laboratory for their willingness and support of laboratory activities, and provision of laboratory materials and facilities. A special appreciation and thanks go to. Mitiku Diriba team leader and Mr. Alemayehu helped me in the laboratory.

I would also like to thank my beloved family for their significant contribution sand initiative filling my heart with brightness, the hard times they gave me to think beyond, and for their financial and moral support.

Last but not least, I would like to acknowledge all informants and my relatives who Spend their time and share their insights with me.

Lists of Acronyms and Abbreviations

ABR: Anaerobic Batch Reactor

AD: Anaerobic Digestion

BMP: Biochemical Methane Potential

BOD_5: Five-day Biochemical Oxygen Demand

C/N: Carbon to Nitrogen ratio

COD: Chemical Oxygen Demand

EC: Electrical Conductivity

EPA: Environmental Protection Agency

GG: Greenhouse Gases

pH: Potential Hydrogenation

SCOD: Soluble Chemical Oxygen Demand

SST: Sustainable Sanitation Technology

TDS: Total Dissolved Solids

TP: Total Phosphorus

TP: Total Phosphorus

TSS: Total Suspended Solids

VSS: Volatile Suspended Solids

VS: Volatile Solids

Eco-san: Ecological sanitation toilet

DMMC: Dry mass moisture content

Table of contents

Contents **Pages**

List of Tables

List of Figures

1. NTRODUCTION

1.1 Background of the study

Proper human waste management (feces and urine) is critical for a healthy life and plays a major role in long-term development (WHO and UNICEF, 2020). Lack of safe sanitation is attributed to many diseases caused by human excreta (fecal-oral diseases) (Mara et al., 2010). According to a 2019 United Nations report, an estimated 297,000 children under the age of five died from diarrheal diseases caused by poor sanitation, hygiene, and unsafe drinking water (UN-water, 2020). About 775,000 people die each year as a result of poor sanitation worldwide (Ritchie and Roser, 2019). This fact is a real indicator of the importance of safe sanitation in interventions to interrupt the transmission of fecal-oral diseases.

Sustainable development goals (SDGs), which cover the period from 2015 to 2030, call for action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity (UN, 2018). In particular, goal six 6 targeted clean water and sanitation as an indicator for the global concerns of sanitation in the reduction of poverty, environmental protection, and health promotion. In 2015, globally, 4.5 billion people lacked safely managed sanitation services, and more than 2.3 billion people still lack basic sanitation (WHO, 2020). Additionally, 892 million people practice open defecation, which exposes pathogens to the living environment.

Urban environments, which are the most populated human habitats, are more venerable to poor sanitation access in less developed countries, where they grow up with their children in polluted environments (Berendes et al., 2018). With the current high rates of urbanization, it seems that the challenge for sanitation in the future will be even greater. The urban population will rise to 6.7 billion by 2050 (Lüthi et al., 2020). In cities and towns, it is increasingly clear that global targets now call for solutions that provide "safely managed sanitation" from the toilet through treatment to the point of disposal or end-use (Lüthi et al., 2020). Urban sanitation requires a high level of technical competency due to the need for interlinked or networked systems that address both the intensely personal sphere of private sanitation and the management of excreta for public health and environmental protection. In 2015, three in five people worldwide did not use safely managed sanitation services, systems where excreta are safely disposed of in situ or safely transported and treated off-site (WHO, 2020). In recent sanitation technology innovations, sanitation facilities are shifting from "collect and dispose of" to "treat and reuse." Those technologies are termed "promising sanitation technologies" for sustainable sanitation systems. They include technologies such as bio-char toilets, bio-gas toilets, and composting toilets.

Biogas (bio-methane) is a multilateral renewable energy source that can replace conventional fuels to produce heat and power; it can also be used as a gaseous fuel in automotive applications. Bio-methane (upgraded biogas) can also substitute for natural gas in chemical production. Recent evaluations indicate that biogas produced via anaerobic digestion (AD) provides significant advantages over other forms of bioenergy because AD is an energy-efficient and environmentally friendly technology (Foreest, 2012). AD technology can reduce GHG emissions by utilizing locally available sources. In addition, the byproduct of this technology, called digestate, is a high-value fertilizer for crop cultivation and can replace common mineral fertilizers (Wagner, 2015). Biogas is produced by bacteria through the biodegradation of organic material under anaerobic conditions. The bio-machination process is one of the most essential processes for treating the biodegradable portion of any solid waste (Munisamy et al., 2021). Biogas can be produced from the co-digestion of municipal biodegradable solid waste with human excrement. This technology has tremendous application in the future for the sustainability of both the environment (treatment of wastes) and agriculture, with the production of energy as an extra benefit (Ullah Khan et al., 2017). Biogas production through anaerobic digestion (AD) is an environmentally friendly (not harmful to the environment) process utilizing the increasing amounts of organic waste produced worldwide (Singhal et al., 2022).

The biogas option is the most sensible, feasible, and economical way for society to treat waste in an environmentally friendly way. Better nutrient management also includes the recirculation of nutrients from human excreta to food production (Drangert et al., 2018), (Downie, 2020). In most cultures, human excreta have historically been used for fertilization and soil improvement (Sugihara, 2020a). Also, emissions of nutrients from human excreta to water bodies are projected to increase even further in the future due to increased population and urbanization (Devaraj et al., 2021), but the development of new and innovative human excreta management solutions that facilitate the recovery of nutrients (and organic matter) from human excreta for reuse in agriculture is also encouraged (Usman et al., 2021). The development of nutrient recovery and reuse solutions reflects a continuing shift away from viewing human excreta as a waste and toward recognizing its value as a resource, and it is part of a larger trend toward more comprehensive resource recovery in the sanitation and wastewater management sectors (Zhang et al., 2016). Biogas is a renewable energy source with numerous applications, and as such, it has gained widespread acceptance. Biogas, like natural gas, can be used as a fuel for cooking, transportation, and electricity generation (Munisamy et al., 2021).

Biogas technology is regarded as one of Africa's renewable technologies capable of addressi ng the continent's energy and environmental challenges. Several sub-Saharan African countries are producing biogas from a variety of waste resources, including slaughterhouse waste, municipal waste, industrial waste, animal dung, and human excreta. After several years of promotion, large-scale biogas production technology in Africa is not at an advanced stage, but there is still a large potential for its development, both at the industrial and small-scale levels (Yadav et al., 2013). This study aimed to predict the bio-methane potential of human excreta for the development of sustainable sanitation in Jimma City, Ethiopia, in 2022.

1.2 Statement of the problem

Human excreta are the main cause of environmental degradation, such as surface and groundwater contamination, air pollution, noise pollution, a foul odor in the city, and the source of many communicable diseases and deaths (Clasen et al., 2010). Poor sanitation and fecal sludge management not only harm people's health but also harm the environment by contaminating water, soils, and food sources (Ziegelbauer et al., 2012).

In developing countries, the provision of proper sanitary services in urban areas is a major issue (Lüthi et al., 2020). The health risks associated with poor urban sanitation are complex because exposures to fecal contamination occur both inside and outside the household (Devaraj et al., 2021). In 2015, globally, 4.5 billion people lacked safely managed sanitation services, and more than 2.3 billion people still lack basic sanitation (WHO, 2020). This global estimate shows more than 892 million people practice open defecation, which exposes pathogens of fecal origin to the living environment.

Since 2007, more people have lived in cities than in rural regions, and this trend is anticipated to continue (Beyene et al., 2015). Furthermore, almost one-third of urban people live in urban areas, and more than 90% of urban slums are found in developing countries (Kundu and Pandey, 2020). In 2012, 61.7 percent of the urban population in sub-Saharan Africa lived in slums with severely poor sanitation. Different studies showed that Ethiopia is one of the Sub-Saharan African countries grouped with the lowest sanitation coverage (WHO and UNICEF, 2020), (Peal et al., 2020). Containment of human excreta is the primary role of sanitation within the environment (Ecohydrology& Hydrobiology, 2018). Open drains are a common fate for human excreta from uncontained household sanitation facilities in low-income urban areas, and most excreta in drains remains untreated, presenting a high-risk fecal exposure pathway (Gretsch et al., 2015). Studies have linked poor urban sanitation with increased diarrheal disease, and urban sanitation interventions have had mixed effects on health (Alirol et al., 2011).

Solid wastes and infections caused by excreta are especially widespread in underdeveloped countries. Because of the inefficient waste management system, these wastes contain significant concentrations of discharged pathogens such as viruses, bacteria, protozoa cysts, and helminth eggs, which can cause diseases in humans (Tran-Thi et al., 2017). In many cities, untreated or partially treated human waste is at risk of "leaking" at various points along the sanitation service chain (Dasgupta et al., 2021; Devaraj et al., 2021), (Lüthi et al., 2020). These problems arise due to untreated or inadequately treated excrement, and the recovery of energy from this waste at the source is not practiced (Mills et al., 2018). Waste can be transformed into a resource as a sustainable sanitation alternative. This issue is included as justification for the problem state because of the importance of the bio-methane process in waste stabilization and the complete stopping of fecal-oral disease transmission. To address the current and tangible problem by creating electricity from human excrement by utilizing acceptable, sustainable technology and environmentally appropriate waste recycling to conserve natural resources and human health (Schiffer et al., 2018).

Many studies have been conducted to treat various organic solid wastes with anaerobic digestion as well as to forecast the biomethane potential of food waste and human excreta. Few studies have been carried out on the characterization and biomethane potential of different waste streams, including municipal solid waste, the co-digestion of food waste and human excreta (feces and urine), cow dung, khat, and the optimization of biochar from the pyrolysis of a mixture of human excreta and solid waste. However, limited research has been done to predict the biomethane potential of fresh human excreta using a lab-scale batch experiment, ultimate (elemental), and proximate (biochemical) analysis for the development of sustainable sanitation and resource recovery (compost) potential that is discharged as slurry from the biogas reactors.

Bio-methane forecasting the potential of fresh human excreta for the development of sustainable sanitation technology may be fully utilized to solve the aforementioned problem, fills the gap, and foresee an alternate path. This study focuses on the biomethane potential of fresh human excreta, based on a lab-scale batch experiment as well as ultimate (elemental) and proximate analysis for the development of sustainable sanitation in Jimma, Ethiopia, in 2022.

1.3 Significance of the study

The study's main objectives were to gather proof of human excreta's potential as a resource for reducing pollution, breaking disease transmission chains, and improving human health. It's also used to make compost or improve compost efficiency, as well as to reduce the consumption of inorganic fertilizer. It contributes to using acceptable, sustainable technology and environmentally appropriate waste recycling to save natural resources and human health by creating electricity from human excreta. This research can also assist in reducing environmental pollution and alleviating present and tangible concerns.

Community, government, and non-governmental organizations (NGOs) gain from this research in terms of sanitation, energy sources, and resource recovery (compost potential). Furthermore, the community will benefit from low-cost, sustainable energy production and improved environmental conditions on a broad scale, as well as contribute to long-term development goals by rapidly boosting sustainable sanitation, which leads to clean water and good health care. The finding helps the stakeholders (non-governmental organizations (NGOs) and government organizations) who are interested in the bio-methane potential of human waste. Additionally, it helps as a baseline for further studies and interventions.

1.4 Research Questions

1. What is the average bio-methane potential of human excreta?
2. What are the estimates of human excreta in terms of COD, BOD_5, TN, NH_4, NO_3, TP, PO_4, TDS, TSS, and VSS concentrations and dry mass moisture content?
3. What is the potential of resource recovery (compost potential) of human excreta?

1.5 Scope of the study

The fundamental purpose of this research is to anticipate the bio-methane potential of fresh human excreta (feces) to build long-term sanitation solutions and resource recovery (compost potential), which is discharged as slurry from the biogas reactor. It's a laboratory-scale experiment with a batch experiment.

2. LITERATURE REVIEW

2.1. Characteristics of human excreta

Human excreta are a byproduct of body processes. Water, protein, undigested lipids, polysaccharides, bacterial biomass, ash, and undigested dietary leftovers are all found in feces. The principal constituents in feces, expressed as a percentage of wet weight, are oxygen (74%), hydrogen (10%), carbon (5%), and nitrogen (0.7%), which includes the hydrogen and oxygen contained in the feces' water fraction; the remaining 25% of feces is made up of solid matter (Nwaneri et al., 2008). Feces have a carbon concentration of 44 to 55 percent of dried solids (about 7 g/cap/day). The total solids (TS) portion of feces has 92 percent volatile solids (Chow et al., 2020). Chemical oxygen demand (COD) and biological oxygen demand (BOD) measurements are also other determinants of the bulk organic content of feces. It is well known that human excrement contains a large number of different pathogens and also affects human health (Peal et al., 2020).

Improper fecal management can result in the pollution of water and soil and the transmission of infectious diseases through person-to-person interaction, water, and food due to pathogens found in human excreta. The diseases transmitted through human excreta account for 4% of deaths in the world, and children are the most affected population (Sugihara, 2020b). Access to improved sanitation is a key intervention to interrupt the chain of fecal-oral diseases. In line with this target, improved sanitation, defined as the hygienic isolation of human excreta from human contact, is now unavailable to an estimated 2.6 billion people around the world (WHO, 2020). Different studies confirm that diseases linked to poor sanitation are particularly related to poverty, accounting for 10% of the overall illness burden worldwide (Prüss-Ustün et al., 2019). The lack of access to improved sanitation is potentially contributing to environmental pollution and its consequences for society.

In situations where sanitation is lacking, human excreta may accumulate around homes, in nearby drains, and at garbage dumps, leading to environmental pollution (Kulabako et al., 2007).

Although the coverage percentage in affluent countries is 95 percent, many countries are falling short of the 75 percent coverage target set by the SDGs for sanitation. The three regions with the lowest sanitation coverage are Sub-Saharan Africa, Oceania, and Southern Asia (WHO and UNICEF, 2020).

In this fragile sanitation crisis in low-income countries, new sanitation platforms are emerging as a solution. Human waste can be transformed into a resource as a sustainable sanitation alternative. This issue is included as justification for the problem state because of the importance of the bio-methane process in waste stabilization and the complete stopping of fecal-oral disease transmission. Address the current and tangible problem, involves creating electricity from human excreta using acceptable, sustainable technology and environmentally appropriate waste recycling to conserve natural resources and human health (Guest et al., 2009).

Human excreta constitute a significant biowaste with enormous potential, similar to cattle manure. Human excreta can be used to produce biogas, which has significant sanitation and fertilizing benefits. Co-digestion or co-composting of human excreta allows for higher-quality biogas or compost production while also helping with long-term waste management (Onojo et al., 2013; Owamah et al., 2014). Human excreta have been shown to have good fertilizing potential, providing essential plant nutrients as well as organic matter contributing toward building soil structure and reducing erosion (Sugihara, 2020a, 2020b).

2.1 Effects on the Environment

Human waste is the primary source of environmental deterioration, including contamination of surface and groundwater, air pollution, and a foul odor in the city, as well as the source of many communicable diseases and deaths (Ahmed and Huq-Hussain, 2011). Poor sanitation and fecal sludge management harm not only human health but also the ecosystem by contaminating water sources, soils, and food sources (Ziegelbauer et al., 2012). Because fecal contamination occurs both inside and outside the home, the health hazards linked with poor urban sanitation are complex (Mills et al., 2018). Many studies have linked poor urban sanitation to an increase in diarrheal disease (Patel and Thillainayagam, 2009). Exposure to fecal contamination in the public domain, including open drains, has been identified as a high risk for children in urban areas by quantitative microbial risk assessments (Clasen et al., 2010). The exposure is may result from the containment of excreta associated with onsite household sanitation (poor fecal sludge management, "FSM") (Mills et al., 2018).

2.2 Ultimate and proximate analysis

The ultimate (elemental) analysis is the chemical properties of the fuel, which consist of the carbon content, oxygen content, hydrogen content, nitrogen content, and sulfur content. The proximate analysis (the physical parameters) is an analysis of the physical properties of the fuel and consists of the moisture content, ash content, volatile matter, and fixed carbon (Onochie et al., 2017).

2.3 Ecological sanitation (Eco-San) Technology and Anaerobic digestion

Ecological sanitation, often known as ecological sanitation technology, is a sanitation system that tries to safely reuse excreta in agriculture (Singh et al., 2017). It is a technology or a device that is defined by a goal to safely "complete the loop" between sanitation and agriculture, primarily for nutrients and organic matter. One of the goals is to use nonrenewable resources as little as possible. Eco-san systems are systems that can provide a hygienically safe mechanism for converting human excreta into nutrients and water that may be returned to the ground (Sugihara, 2020a).

Anaerobic digestion is a potentially environmentally friendly technology that produces biogas, and its residues are soil conditioners. Organic waste items, such as vegetables, are recognized to contain sufficient nutrients for the growth and metabolism of anaerobic bacteria in biogas (Munisamy et al., 2021). Biogas production from municipal solid waste, food processing waste and waste-activated sludge has been reported in recent years (Ullah Khan et al., 2017). Anaerobic digestion is a viable alternative for generating electricity from the MSW while also alleviating the disposal issue, and it has a positive development impact on the environment. The impacts may contribute to reducing the greenhouse effect and global warming (Yusuf et al., 2011).

Anaerobic digestion (AD) is the process of microorganisms decomposing organic matter and producing CH_4 and CO_2 in the absence of oxygen. The presence and activity of particular bacterial species that form a community, each with specialized ecological responsibilities and complex nutritional requirements, are required for anaerobic digestion. The AD process is thought to be caused by four separate bacterial groups, as depicted in Figure 1, and their synergistic connection (Chow et al., 2020).

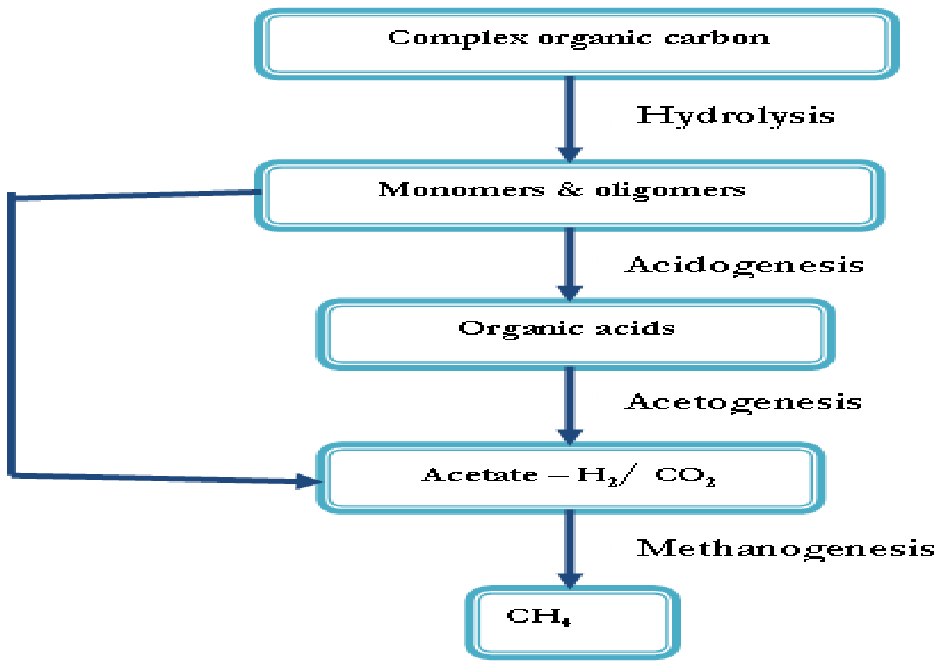


Figure 1: Multiphase nature of Anaerobic Digestion

Source: (Deublein and Steinhauser, 2011).

When compared to other bioenergy production technologies, AD biogas generation has a lot of advantages and is one of the most energy-efficient and environmentally friendly bioenergy production technologies (Deublein and Steinhauser, 2011). Anaerobic digestion (AD) has become an important process for addressing environmental and energy concerns in the last decades of the twentieth century, with many recent studies reporting that AD is an efficient alternative technology that combines bio-energy production with sustainable waste management. It is becoming more successful as a result of the low cost of available feedstock, the diverse range of biogas applications (e.g., fuel, electricity, and heating), as well as the need to address global warming, energy security, and waste management (Barragán-Escandón et al., 2020; Kaparaju and Rintala, 2013; Ullah Khan et al., 2017).

This method is based on biochemical degradation processes, which are commonly used to treat and recover energy from various biomasses. Anaerobic digestion provides several advantages over other procedures such as incineration, gasification, or pyrolysis, which makes it appealing to the industrial energy generation industry (Zhang et al., 2016). Biogas and digestate (a fertilizer) are two added-value products of anaerobic digestion (Seppälä et al., 2013). During anaerobic digestion (AD), the microorganisms break down the organic matter (COD) in 79% of the waste, resulting in the creation of biogas with 55–75 % CH_4, which can be used for cooking, heating, or energy generation.

The AD process stabilizes the treated waste by 82% by significantly reducing particulates, germs, and odors, as well as creating a high-nutrient soil fertilizer (Lansing et al., 2008). Compared to traditional disposal procedures, the AD process has significant advantages. Large areas of land are not required; biomass bulking within the digester is significantly reduced compared to other treatment methods; bad odors are avoided; the chemical oxygen demand (COD) is significantly reduced; nutrient requirements are minimal; and methane and carbon dioxide are obtained as final metabolic end-products (Droste, 1996).

2.4 How much energy can we get from AD?

- Up to 75–85 % of the organic fraction can be converted into biogas.
- It has a methane content of 50–60% (but this will depend on the substrate).
- Biogas typically has a thermal value of about 22 MJ per m3.
- The thermal value of methane is 36 MJ per m3(Yadav et al., 2013).

2.5 Anaerobic digestion benefits

Anaerobic digestion can both produce and save money. It provides a holistic waste treatment solution under regulated conditions, creates net energy, regulates odors, eliminates pathogens, reduces the environmental impact of waste emissions, and maximizes resource recovery. Anaerobic digestion systems for biogas production help to reduce pollution, greenhouse gas emissions, fossil fuel consumption, and chemical fertilizer use, all while improving the quality of life for settlers in rural and suburban regions. Furthermore, it has grown in popularity in recent years as a cost-effective method for nutrient recirculation and pollution reduction (Zhang et al., 2016). Biogas is utilized in a variety of activities, including internal combustion engines, gas turbines, fuel cells, water heaters, and industrial heaters. Biogas is utilized around the world to generate power, with an overall conversion efficiency of 10–16 percent (Singhal et al., 2022).

2.6 Byproducts of anaerobic digestion

AD is a cost-effective way to manage biodegradable waste that produces two byproducts in the process. The first byproduct is biogas. The use or sale of both can provide great financial income. Anaerobic digestion of biodegradable garbage produces potential energy while also lowering greenhouse gas emissions. Methane, a highly energetic component of biogas, is produced as a by-product of anaerobic wastewater treatment and can be used as fuel for boilers, reactor heating, and electricity generation. Methane, carbon dioxide, moisture, and hydrogen sulfide are the four main components of biogas. The typical proportion of biogas produced by efficiently working anaerobic digestion systems is 60–70% CH_4, with the rest being CO_2. The energy content of biogas is equivalent to that of CH_4, which has a 37 MJ/m3 energy value.

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. The biodegradable COD from the substrate is maintained in the end products since no oxidation by ambient O_2 is possible. CH_4 has a COD of 2 moles (= 64 g of COD) of oxygen per mole (= 16 g) of CH_4 according to stoichiometry. As a result, 1 gram of CH_4 equals 4 grams of COD.

The amount of CH_4 that can be produced during the anaerobic digestion process from organic material is directly proportional to the substrate content of convertible COD. Since no oxidation by atmospheric O_2 can occur, the biodegradable COD from the substrate will be preserved in the end products. Stoichiometrically, CH_4 has a COD of 2 moles (= 64 g of COD) of oxygen per mole (= 16 g) of CH_4. Thus, 1 g of CH_4 is equivalent to 4 g of COD. Further calculations suggest that 1 kg of COD can create 0.355 m^3 CH_4 at STP, equating to 14 132 kJ of useful energy (as CH_4). Biogas can be preserved for a long time and at a low cost. This trait enables biogas to be converted into electricity at times when electricity is expensive or when there is a significant electricity demand(Köttner et al., 2003; Mata-Alvarez, 2005a).

The second byproduct is the digester. Anaerobic digestion can be thought of as a way to handle organic wastes, but to get the most out of these wastes; the digestate must serve a useful purpose and provide a benefit to the producer. Anaerobic digestion extracts carbon, hydrogen, and oxygen from the feedstock, according to Fabien's (Angelidaki and Ellegaard, 2003) research. Essential plant nutrients are more readily available in digestate than in untreated organic waste.

Mineralization of nutrients (N, P, and K) improves plant absorption. Digestate, for example, contains 25% more NH_4-N (inorganic nitrogen) and has a higher pH value than untreated liquid manure. It decreases scent annoyance by approximately 80%. Digestive enzymes are also beneficial to the soil's humus equilibrium. As a result, it can be utilized as a fertilizer or a soil amendment in farming and landscaping. Due to the use of organic matter, this method allows for the formation of a nutrient cycle and the maintenance or improvement of soil structure. The use of digestate is determined by its quality and the type of plant that produces it. For example, the digested sludge can be used as fertilizer on farmland without further treatment (Angelidaki and Ellegaard, 2003).

2.7 Factors affecting anaerobic digestion

Acetic acid-forming bacteria (acetogens) and methane-forming bacteria are among the microorganisms that affect anaerobic digestion (methanogens). In the conversion of biomass to biogas, these organisms support many chemical processes. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four biological and chemical steps of anaerobic digestion (Noraini et al., 2017).

2.7.1. Temperature

Another key environmental component that harms anaerobic digestion processes is temperature. Temperature is one of the crucial elements that researchers frequently overlook. The pace of reaction should theoretically increase as the ambient temperature rises. As a result, the production of biogas will rise. In anaerobic digestion, there are three temperature ranges to consider: 1) Psychrophilic: 0–15°C; 2) Mesophilic: 15–45°C; and 3) Thermophilic: 45–65°C (Yusuf et al., 2011).

In most conventional digesters, mesophilic temperatures of around 35 °C were used in the system. Thermophilic temperatures of 55°C to 60°C, on the other hand, are worth considering because they produce more biogas in a shorter amount of time (Rajaonahy et al., 2016). Failure to correctly manage the reaction temperature can result in a reduction in process efficiency and, as a result, a decrease in reaction rate. When it comes to reaction rates, thermophilic temperatures give a faster rate over a shorter period, resulting in a higher gas yield. According to the study, the performance of waste-activated sludge and food waste co-digestion was better at higher temperatures (B et al., 2014).

Faster fermentation rates result from higher temperatures during digestion, which has a direct impact on loading rates and also reduces bacterial and viral pathogens. The solubilization rate was determined using suspended solid (SS) removal, and it was discovered that between 25°C and 45°C, the solubilization rate is quite high, ranging between 62.2 percent and 72.7 percent. This shows that under these temperature ranges, microbial activity was strong, contributing to the high solubilization rate. Furthermore, abrupt transitions from mesophilic to thermophilic or vice versa, as well as temperature fluctuations placed on the system, will have a direct impact on the process. The output of biogas will decrease until they have successfully restored the necessary populations for the optimal process. Furthermore, even small temperature changes in the digestion process, such as from 35 °C to 30 °C or vice versa, could significantly reduce the biogas production rate. Very little CH4 is created at very low temperatures (below 10 °C). The microbial cells, on the other hand, remain viable and continue to proliferate, producing CH4 after the incubation time is up (hydraulic retention time) (Chen et al., 2008).

2.7.2.HRT (Hydraulic retention time)

Another significant operational component in the anaerobic digestion process is the hydraulic retention time. The HRT is determined by the wastewater characteristics, carbon concentration, and ambient conditions and must be long enough to allow anaerobic bacteria to digest the waste sufficiently (Wilkie, 2005). The HRT varies depending on the kind of digester and might range from 10 hours to several days (10 — 30).In contrast, the minimum solid retention time (HRT) at a given temperature is increased to 35 °C.

2.7.3. pH

For anaerobic digestion operations, pH is the most significant operational parameter. It has a direct impact on the growth and metabolism of microorganisms. The propionate anaerobic conversion is substantially faster at neutral or weakly alkaline pH (7 to 8) than at weakly acid pH (Dhaked et al., 2003) (pH 6). By feeding the digester at an optimal loading rate, the pH of the digester can be controlled within a target range of 6.8–7.2. The pH of the digester is affected by the amount of carbon dioxide and volatile fatty acids produced during the anaerobic process (Yadvika et al., 2004).

The activity of methane bacteria is inhibited at pH levels below 6.0–6.5. Chemicals are added to the organic substrate to provide a buffer capacity to prevent pH decreases. The most commonly utilized compounds are sodium bicarbonate, sodium hydroxide, sodium carbonate, and sodium sulfide (Esposito et al., 2012). The ammonia levels are safe if the pH is maintained within an adequate range. This system depends on ammonia, and if the ammonia levels are not safe, it will result in reactor failure (Chen et al., 2008).

Methanogens and carcinogens are particularly sensitive to pH fluctuations, with an optimal pH range of 7.0–7.4 in most situations. A pH range of 6.7–7.4 is also required for optimal CH_4 generation(Mata-Alvarez, 2005b). When the pH goes below 6.0, acute poisoning develops, which is mainly caused by the presence of undissociated volatile fatty acids generated by acidogenic bacteria (Austermann-Haun et al., 1994). Methanogens are more acid-sensitive than acidogenic bacteria. Additionally, an increase in volatile acid concentration could suggest a system malfunction (Wilkie, 2005).

The maintenance of an acceptable pH range is brought about by the combined activities of the acetogenic and methanogenic populations. Bicarbonate produced by methanogens serves as a buffering agent during pH reduction (Munisamy et al., 2021). The presence of nutrients (i.e., nitrogen, phosphorus, and sulfur, as well as other trace elements needed by the bacteria) plays a crucial role in this process (O'Kennedy, 2000).

The best COD: N: P ratio for the AD process is recommended to be 700:5:1. It has also been suggested that, for optimal gas production, the C: N ratio should be 25:1. Methanogenic bacteria, in general, have simple nutrient requirements, and those species that require organic materials such as fatty acids and amino acids for growth obtain them from other bacterial species that produce them during wastewater catabolism (Mata-Alvarez, 2005a). According to (Gerardi, 2003), residual values of ammoniacal nitrogen and orthophosphate phosphorus should not be limited in the digester. Residual values of 5 mg/l of NH_4^+–N and 1–2 mg/l of HPO_4—P are commonly recommended.

2.8 Conceptual framework

While most urban decision-makers and planners are aware of sanitation's critical health and environmental advantages, many are unaware that many components of sanitation waste streams are potentially recoverable and reusable, for example in the agriculture or energy sectors. This can lead to the formation of new enterprises and jobs, as well as improved resource efficiency in urban systems. Human excreta, in particular, have a lot of promise as an alternative fertilizer source and show great potential. Thus, in planning sustainable sanitation, this approach should not be centered on technology or the imperative of waste disposal but instead, start with a focus on resources and their management.

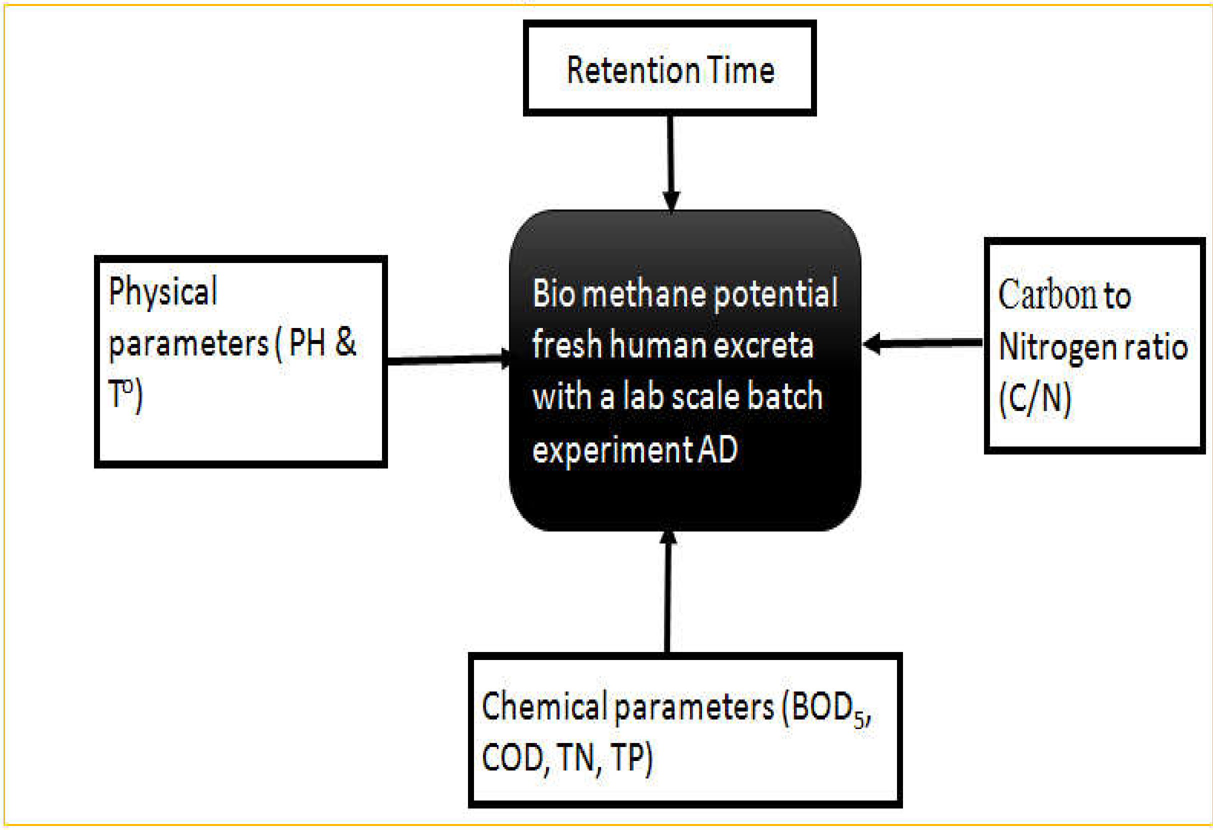


Figure 2: Conceptual framework of Biogas Potential of fresh human excreta (feces)

3. OBJECTIVES

3.1. General objective

- To characterize human excreta and predict its bio-methane potential in Jimma town, Ethiopia, 2022

3.2. Specific objectives

- To characterize the human feces
- To predict the bio-methane potential of human feces
- To determine the potential of resources recovery (compost potential) which is discharged as slurry from the biogas reactor

4. METHODOLOGY

4.1 Study area

The study was conducted in Jimma City (town), which has a total area of 220 km2. Jimma town is located 352 kilo-meters 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, 335 km southwest of the capital city, Addis Ababa (CSA-Ethiopia, 2013).

Due to a lack of systematic land-use classification, most people live in unstructured and scattered residential areas mixed with hotels, bars, and restaurants; big shops; milling houses; medium and small clinics; small furniture manufacturing centres; and garages. Most of the area is occupied by private residential houses and small governmental and commercial buildings. A point worth noting is that there are no big manufacturing industries. On the outskirts of the town, subsistence farming is prevalent. The central part of the town is highly congested and characterized by active business transactions. A large number of people live in this central part of the congested area with poor sanitary facilities. In the town, safely managed sanitation is only 13% among households, and this convergence was much lower in the urban slums of the town (Donacho, Tucho and Hailu, 2022; Donacho, Tucho, Zeine Ousman, et al., 2022). The problem of access to sanitation in Jimma Town has a significantly associated household characteristic. The recent findings show that the sanitation technology options are limited to pit latrines, which are not supported by the current urban expansion and land use.

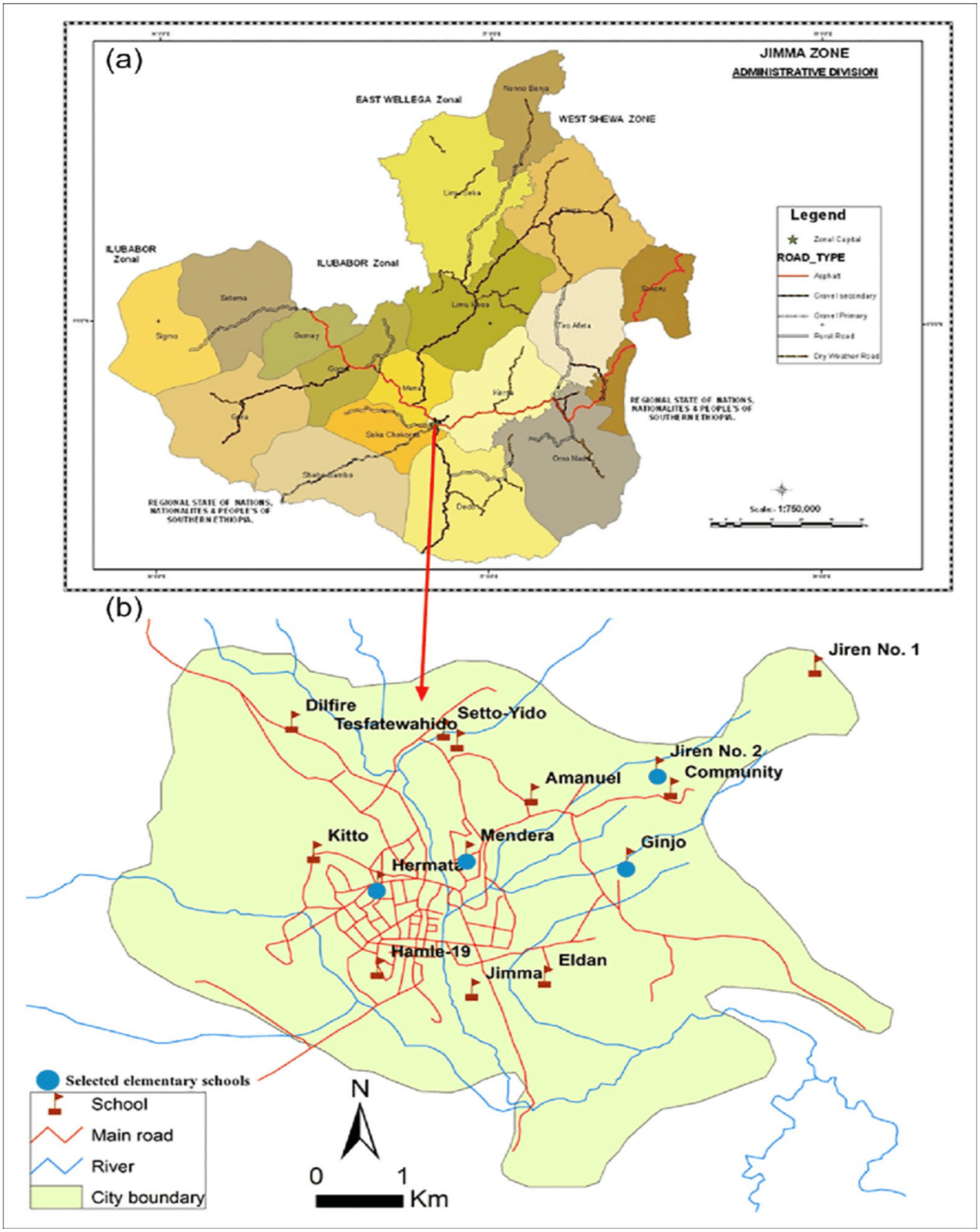


Figure 3: Map of Jimma Town, 2022(Deneke, 2007).

4.2Study design and period

A cross-sectional lab-based (Bach experiment) study was conducted from May 2022 to August 2022

4.3Study Variables

4.3.1. Dependent variable

Prediction of the biogas potential of fresh human feces and its compost potential with lab-scale-Batch experiment.

4.3.2. Independent variables

- Physicochemical parameters: BOD_5, COD,TN, TP, VSS, TDS, and dry moisture content.
- The volume of methane and amount of digestate produced

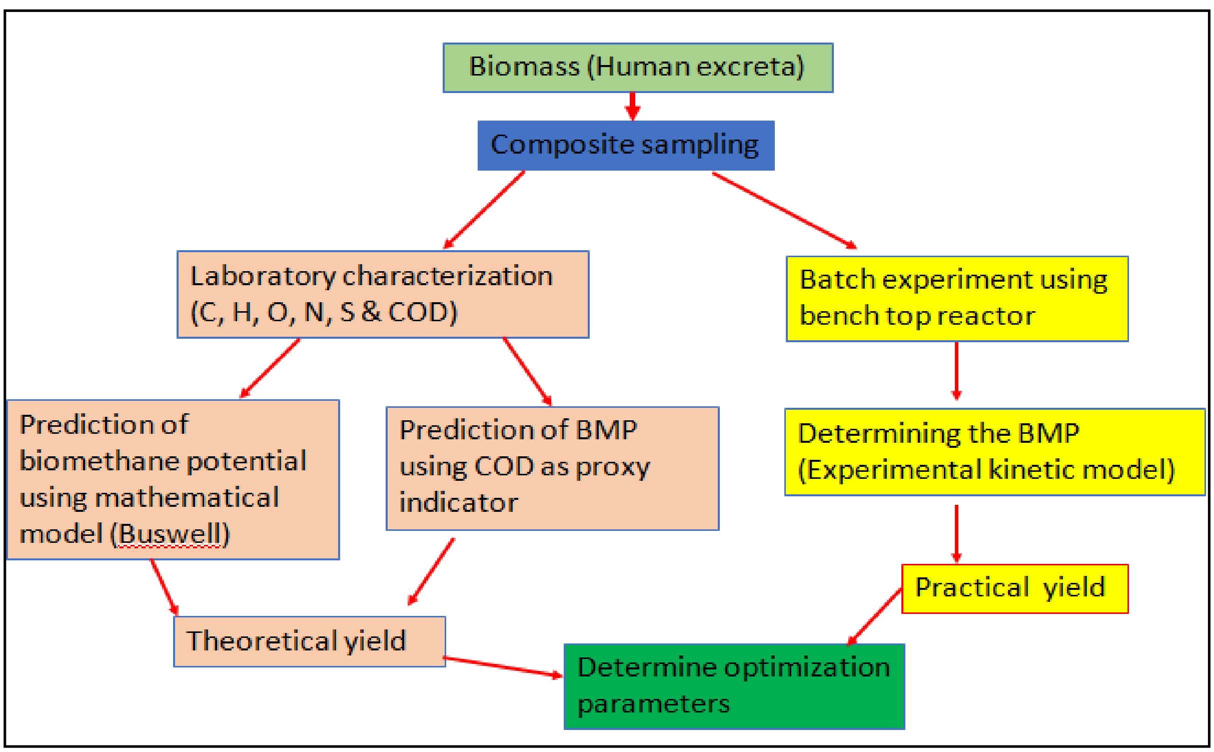


Figure 4: Methodology of the study

The following figure serves as a visual representation of the methodology

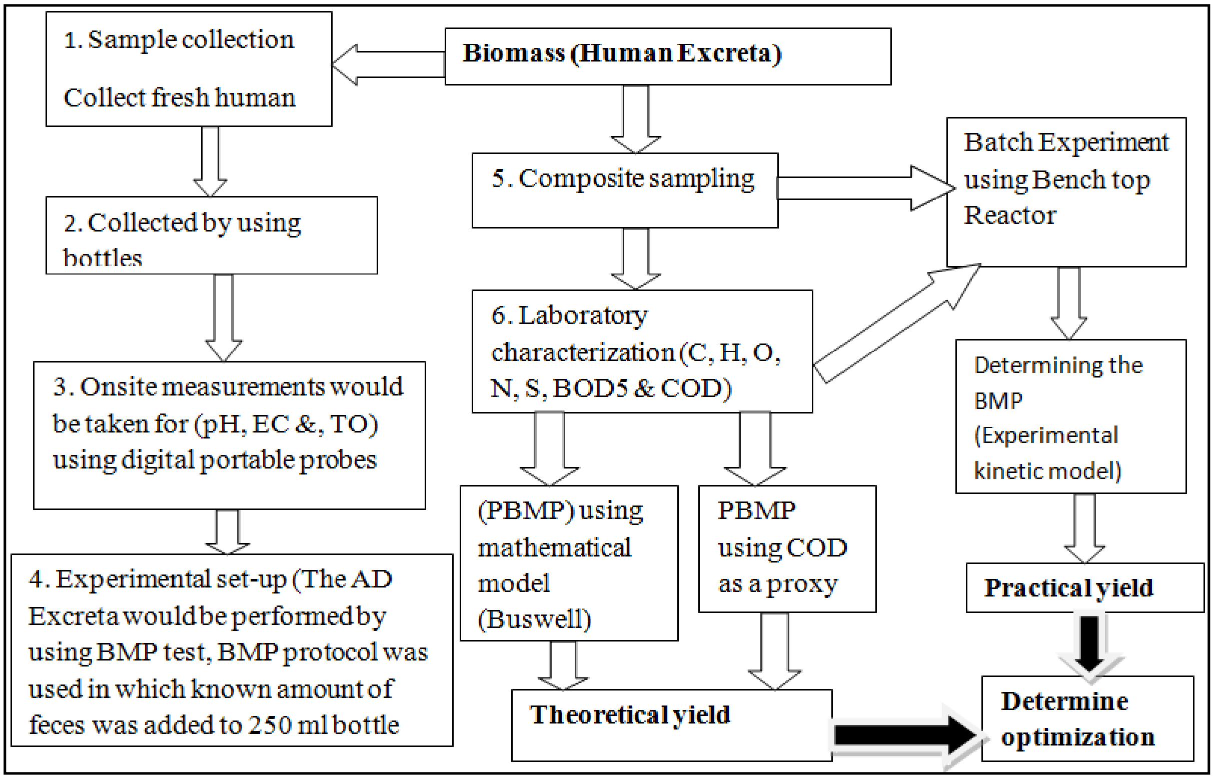


Figure 5: General flow of Methodology of the study

4.4Sampling

4.4.1. Sampling Periods and Sites

The research was carried out between May to August 2022.The sampling site was in Jimma City, and Eco-San was prepared on Bosa-Adis Kebele in a 2-by-2-meter space on individual householders' land that has public access points and is interested in participating in using the toilet for experimental purposes.

4.4.2Test Toilet Design, User Interface, and Experimental Detail

In this study, a urine-diversion, raised-dry toilet was constructed. It was installed in a public place in Bosa Addis kebele in Jimma town. It also supports researchers' demonstrations for users. The technology was designed to allow easy handling of human feces, separated by a urine divert slab as a user interface, where human feces were collected in a collection box and urine was collected in a separate jar. It was developed in a way so as not to expose the users and researchers during handling. It also protected against fly exposure and odor reduction, and the technology was well and adapted. It is user-friendly. This newly adopted urine diversion 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 were used in this study's experimental work (See Annex 2).

The anaerobic digestion of excreta (feces only) was performed using the biochemical methane potential (BMP) test. The total volume of methane production during the digestion period, per amount of feces added, was recorded. The BMP protocol was used, in which a known amount of feces was added to 250-mL serum bottles, and the bottles were gassed with N_2 for3 minutes 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, it was manually mixed in the bottle 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 day for 28 days or until the amount of methane produced was 1% of the total methane obtained. Additional test: The concentration of gas was measured by a multi-gas monitor type 1302 (Bruel& Kjaer multi-gas monitor type 1302).

The proximate (moisture content, volatile matter, ash content, and fixed carbon) and ultimate analyses of the sample (total nitrogen, total sulfur, total phosphorus, total potassium organic carbon, COD, and BOD) were determined using Standard Methods (APHA, 2005). The microwave plasma-atomic emission spectrometer (MP-AES method: BCTL/100 MP-AES) was also used to determine the nutrient composition of the feces sample.

4.4.3. Sample Collection Preparation and Storage

A feces sample was collected by a urine-diversion, raised-dry toilet that was constructed in this case study. During one day of feces sample collection, 30 community members from the Bosa Addis kebele in Jimma town used the test toilet. Before the study, the ethical considerations of the test were approved by the Jimma University institutional ethical review board (IRB); additionally, the participants signed written informed consent.

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 ^{o}C for 24 hours 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 fixed. These samples were properly and carefully labelled, sealed, and transported to the laboratory of the Department of Environmental Health Sciences at Jimma University. Cold storage was maintained throughout the process until analysis.

4.5. Experimental set-up

The anaerobic digestion of excreta (feces) was performed using the biochemical methane potential (BMP) test. The total volume of methane production during the digestion period, per amount of feces added, was recorded. The BMP protocol was used, in which a known amount of feces was added to 250mL bottles. pH was measured, and the bottles were gassed with N_2 for3 minutes to eliminate the oxygen and sealed immediately using rubber septa and aluminum foil, super-glue, and wax.

Once sealed, the bottles were placed in an incubator and maintained at a constant mesophilic temperature of 35 °C. It was mixed manually in the bottle every day during the entire incubation period. 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 day for 28 days or until the amount of methane produced was 1% of the total methane obtained. In the analysis, the total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) of the sample were determined according to Standard Methods (APHA, 2005).

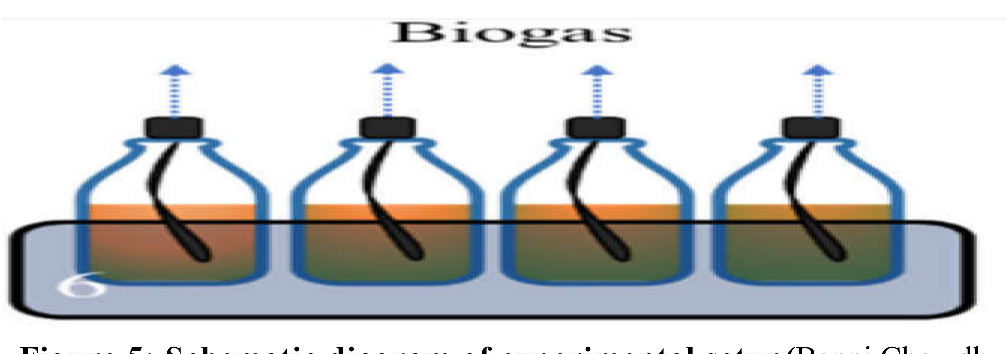


Figure 5: Schematic diagram of experimental setup(Bappi Chowdhury, 2020)

4.6 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. Herein, the fixed carbon is the portion of combustible residue left after the removal of moisture, ash, and volatile materials from feces. Thus, one gram of the sampled feces was prepared in three replicates after homogenizing. Then, the determination of the percentage of moisture, volatile, ash, and fixed carbon content of the feces was carried out based on ASTM standard methods for chemical analysis of wood charcoal (D1762–84, 2007). The precision of measurement was evaluated by repeating each of the three triplicate samples.

The ultimate analyses of feces matter provide the weight fractions of non-mineral major elements (i.e., carbon, hydrogen, nitrogen, oxygen, and sulfur), which can be used to examine the extent of heating value and the organic constituents in the samples. It was conducted by using an elemental analyzer (Model: Vario EL III Element Analyzer; Elementary Co., Germany). However, in this study, the ultimate analysis was limited to the determination of the carbon, nitrogen, and sulfur content of the feces. Similarly, to evaluate the precision of measurement, each sample was carried out in triplicate.

4.7Theoretical maximum methane production

4.7.1. Maximum methane production using the Buswell equation

Buswell equation provides stoichiometry calculation on the products from the anaerobic breakdown of a generic organic material of chemical composition $C_cH_hO_oN_nS_s$ (Buswell and Mueller, 1952).

$$C_cH_hO_oN_nS_s = \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O$$
$$= \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + nNH_3 + sH_2S$$

$$BMP = \frac{22.4(\frac{c}{2} + \frac{h}{8} - \frac{o}{4} - \frac{3n}{8})}{12c + h + 16o + 14n}$$

***Equation 1**: Buswell equation for theoretical maximum methane production estimation*

Where BMP is the normalized methane volume (CH_4ml/g /VS). The molar proportion of the mass fraction of elements C, H, O, N, and S in the organic fraction of biomass is represented by the molar proportion of its elements (c, h, o, n, and s). 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.

4.7.2. Maximum methane production using Chemical oxygen demand

Chemical oxygen demand (COD) is commonly used in the water and wastewater industries 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 (Tarvin and Buswell, 1934). 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)

$$1 \quad kg of COD = 0.4\, m3\ of CH4\ produced during the digestion process$$ (R.L., 1997).

4.8. Sample Analysis

In the laboratory of Jimma University's Department of Environmental Health Sciences and Technology, human excreta or feces samples were analyzed using standard methodologies for the examination of human excreta and wastewater (Rice et al., 2012). Samples from eco-san calorimetrically analyzed for nitrogen-containing parameters (TN, NO_3), phosphorus-containing parameters (TP), and COD, according to HACH instructions, using a spectrophotometer (DR/2010 HACH, Loveland, USA). The Azide modification Winkler technique was used to determine BOD_5. For each parameter, a triple analysis was performed. The following formula was used to calculate removal efficiency:

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

$$Y_{CH_4}[m^3 Kg^{-1}] = \frac{CH_{4-output}}{VS_{-input}}$$

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 22 MJ. The experiment was done with human feces.

4.9. The sample treatment procedure for elemental and proximate analysis

The 5gm fresh and digestate samples are placed in clean acid-washed porcelain and oven-dried at 105 ^oc for 24 hr in the drying oven. The dried samples are then ground to a fine powder form by using an acid-washed mortar and pestle and passed through a 2.0mm sieve. The powdered sample will have kept in polythene packets for further analysis. 5.0 g of grounded powder samples are weighted are transferred to a clean crucible, which is labeled according to sample number and dry ashing process is carried out in a muffle furnace by a stepwise increase of the temperature up to 550^{o}c and then left to ash at this temperature for 6hr. The sample will be removed from the furnace and allowed to cool. The ash watches glass and placed on a hot plate. The digestion will be performed at a temperature of 90 to 95^{o}c for 1hr. The ash will be dissolved in 5ml of 9.25% HCl and, digested again on a hot plate until the white fumes ceased to exist and the sample reached 2ml. After cooling, 20ml of distilled water is added and filtered using a Whatman filter. The filtered sample is then diluted up to the mark of a 50ml standard volumetric flask, and stored in a polyethylene container until analysis.

Nitrogen determination

KjeldahlUDK159 digestion, distillation, and titration apparatus, codeNemkeUS were used for the analysis of nitrogen in the sample. The analysis was done according to AACC method 46(2010) and EPA method 1687.The Kjeldahl procedure followed three major steps, these were digestion, distillation, and titration. For this purpose 5ml of the sample was measured using a measuringcylinder and it was transferred into a digestion flask and hydrolyzed 15mlof 98% sulfuric acid solution and the catalyst was added.

The flask was put in the digestion chamber at 430^{oc} adjusted temperature for 60 minutes. And then the digested sample was neutralized by 50% hydroxide solution to convert ammonium ion to ammonia gas and the ammonia gas was bubbled by steam and trapped by boric acid solution finally, titration was made by 20% hydrochloric acid and nitrogen was determined (read).

Total phosphorus

For this purpose, 2mg of feces sample was measured by using digital measurement transferred into each 250ml flask. And after that add 50ml d/water into each sample containing the flask, then homogenized by hotplate stirrer by using the magnetic tool. After homogenization, the sample was extracted by using filter paper into another 250ml flask for 24 hours. The filtrate (0.5 mL) and the 2.0 mL sulfuric acid solution (2.0 mol L^{-1}) were placed in 21.6 mL volume commercial headspace sample vials, which had a small tube containing 0.5 mL of a potassium permanganate solution (0.1 mol L^{-1}). After the headspace vial was sealed with a septum, it was shaken to ensure good mixing and preparation for the photo-spectrometer measurement.

Determination of sulfur

The sulfur content of fertilizer is determined gravimetrically by digesting the fertilizer in hydrochloric acid, then precipitate as barium sulfate by adding chloride solution and filter to por. 4sintered glass funnel.

Procedures

- Using a mortar and pestle or grinder, grind to affine power a small sample of the sample.
- Accurately sample weight powder sample containing 100-200mg(1gm in 400ml)beaker.
- Added 200ml of distilled water, and 15 ml of HCL heat to boiling point and then heat gently for 10min.
- Filter through a gooch crucible containing glass filter paper and wash with hot water. Set washed aside.
- Quantitatively transfer filtrates back to the beaker to bring nearly boiling point.
- Add slowly, with constant swiring, slightly excess (15ml) 10% barium chloride solution.
- Digest on low temperature, hot plate adjusted so that a solution does not boil or on steam bath 1hr., and late stand at room temperature, overnight.
- Filter though gooch crucible glass fiber previously dried at 250 degree Celsius, cooled, and weighed.
- Wash with hot distilled water 10 times and after final washing check the presence of chloride ions by adding one drop of 0.1M silver nitrate to the filtrate. if present continued washing until it's free.
- Dry the crucible with its contents for 1hr, at 250 degrees Celsius, and cool to room temperature and weight.

Moisture content

The percentage of moisture content of the sample was determined using the formula shown below after weighted 5gm of the sample into the dish and then drying the sample in the oven at $105^{o}{}_{c}$for 24hr.

%Mc=W-D*100/W

Where Mc= moisture content

W= initial weight (gm)

D= weight of the sample after drying at 105^{o}c (gm).

Total solid

For the determination of total solid, a clean evaporating dish (crucible) was used and firstly the dish was dried in an oven adjusted at 105^{o}_{c} for one hr, and it was cooled. Then, 5gm of digestate and fresh feces sample was weighed using a weight scale, and it was placed in a pre-dried and weighted evaporated dish. Then, the dish was put inside the oven which was maintained at 105^{o}c. the dish was allowed in the oven for 24 hr sand then taken out, cooled in desiccators, and weighed (92,94).

%TS= MDS*100/MS.

TS = total solid

MDS= mass of the dry sample after drying at 105^{o}_{c}

4.10 Data Quality Management

For all procedures in the set of experiments, standard methodologies were used (Eaton A.D., 1995). All of the chemical reagents utilized were of analytical grade, and their expiration dates were monitored. To ensure accuracy, each test required a triplicate sample analysis. Experiments using a blank were conducted. The data collected for analysis from eco-san of Bosa-Adis Kebelein Jimma City and lab-scale treatment of fresh human excreta for characterization and performance as well as ultimate and proximate analysis evaluation was recorded, organized, and summarized using descriptive statistics methods using Microsoft Excel. The results were presented in tables (mean value and percentage) and graphs. Finally, the study's findings were reported and discussed with the literature.

4.11 Ethical clearance

Before the start of data collection, ethical clearance was obtained from the Ethical Clearance Committee of Jimma University. A formal letter was written to all concerned bodies, and permission was secured at all levels. Written or informed verbal consent was obtained from each participant.

4.12 Dissemination plan

The findings of the study will be shared with all relevant bodies via Jimma University's Department of Environmental Health Science and Technology, as well as with other interested organizations. The manuscript will be created and sent to reputable, peer-reviewed publications for publication.

5. RESULTS

5.1. Characterization of Human Excreta

5.1.1 Proximate and Ultimate Composition of Human Feces

For the experimental work, raw (fresh) human feces were collected using a properly designed urine diversion toilet for urban setups. The collected raw feces were analyzed, and the key properties (proximate and ultimate analysis) were examined. Table 1 shows the proximate composition of raw human feces in percent weight/weight (% w/w) with the standard error. The moisture mean was 26.72 (SD = 7.93), and the ash content mean was 3.86 (SD = 0.28).

The proximate analysis (the physical parameters) is the analysis of the physical properties of the waste, which consists of the moisture content, ash content, volatile matter, and fixed carbon. Accordingly, the mean moisture content of human feces was 26.72 (SD = 7.93), the volatile matter was 28.72 (SD = 4.15), the ash content was 3.86 (SD = 0.28), and fixed carbon was 40.67 (SD = 9.54) (Table 1).

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

Properties	Unit	Experiment 1	Experiment 2	Experiment 3	Mean Value (SD)
Moisture content	(%w/w)	34.60	20.20	19.60	26.72 (±7.93)
Volatile Matter	(%w/w)	24.78	28.78	27.49	28.72 (±4.15)
Ash content	(%w/w)	4.27	3.75	3.77	3.86(±0.28)
Fixed carbon	(%w/w)	36.30	48.00	49.10	40.67(±9.54)

The ultimate analysis, which was limited to the determination of total nitrogen (mg/kg),total phosphorus (mg/k), potassium (mg/kg), total sulfur (mg/kg), and total organic carbon matter (mg/kg), is shown in table 2.The ratio of C:N Experment1-3 (10.94), 8.04 and 8.47 respectively and Mean. and Std.dev. were (9.15 ±1.28). The ratio of C: S (191) is higher than the ratio of N: S (21.32) analyzed for the raw human feces. Total organic carbon constitutes the highest percentage (38.3%), followed by total nitrogen (4.26 %), potassium (2.29%),total phosphorus (1.12%),and total sulfur (0.2%) in raw human feces.

Table 2: Ultimate analysis of the raw feces, Jimma City, Ethiopia, 2022

Parameters		**Experiment 1**	**Experiment 2**	**Experiment 3**	**Mean**	**(SD)**
Total Nitrogen		3.06	4.06	4.01	3.71	0.46
Total phosphorus		1.001	1.32	1.025	1.12	0.18
Potassium (K),mg/kg		1.95	2.58	2.33	2.29	0.26
Total Sulfur		0.20	0.20	0.20	0.20	0.00
Total Organic carbon		64.10	78.90	79.01	74.00	7.00
Ratio	Nitrogen to carbon (C:N)	20.9	19.43	20.01	20.11	0.46
	Nitrogen to Sulfur (N:S)	15.3	20.3	18.55	2.30	0.15
	Carbon to Sulfur (C:S)	191.50	197.00	186.00	191.50	4.49
COD mg/L		1,152	1,024	1,088	1088	0.00
BOD mg/L		660.71	696.43	648.81	668.65	20.24

5.1.2.Bio-methane potential (Experimental yield) of human Excreta

In the current experiment, the AD biogas generated was measured every 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 were presented in figure 2 below. Accordingly, sample one was 395.48 ml/150 g, sample two was 383.70 ml/150 g, and sample three was 400.8 ml/150 g. Following the conversion of ml/g to m3/kg, sample one was 0.395m^3/kg, sample two was 0.384m^3/kg, and sample three was 0.401m^3/kg. Based on the energy conversion of methane to MJ by multiplying the values, sample one had 14.24 MJ/kg, sample two had 13.81 MJ/kg, and sample three had 14.43 MJ/kg (Table 3).

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

Experiment	**CH_4 (m^3) /kg**	**MJ/Kg**
Experiment 1	0.395	14.22
Experiment 2	0.384	13.82
Experiment 3	0.401	14.44
Mean Yield	0.393	14.16

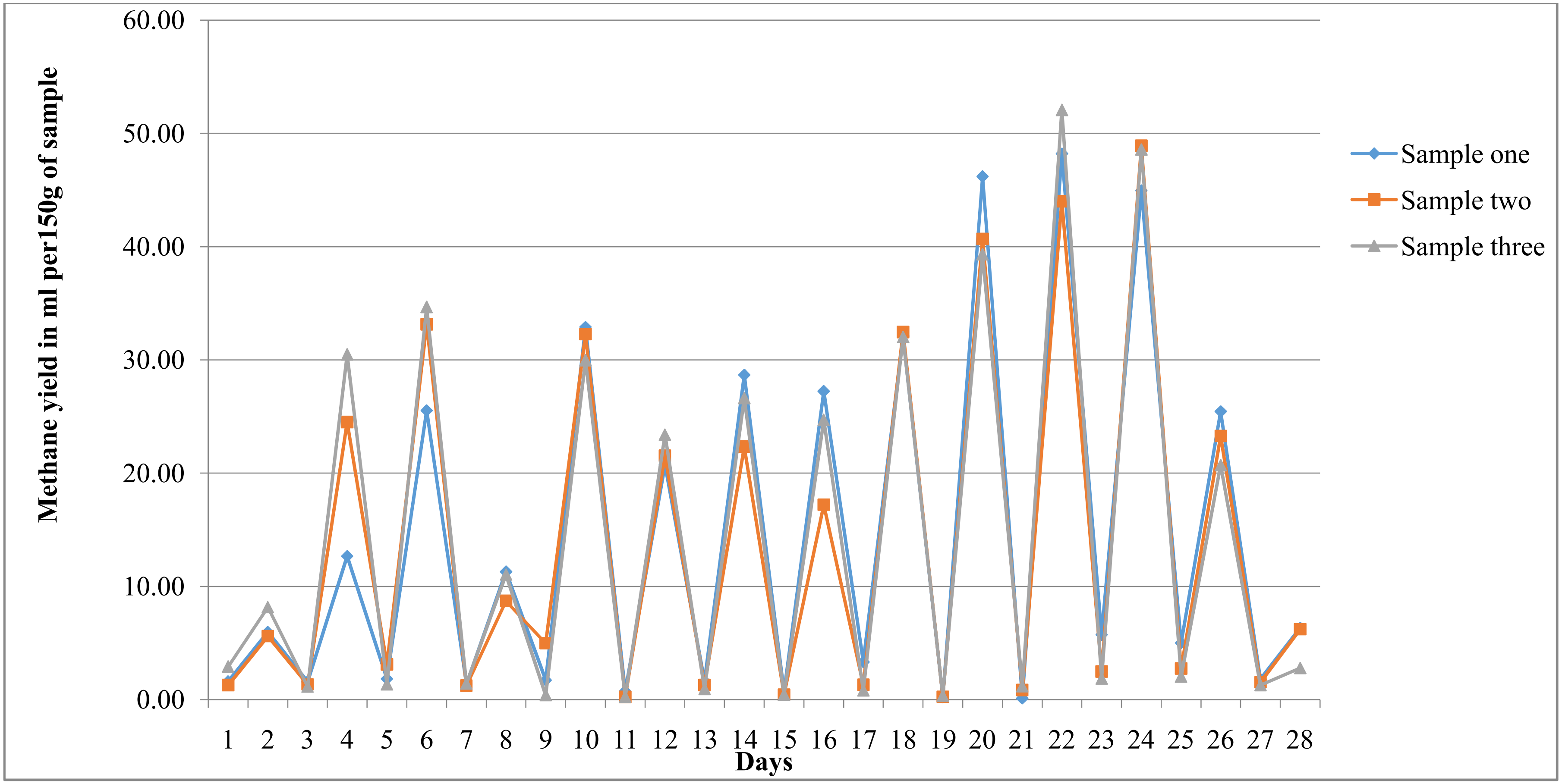


Figure 6: Biogas yield of human feces during 28 days incubation: batch experiment results

5.2. Bio-Methane Potential (Theoretical Yield) of Human Feces

The methane theoretical yield of human Feces was calculated based on two equations (Eq1 and Eq2). Following the Buswell equation According to a literature elemental analysis of human feces (Onabanjo et al., 2016), human feces contain the following: carbon (51%), hydrogen (7%), oxygen (21%), and nitrogen (4%). Using the above formula Based on the convection factor, human feces generate 15.65 MJ/kg. The BMP is based on the COD value of a feces sample from our experiment. It was triplicated. The COD mg/L of the sample was calculated using the relationship between COD and methane production using the following formula: 1 kg of COD is equal to 0.4 m3 of CH4. On the other hand, 1 m3 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 in table 4 below.

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

Estimation method	Methane yield m^3/ kg	Thermal value MJ/Kg	[a] CH_4 yield m^3/cap/year	[b] Thermal value MJ/Cap/Year
Equation 1	0.62	22.32	45.26	1,629.36
Equation 2	0.325	11.69	23.73	853.37
BMP Experiment 1	0.395	14.22	28.83	1038.06
BMP Experiment 2	0.384	13.82	28.03	1,008.86
BMP Experiment 3	0.401	14.44	29.27	1,054.12

Key: a: Assuming an average adult person produces 200 g of feces per day (Heaton KW, 2018), **b:** The thermal value of human feces calculated using the conversion of 1 m^3 of methane generates 36 MJ of energy.

5.3. Compost Potential of Human Feces AD Slurry (Resources Recovery)

In this experiment, the fertilizer potential of human feces was tested using standard laboratory methods. The chemical composition of feces was tested. The two categories of nutrients tested 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. Table 5: Micronutrient and macronutrient contents of human feces: results from a batch experiment, Jimma city, Ethiopia, 2022

Nutrient Type		**Experiment one**	**Experiment two**	**Experiment three**	**Mean Difference**	**Std.dve.**
Micronutrient	Manganese (as Mn),mg/kg	0.043	0.053	0.051	0.049	0.0043
	Iron (as Fe),mg/kg	0.11	0.14	0.14	0.13	0.014
	Copper (as Cu),mg/kg	40.05	31.50	32.50	34.68333	3.817
	Zink (as Zn),mg/kg	0.023	0.029	0.029	0.027	0.028
Macronutrient	Sulfur (as S),mg/kg	0.20	0.20	0.2 0	0.2	0.00
	Nitrogen (as N), mg/kg	3.50	4.90	4.39	4.26	0.58
	Phosphorus (as P),mg/kg	1.001	1.32	1.025	1.12	0.18
	Potassium (as K),mg/kg	1.95	2.58	2.33	2.29	0.26
	Calcium (as Ca),mg/kg	0.635	0.95	0.98	0.855	0.17
	Boron (as B),mg/kg	2.5	1.80	2.00	2.1	0.29

Table 5 above 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 fundamental nutrients for plant growth. Nitrogen 4.26gm/k, 2.26%, potassium (2.29gm/kg 2.29%), total phosphorus (1.12mg/kg 1.12%), and total sulfur (0.2%).

6. DISCUSSION

Fresh human feces samples were collected in this study using a urine-diverting dry test toilet designed specifically for this purpose. In the sample analysis, the characterization of the human excreta based on their pollutant concentrations, the prediction of the bio-methane potential (theoretical yield) of human feces using the characterization results, the prediction of the bio-methane potential of the human feces using a lab-scale batch anaerobic experiment, and the potential for resource recovery of the human feces were all analyzed to check the fertilizer potential of human feces.

This laboratory-based experimental study was conducted to evaluate the bio-methane potential and compost potential of human feces. The finding demonstrated the characterization of the human feces based on their proximate and ultimate analyses, the prediction of the bio-methane potential (theoretical yield) of human feces using the characterization results, and the prediction of the bio-methane potential of the human feces using a lab-scale batch anaerobic experiment. Additionally, nutritional analysis was used to determine the fertilizer potential of human feces.

The key properties (proximate and ultimate analysis) of the collected raw feces were investig ated mean moisture content was 26.72 (S± 7.93), and the mean ash content was 3.86 (SD 0.±28) The proximate analysis (the physical parameters) is an examination of the waste's physical properties, which include moisture content, ash content, volatile matter, and fixedcarbon.Human feces had a mean moisture content of 26.72 % (SD = 7.93), a volatile matter content of 28.72 % (SD = 4.15), an ash content of 3.86 % (SD = 0.28), and a fixed carbon content of 40.67 % (SD = 9.54).

These findings show 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. Findings from a similar study show human feces have a 51% ash content, 17% volatile matter, a moisture content ranging from 53% to 92% (Riungu J, 2019) , and 32% fixed carbon (Nishimuta M, 2006) Other studies also suggest that low moisture contents (64%) ensure aerobic degradation of feces, whereas higher moisture levels cause both aerobic and anaerobic decomposition (Zavala and Funamizu, 2005).
The ratio of C:N 20.11%).Total organic carbon constitutes the highest percentage (74%), followed by total nitrogen (4.26 %), potassium (2.29%), total phosphorus (1.12%), and total sulfur (0.2%) in human feces.

The COD and BOD were 466.07 mg/L and 1,088 mg/L, respectively. This finding indicates 93mg/cap/day, and 217mg/cap/day. The methane theoretical yield of human excreta was calculated based on two equations (Eq1 and Eq2). Following the Buswell equation According to a literature elemental analysis of human feces (Onabanjo et al., 2016), human feces contain the following: carbon (51%), hydrogen (7%), oxygen (21%), and nitrogen (4%). Using the above formula Based on the convection factor, human feces generate. 22 MJ/kg.

The BMP is based on the COD value of a feces sample from our experiment. The COD mg/L of the sample was calculated using the relationship between COD and methane production using the following formula: 1 kg of COD is equal to 0.4 m3 of CH4. On the other hand, 1 m3 of methane generates 36 MJ of energy. Therefore, the mean MJ per kg of human feces was 11.69.

Biogas generation was begun on the second day of the test period, which is similar to the study done in Sokoto, Nige Nigeria((Dangoggo M, 1996).The development of methanogenesis bacteria lagging during the starting stage of the trial period and unable to catabolize natural corrosive, due to this corrosive accumulation possibly expanding and causing pH decrement within the digester and would result in low biogas generation within the, to begin with, 16 days of the experiment.

This is expected since within the acidogenesis organize organic compounds are broken down into naturally corrosive by acidogenic bacteria. Within the early stage of maturation carbonic corrosive generation is higher than its consumption. Methanogenesis bacteria cannot survive in extreme pH values (J.L. Walsh, 1989), (Mantana P, 2005).

The volume of biogas created is directly relative to digestion time (Nabila L, 2015). In any case, from 17 days after beginning the experiment until 25 days biogas generation was increased this may be due to the increase of pH from an acidic medium to a neutral range. This is often likely due to the lessening of carbonic corrosive accumulation within the medium since the improvement of methanogenesis within the digester, utilized carbonic corrosive as a substrate and changed over it into methane due to this the pH of the digester could be expanded and might have resulted for more biogas yield. The capacity of the acid digestion system got to be strong over time (Zhengyun Z, 2013). The pH of the digester influences the growth of methanogenesis (B., 2014).Then at the end of the experiment biogas generation decreased and eventually come to zero. Usually due to the depletion of supplements and smelling salts or alkali (ammonia) accumulation within the digester.

In the current experiment, the AD biogas generated was measured every 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 was presented. Accordingly, from 150gm of sample each experiment bottle we got, Experiment one was 395.48 ml/ g, Experiment two was 383.70 ml/ g, and Experiment three was 400.8 ml/ g from 150gm of each experiment, an average of 393.326ml/gm. Following the conversion of ml/g to m^3/kg, sample one was 0.395m^3/kg, sample two was 0.384m^3/kg, and sample three was 0.401m^3/kg. Based on the energy conversion of methane to MJ by multiplying the values, sample one had 14.24 MJ/kg, sample two had 13.81 MJ/kg, and sample three had 14.43 MJ/kg. This finding is consistent with the study finding the result of feces gasification (Onabanjo et al., 2016) and Hydrothermal liquefaction (Badrolnizam et al., 2019) of human feces which shows, 15 MJ/Kg and 12.36 MJ/Kg respectively.

The CH4 recuperated from anaerobic digestion systems is regularly of great quality and not only represents energy recovery but too avoids the discharge of CH4 into the environment(Pearson, 1996)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 (Pearson, 1996)and (Bitton, 1999)

The bio-fertilization potential of human feces was evaluated in our study using nutrient analysis, particularly the NPK. Human feces contain nutrients that are very important for plant growth. For instance, it contains potassium (2.29 mg/kg, 2.29%),Phosphorus (1.12mg/kg,1.12% and nitrogen (4.29gm/kg, 4.26%). This finding is consistent with others from other studies(Sugihara, 2020b; Usman et al., 2021). The ratio of C:N (9.15), The ratio C: S (191) is higher than the ratio of N: S (21.32) analyzed after energy recovery in human feces. Human feces is rich in phosphorus and potassium, and Nitrogen which is important plant nutrient, and it also contains carbon, which can increase the fraction of organic matter in soils. More organic matter in soils is especially important to improve the soil structure. It is additionally known that an increment in organic matter through the utilization of compost can make plants more salt-tolerant as appeared in Swiss chard and common beans (Smith, 2001) and apple trees (Engel, 2001).

The utilization of renewable energy (biogas) from organic waste as a resource isn't as it were "greener" concerning most toxins, but offers a successful strategy for the treatment and transfer of expansive amounts of organic waste. Biogas recovery from anaerobic digesters yields resources with significant financial and intangible esteem. Since anaerobic absorption removes carbon, nutrients contained within the organic matter are preserved and mineralized to more dissolvable and naturally accessible shapes; the digestate has higher supplements than in untreated natural waste. Fabien (2003) reported that digestate has 25% more accessible NH4-N (inorganic nitrogen) and better pH esteem than untreated fluid squanders. Thus it can be utilized as fertilizer or soil amendment in agriculture (Fabien, 2003) and(Angelidaki and Ellegaard, 2003), those nutrients (macro-nutrients and micro-nutrients) in table 5 keep up or improves soil structure due to the application of organic matter conjointly contain nutrients PNK those nutrients are very vital for plant fertilizer.

This gives a more predictable, quick-release natural fertilizer that can be applied to cropland for maximum plant nutrient take-up with minimal loss to the environment. This fertilizer can increment the yields of crops, progress the fertility of the soil and have the potential for wide utilization. According to (Fabien, 2003) the treatment can moreover lead to a reduction of up to 80% of the odor and it crushes essentially all weed seeds, in this way diminishing the requirement for herbicide and other weed control measures.

The AD fertilizer can be also applied in combination with chemical fertilizers. The reasonably combined application of AD fertilizer with chemical fertilizer can make up for each other's insufficiencies and reduce the contradiction between the requirements of crops for nutrient components and the fertilizer Other than that, AD fertilizer contains relatively diversified nutrients and has slow-and- speedy-acting manorial impact concurrently, able of promoting the development of crops and the movement of soil organisms and protecting the richness of the soil. This will decrease the utilization of chemical fertilizer, cut down the agricultural cost, avoid the destruction of soil structure resulting from much application of chemical fertilizer and protect the ecological environment of soil to supply the conditions for a maintained increment in yield (Abebe Worku., 2007). In this manner, organic fertilizer that can be recouped is significant in which supply of the soil.

Limitations of the study

We did not include a sample of human urine because we only analyzed the feces, which could have resulted in different results. In this study, the lab-scale evaluation result is from a controlled environment; if it is conducted in a real environment, it may have a different result, so we recommend the pilot study in a real environment to optimize the finding for a specific study site. The limit of articles done on only feces.

7. CONCLUSION AND RECOMMENDATIONS

7.1. Conclusion

In conclusion, this study demonstrated the experimental biogas generation of sample human feces in a batch experiment. The theoretical methane yield and potential for resource recovery of human feces were all analyzed to check the fertilizer potential of human feces. The methane meter cubes per head per year were 28.71 (28.03–29.27) in the experimental result and 45.26 for the theoretical yield of methane. The results obtained from this study showed that the bio-methane potential of human feces satisfied energy recovery and alternative sanitation options, providing a positive remedy for the sanitation crisis in urban settings.

On the other hand, the compost potential of the slurry of the biogas reactor has positive nutrient values that have significant fertilizer potential that can replace inorganic fertilizer. Biogas toilets will be important alternatives to traditional sanitation solutions if they are implemented in future urban sanitation platforms. More research into the technical feasibility and sanitation technologies associated with the biogas reactor, as well as a local sanitation system, is required to connect this advanced waste treatment option to urban settings.

7.2Recommendations

The following recommendations are made based on the experimental work done in this study on the possibility of biogas toilets as a sanitation option for urban sanitation solutions, energy recov ery from human feces, and the compost potential of human feces:

- Further research into the technical feasibility and sanitation technologies associated with the biogas reactor, as well as a local sanitation system, is required to connect this advanced waste treatment option to urban settings.
- Additional small-scale field tests required to integrate the byproducts of a biogas reactor in agricultural fields have to be conducted to evaluate the plant nutritional value of the feces compost.
- Despite the scientific findings supporting energy recovery and compost potential of human feces, the community acceptance and cultural implications of using feces products may require further study to change this approach to alleviate the sanitation crisis in many towns in Ethiopia.

REFERENCES

Ahmed A and Huq-Hussain S (2011) Solid waste management system of Narayanganj city: An environmental study. *Journal of Soil Science and Environmental Management* 2(8): 212–219.

Alirol E, Getaz L, Stoll B, et al. (2011) Urbanisation and infectious diseases in a globalised world. *The Lancet infectious diseases* 11(2). Elsevier: 131–141.

Angelidaki I and Ellegaard L (2003) Codigestion of manure and organic wastes in centralized biogas plants: status and future trends. *Applied Biochemistry and Biotechnology* 109(1–3): 95–105. DOI: 10.1385/abab:109:1-3:95.

Austermann-Haun U, Seyfried CF, Kunst S, et al. (1994) Anaerobic pretreatment in campaign industries.

B SB, P JP and Madhu G (2014) Optimization of Process Parameters Affecting Biogas Production from Organic Fraction of Municipal Solid Waste via Anaerobic Digestion. *International Journal of Bioengineering and Life Sciences* 8(1): 43–48.

Badrolnizam RS, Elham OSJ, Hadzifah SN, et al. (2019) Sewage sludge conversion via hydrothermal liquefaction (HTL) – A preliminary study. *Journal of Physics: Conference Series* 1349(1). IOP Publishing: 012108. DOI: 10.1088/1742-6596/1349/1/012108.

Barragán-Escandón A, Olmedo Ruiz JM, Curillo Tigre JD, et al. (2020) Assessment of power generation using biogas from landfills in an equatorial tropical context. *Sustainability* 12(7). MDPI: 2669.

Berendes DM, Kirby AE, Clennon JA, et al. (2018) Urban sanitation coverage and environmental fecal contamination: Links between the household and public environments of Accra, Ghana. *PLoS ONE* 13(7): e0199304. DOI: 10.1371/journal.pone.0199304.

Beyene A, Hailu T, Faris K, et al. (2015) Current state and trends of access to sanitation in Ethiopia and the need to revise indicators to monitor progress in the Post-2015 era. *BMC Public Health* 15(1): 451. DOI: 10.1186/s12889-015-1804-4.

Buswell AM and Mueller HF (1952) Mechanism of methane fermentation. *Industrial & Engineering Chemistry* 44(3). ACS Publications: 550–552.

Chen Y, Cheng JJ and Creamer KS (2008) Inhibition of anaerobic digestion process: A review. *Bioresource Technology* 99(10): 4044–4064. DOI: 10.1016/j.biortech.2007.01.057.

Chow WL, Chong S, Lim J-W, et al. (2020) Anaerobic Co-Digestion of Wastewater Sludge: A Review of Potential Co-Substrates and Operating Factors for Improved Methane Yield. *undefined*.

Clasen TF, Bostoen K, Schmidt W-P, et al. (2010) Interventions to Improve Excreta Disposal for Preventing Diarrhoea. *Cochrane Database of Systematic Reviews* (6). Available at: https://digitalcommons.georgiasouthern.edu/epid-facpubs/8 (accessed 2 November 2022).

CSA-Ethiopia (2013) *Population-Projection-At-Wereda-Level-from-2014-2017*. Addis Ababa, Ethiopia: Central Statistical Agency. Available at: https://www.statsethiopia.gov.et/population-projection/.

Dasgupta S, Agarwal N and Mukherjee A (2021) Moving up the On-Site Sanitation ladder in urban India through better systems and standards. *Journal of Environmental Management* 280: 111656. DOI: 10.1016/j.jenvman.2020.111656.

Deublein D and Steinhauser A (2011) *Biogas from Waste and Renewable Resources: An Introduction*. John Wiley & Sons.

Devaraj R, Raman RK, Wankhade K, et al. (2021) Planning fecal sludge management systems: Challenges observed in a small town in southern India. *Journal of Environmental Management* 281: 111811. DOI: 10.1016/j.jenvman.2020.111811.

Dhaked RK, Waghmare CK, Alam SI, et al. (2003) Effect of propionate toxicity on methanogenesis of night soil at phychrophilic temperature. *Bioresource Technology* 87(3): 299–303. DOI: 10.1016/s0960-8524(02)00227-4.

Donacho DO, Tucho GT, Zeine Ousman W, et al. (2022) Evidence-Based User Interface Sanitation Technology Selection for Urban Slums: A Multi-Criteria Analysis; The Case of Jimma Town, Ethiopia. *Environmental health insights* 16. SAGE Publications Sage UK: London, England: 11786302221127270.

Donacho DO, Tucho GT and Hailu AB (2022) Households' access to safely managed sanitation facility and its determinant factors in Jimma town, Ethiopia. *Journal of Water, Sanitation and Hygiene for Development* 12(2). IWA Publishing: 217–226.

Downie C (2020) Strategies for Survival: The International Energy Agency's response to a new world. *Energy Policy* 141: 111452. DOI: 10.1016/j.enpol.2020.111452.

Drangert J-O, Tonderski K and McConville J (2018) Extending the European Union Waste Hierarchy to Guide Nutrient-Effective Urban Sanitation toward Global Food Security—Opportunities for Phosphorus Recovery. *Frontiers in Sustainable Food Systems* 2.

Droste R (1996) Theory And Practice Of Water And Wastewater Treatment. *undefined*. Available at: https://www.semanticscholar.org/paper/BIOLOGICAL-WASTE-WATER-TREATMENT%3A-1.-MONITORING-OF-Iordan-Ardelean/fe8c6cef4a3706c279381ecd74d2e70d362861ec (accessed 2 November 2022).

Ecohydrology & Hydrobiology (2018) Fecal contamination of soil and water in sub-Saharan Africa cities: The case of Addis Ababa, Ethiopia. 18(2). Elsevier: 225–230. DOI: 10.1016/j.ecohyd.2017.10.003.

Esposito G, Frunzo L, Liotta F, et al. (2012) Bio-Methane Potential Tests To Measure The Biogas Production From The Digestion and Co-Digestion of Complex Organic Substrates. *The Open Environmental Engineering Journal* 5(1). Available at: https://benthamopen.com/ABSTRACT/TOENVIEJ-5-1 (accessed 2 November 2022).

Foreest F van (2012) *Perspectives for Biogas in Europe*. December. Oxford Institute for Energy Studies. DOI: 10.26889/9781907555633.

Gerardi MH (2003) *The Microbiology of Anaerobic Digesters*. John Wiley & Sons.

Gretsch SR, Ampofo JA, Baker KK, et al. (2015) Quantification of exposure to fecal contamination in open drains in four neighborhoods in Accra, Ghana. *Journal of Water and Health* 14(2): 255–266. DOI: 10.2166/wh.2015.138.

Guest JS, Skerlos SJ, Barnard JL, et al. (2009) A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater. *Environmental Science & Technology* 43(16). American Chemical Society: 6126–6130. DOI: 10.1021/es9010515.

Kaparaju P and Rintala J (2013) 17 - Generation of heat and power from biogas for stationary applications: boilers, gas engines and turbines, combined heat and power (CHP) plants and fuel cells. In: Wellinger A, Murphy J, and Baxter D (eds) *The Biogas Handbook*. Woodhead Publishing Series in Energy. Woodhead Publishing, pp. 404–427. DOI: 10.1533/9780857097415.3.404.

Köttner M, Kaiser A and Avendaño MV (2003) Dry fermentation biogas technology – a practical approach for closed loop sanitation, waste stabilisation and nutrient recovery.: 8.

Kulabako NR, Nalubega M and Thunvik R (2007) Study of the impact of land use and hydrogeological settings on the shallow groundwater quality in a peri-urban area of Kampala, Uganda. *Science of The Total Environment* 381(1): 180–199. DOI: 10.1016/j.scitotenv.2007.03.035.

Kundu D and Pandey AK (2020) World urbanisation: trends and patterns. In: *Developing National Urban Policies*. Springer, pp. 13–49.

Lansing S, Botero RB and Martin JF (2008) Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresource Technology* 99(13): 5881–5890. DOI: 10.1016/j.biortech.2007.09.090.

Lüthi C, Hoffmann S and Willetts J (2020) *City-Wide Sanitation: The Urban Sustainability Challenge*. Frontiers Media SA.

Mara D, Lane J, Scott B, et al. (2010) Sanitation and health. *PLoS medicine* 7(11). Public Library of Science San Francisco, USA: e1000363.

Mata-Alvarez J (2005a) *Biomethanization of the Organic Fraction of Municipal Solid Wastes*. DOI: 10.2166/9781780402994.

Mata-Alvarez J (2005b) *Biomethanization of the Organic Fraction of Municipal Solid Wastes*. DOI: 10.2166/9781780402994.

Mills F, Willetts J, Petterson S, et al. (2018) Faecal Pathogen Flows and Their Public Health Risks in Urban Environments: A Proposed Approach to Inform Sanitation Planning. *International Journal of Environmental Research and Public Health* 15(2). 2. Multidisciplinary Digital Publishing Institute: 181. DOI: 10.3390/ijerph15020181.

Munisamy P, Ravichandran M, Natarajan SD, et al. (2021) Biological aspects of anaerobic digestion and its kinetics: An overview. *Journal of Microbiology, Biotechnology and Food Sciences* 2021. Faculty of Biotechnology and Food Sciences in Nitra, Slovakia: 1090–1097.

Noraini M, Sanusi S, Elham J, et al. (2017) FACTORS AFFECTING PRODUCTION OF BIOGAS FROM ORGANIC SOLID WASTE VIA ANAEROBIC DIGESTION PROCESS: A REVIEW. *SOLID STATE SCIENCE AND TECHNOLOGY* 25: 29–39.

Nwaneri C, Foxon K, Bakare B, et al. (2008) Biological degradation processes within a pit latrine. 1.

O'Kennedy OD (2000) *Application of biogranules in the anaerobic treatment of distillery effluents*. Thesis. Stellenbosch : Stellenbosch University. Available at: https://scholar.sun.ac.za:443/handle/10019.1/51617 (accessed 2 November 2022).

Onabanjo T, Patchigolla K, Wagland ST, et al. (2016) Energy recovery from human faeces via gasification: A thermodynamic equilibrium modelling approach. *Energy Conversion and Management* 118: 364–376. DOI: 10.1016/j.enconman.2016.04.005.

Onochie UP, Obanor AI, Aliu SA, et al. (2017) PROXIMATE AND ULTIMATE ANALYSIS OF FUEL PELLETS FROM OIL PALM RESIDUES. *Nigerian Journal of Technology* 36(3). 3: 987–990. DOI: 10.4314/njt.v36i3.44.

Onojo J, Okafor E, Ononiwu G, et al. (2013) Estimation Of The Electric Power Potential Of Human Waste Using Students Hostel Soak-Away Pits. *American Journal of Engineering Research (AJER)* 02(09): 198–203.

Owamah HI, Dahunsi SO, Oranusi US, et al. (2014) Fertilizer and sanitary quality of digestate biofertilizer from the co-digestion of food waste and human excreta. *Waste Management* 34(4): 747–752. DOI: 10.1016/j.wasman.2014.01.017.

Patel K and Thillainayagam AV (2009) Diarrhoea. *Medicine* 37(1). Acute medicine Part 1 of 2: 23–27. DOI: 10.1016/j.mpmed.2008.11.003.

Peal A, Evans B, Ahilan S, et al. (2020) Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science* 8. Available at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.00001 (accessed 3 November 2022).

Prüss-Ustün A, Wolf J, Bartram J, et al. (2019) Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low-and middle-income countries. *International journal of hygiene and environmental health* 222(5). Elsevier: 765–777.

Rajaonahy MR, Rakotondramiarana HT, Rakotoarisoa LL, et al. (2016) Experimental Investigation of Anaerobic Co- Digestion of some Organic Wastes in Madagascar. 3(1): 7.

Rice EW, Baird RB, Eaton AD, et al. (2012) *Standard Methods for the Examination of Water and Wastewater*. American public health association Washington, DC.

Ritchie H and Roser M (2019) Sanitation. *Our World in Data*. Available at: https://ourworldindata.org/sanitation.

Schiffer H-W, Kober T and Panos E (2018) World Energy Council's Global Energy Scenarios to 2060. *Zeitschrift für Energiewirtschaft* 42(2): 91–102. DOI: 10.1007/s12398-018-0225-3.

Seppälä M, Pyykkönen V, Väisänen A, et al. (2013) Biomethane production from maize and liquid cow manure – Effect of share of maize, post-methanation potential and digestate characteristics. *Fuel* 107: 209–216. DOI: 10.1016/j.fuel.2012.12.069.

Singh S, Patro S, Dey S, et al. (2017) Technology Options for the Sanitation Value Chain. *Center for Study of Science and Technology (CSTEP). Bangalore, India*.

Singhal Y, Bansal DrS and Singh R (2022) Evaluation of Biogas Production from Solid Waste using Pretreatment Method in Anaerobic Condition.

Sugihara R (2020a) Reuse of Human Excreta in Developing Countries: Agricultural Fertilization Optimization. *Consilience* (22). Columbia University: 58–64. Available at: https://www.jstor.org/stable/26924962 (accessed 2 November 2022).

Sugihara R (2020b) Reuse of Human Excreta in Developing Countries: Agricultural Fertilization Optimization. *Consilience* (22). Columbia University: 58–64. Available at: https://www.jstor.org/stable/26924962 (accessed 2 November 2022).

Tarvin D and Buswell AM (1934) The methane fermentation of organic acids and carbohydrates1, 2. *Journal of the American Chemical Society* 56(8). ACS Publications: 1751–1755.

Tran-Thi N, Lowe RJ, Schurer JM, et al. (2017) Turning poop into profit: Cost-effectiveness and soil transmitted helminth infection risk associated with human excreta reuse in Vietnam. *PLOS Neglected Tropical Diseases* 11(11). Public Library of Science: e0006088. DOI: 10.1371/journal.pntd.0006088.

Ullah Khan I, Hafiz Dzarfan Othman M, Hashim H, et al. (2017) Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage. *Energy Conversion and Management* 150: 277–294. DOI: 10.1016/j.enconman.2017.08.035.

UN (2018) *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*. United Nations New York.

UN-water (2020) Water , Sanitation and Hygiene fact sheet.

Usman MN, Suleiman MA and Binni MI (2021) Anaerobic digestion of agricultural wastes: A potential remedy for energy shortfalls in Nigeria. *Scholarena* 4(1).

Wagner L (2015) Trends from the use of biogas technology in Germany. In: *Proceedings of the VIV Asia biogas conference*, 2015.

WHO (2020) *Global Health Observatory (GHO) Data Use of Basic and Safely Managed Sanitation Services*.

WHO and UNICEF (2020) *State of the world's sanitation: An urgent call to transform sanitation for better health, environments, economies and societies*. New York. Available at: https://www.who.int/publications-detail-redirect/9789240014473.

Wilkie AC (2005) Anaerobic digestion: biology and benefits. *Dairy manure management: treatment, handling, and community relations*. Natural Resource, Agriculture, and Engineering Services (NRAES), Cornell …: 63–72.

Yadav S, Kumar B and Thipse SS (2013) Characteristics of Biogas Operated Automotive SI Engine to Reduce Exhaust Emission for Green Development. *SAE Technical Papers* 5. DOI: 10.4271/2013-26-0012.

Yadvika, Santosh, Sreekrishnan TR, et al. (2004) Enhancement of biogas production from solid substrates using different techniques—a review. *Bioresource Technology* 95(1): 1–10. DOI: 10.1016/j.biortech.2004.02.010.

Yusuf MOL, Debora A and Ogheneruona DE (2011) Ambient temperature kinetic assessment of biogas production from co-digestion of horse and cow dung. *Research in Agricultural Engineering* 57(No. 3): 97–104. DOI: 10.17221/25/2010-RAE.

Zavala MAL and Funamizu N (2005) Effect of Moisture Content on the Composting Process In a Biotoilet System. *Compost Science & Utilization* 13(3). Taylor & Francis: 208–216. DOI: 10.1080/1065657X.2005.10702242.

Zhang Q, Hu J and Lee D-J (2016) Biogas from anaerobic digestion processes: Research updates. *Renewable Energy* 98. Special Issue: New Horizons in Biofuels Production and Technologies: 108–119. DOI: 10.1016/j.renene.2016.02.029.

Ziegelbauer K, Speich B, Mäusezahl D, et al. (2012) Effect of Sanitation on Soil-Transmitted Helminth Infection: Systematic Review and Meta-Analysis. *PLOS Medicine* 9(1). Public Library of Science: e1001162. DOI: 10.1371/journal.pmed.1001162.

B., A. (2014). Biogas production of cow dung and banana peels.

Dangoggo M, A. M. (1996). The effect of seedings with bacteria on biogas production rate. *Renewable Energy, ELsevier* .

J.L. Walsh, C. R. (1989). *Utilization of biogas.* Georgia ,Atlanta G: ELSEVIER.

Mantana P, S. U. (2005). A Discussion on Facters Afecting Biogas Production and Field Investigation of Novel Duplex Digester. *Biogas Digester* , SESI J 15(2).;1-2.

Nabila L, O. H. (2015). Experimental Facters Affecting the Prodtion of Biogas during Anaerobic Digestion of Biodegradable waste. *Int J Environ Sci Dev.* , 6(6),451-4.

Zhengyun Z, D. H. (2013). Biogas yield potential Research of the wastes from Banana Manufucturing process under Msofphilic Anaerobic fermentation. *Res Appl Sci Eng Technol* , 5(19):4740-4.

Annex 1: Data collection format

The bio-methane potential of human feces

Data collection table for (Bio-methane potential of human feces) BMP test

(Code :______)

Tests		**Observation (Results)**					**Remark**
		Sample one	**Sample two**	**Sample three**	**Mean**	**Standard deviation**	
TS (wt %)							
VS (wt %)							
VS/TS							
Carbon (%)							
Nitrogen (%)							
Ph							
C/N ratio							
COD_D (mg/L)							
COD_T (mg/L)							
Methane yield (CH_4) **(Every other day)**	2nd day						
	4th day						
	6th day						
	8th day						

	10^{th} day						
	12^{th} day						
	14^{th} day						
	16^{th} day						
	18^{th} day						
	20^{th} day						
	22^{nd} day						
	24^{th} day						
	26^{th} day						
	28^{th} day						
	+ 30^{th} day						
Total CH_4 m^3/ 28days							
Methane yield $Y_{CH_4}[m^3Kg^{-1}] = \frac{CH_{4-output}}{VS_{-input}}$							

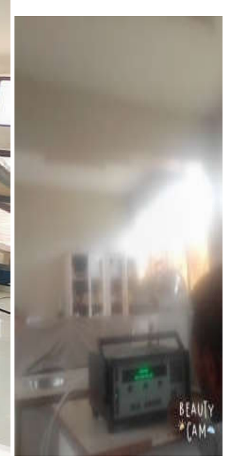
Annex 2:

Pictures for analysis Biomethane potential 28-day experimental batch experiment procedure

B, Feces, and Urine divert slab **A, Eco-Sn dry toilet**

C:Human sample deposit place

D: Sample Bottle (250ml bottle



E: Sample measurement machine F: Sample contains bottle G:multi-gas measurement

Pictures for macronutrient and micronutrient procedure

H: Diluted sample I: Analyze machine