DEVELOPMENT OF A MATHEMATICAL MODEL FOR PREDICTING BIO-SLURRY TEMPERATURE AND SUBSEQUENT GAS PRODUCTION RATE FOR UNDERGROUND BRICK-BUILT BIOGAS DIGESTER USING AMBIENT AIR TEMPERATURE FORECAST

A Thesis Submitted in Partial Fulfilment of the requirements for the Degree of Doctor of Philosophy (PhD) In Physics

By

Nekhubvi Vhutshilo 1st Mountaineer

Student Number:11520748

School of Mathematical and Natural Sciences,

University of Venda

THOHOYANDOU, LIMPOPO PROVINCE

Supervisor: Dr David Tinarwo

Co-Supervisor: Prof Harro von Blottnitz

August 2022

Declaration

Nekhubvi Vhutshilo 1st Mountaineer declares that this research work is original and has not been submitted for any other degree at any other university or tertiary institution. The research work does not contain other persons' writing unless acknowledged and referenced accordingly.

Signed (Student): Date: 19/08/2022

Nekhubvi Vhutshilo 1st Mountaineer

Abstract

Background: Heat energy is essential for the anaerobic digestion of organic materials such as household, human or agricultural waste. Many developing countries have witnessed efforts to implement anaerobic digestion technology for biogas production as a strategy to enhance energy supply and poverty eradication in rural communities. Underground, brick, and mortar built fixed dome type digesters are the most deployed small-scale biogas technology in sub-Saharan Africa (SSA) countries such as Rwanda, Ethiopia, Tanzania, Kenya, Uganda, Burkino Faso, Cameroon, Benin, Senegal, and South Africa despite their relatively high initial costs. They have a long lifespan and no moving or rusting parts involved. The basic design is compact, saves space, is well insulated, and does not need additional heating, hence suitable for developing countries. The technology is labour-intensive that involves digging the pit and constructing the structure from underground, thus creating local employment. Unlike prefabricated biogas digesters, underground, brick, and mortar-built fixed dome type digesters are more robust than the latter, with minimal gas pipes corrosion experienced.

However, little literature on this type of digesters' actual field operation and performance within the SSA context is available. The end-user must know what needs to be done and what the system's outcome is supposed to be. Besides determining parameters like total solids, volatile solids, carbon-nitrogen ratio, hydrolysis rate, organic loading rate, and hydraulic retention time, the temperature inside the digester becomes one of the metrics to evaluate the anaerobic digestion process. The digestion temperature critically affects the biogas yield, considering all other conditions unchanged. Knowing the operational temperature, one can estimate the maximum specific growth rate of the microorganisms and the biogas production rate. Prediction models for the internal operating temperature of these digesters under local conditions typical of Limpopo province of South Africa, where most of these digesters have

been installed, are still lacking. To ordinary users in rural areas, the prediction of the possible 'duration of use,' for example, the duration of continuous cooking, is essential. However, regardless of fulfilling all other operational requirements to predict daily gas production, internal digester temperature remains the missing link to having a complete set for a quick and easy gas yield estimation.

Aim of the study: The overall objective was to develop a locally applicable model for predicting the bio-slurry operating temperature of underground brick-built domestic size biogas digesters. The work established a correlation of ambient air temperature with the slurry temperature inside the digester using a heat transfer mechanism through the media between the fermenting slurry and the ambient air.

Methodology: A thermodynamic study of a small-scale fixed-dome Deenbandhu biogas digester model was performed by monitoring the digester's temperature and surroundings. The K-type chromium-nickel temperature sensors with a sensitivity of 41 μV/°C and a response time of 0.8 s in liquids were positioned at the centre of the digester to measure the slurry temperature. Another temperature sensor was placed 2.0 m above the ground to measure ambient air temperature. The sensors were connected to the data logger and programmed to record temperature readings every second, automatically averaged hourly and daily. The soil surface heat flux was computed using Fourier's law of heat conduction to strengthen the model.

Results: The average daily bio-slurry temperature of the digesters ranged between psychrophilic and mesophilic ranges. The results show a strong correlation between bio-slurry and ambient air temperature. A strong correlation was obtained between the measured and predicted temperature of the fermenting slurry inside the digester with a $\Pr(>|t|)$ value less than $2e^{-16}$ ***, showing that the model is most significant. A Q-Q plot was also used to measure the importance of each observation to the regression.

Conclusion: The developed models can accurately estimate the bio-slurry temperature inside the digester using local ambient air temperature data. The set equation adds value as input to the research of small-scale household biogas digesters. Furthermore, the biogas production rate was calculated using data on predicted slurry temperature. It was found that the biogas production rate is satisfactory, given the condition of the study area. The biogas production rate varies from as low as 0.18 $m^3 m^{-3} d^{-1}$ during the cold month to 0.48 $m^3 m^{-3} d^{-1}$ during the warmest month. Temperatures above 20 ℃ were more conducive to a high biogas production rate.

Keywords: Temperature, Biogas digester, Heat transfer, Thermodynamics, Radiation, Heat Loss, Heat Gain.

Acknowledgements

Thank Dr David Tinarwo and Professor Harro von Blottnitz for their guidance and encouragement. They helped me understand the background and objectives of this thesis well. I would not have achieved this work without their continuous guidance, patience, and wisdom. They also allowed me to share my research work at an international forum in Germany; I also had an opportunity to visit a biogas laboratory and large–scale biogas digester system for electricity. They further accepted me as their PhD student and academically supported me. The study was funded by the Department of Science and Innovation (DSI) and managed by the National Research Foundation (NRF), Limpopo Economic development and tourism (LEDET), and Water Research Commission (WRC). I want to extend my gratitude to all staff members of Vele secondary school and community members of Gogogo, Fefe, and Mavhode village for working with me. I thank all reviewers for their constructive comments during the proposal, scientific papers, and thesis. I want to give my heartfelt appreciation to my wife, Anita. Finally, I thank all members of the Physics Department of the University of Venda for their guidance.

Table of contents

List of Figures

List of Tables

Acronyms

Above-ground biomass (AGB)

Anaerobic digestion (AD)

Biochemical Oxygen Demand (BOD)

Carbon Dioxide (CO_2),

Carbon/Nitrogen (C/N)

Chemical Oxygen Demand (COD)

Degree Celsius (°C)

Department of Basic Education (DBE)

Department of Environmental, Forestry, and Fisheries (DEFF)

Digester Volume, V_d,

Finite Element Method (FEM)

The flow rate of a digester, Q_d

Greenhouse gases (GHG)

Hydraulic Retention Time (HRT)

Hydrogen Sulphide (H_2S)

Infrared spectrum (IR)

Mega Watt (MW)

Methane (CH_4)

Multiphase flow anaerobic digester (MFD)

National Development Agency [NDA].

National School Nutrition Programme (NSNP)

Organic Loading Rate (OLR)

South Africa (SA)

Sub-Sahara Africa (SSA)

Thulamela Local Municipality (TLM)

Vhembe district municipality (VDM)

Volatile Solids (VS)

Nomenclature

Kilogram(kg)

kilowatt-hour(kWh)

Megawatt hour(MWh)

Litre, *L*

Millilitre per gram, mL/g

Volumetric biogas yield, (L/L)/day

Specific heat, kJ/kg K

Cubic meter (m^3)

Joules, (J)

Air temperature (T_a)

T_s , is slurry temperature.

β_0 , is the theoretical slurry temperature intercept.

β_1 , is the theoretical slope of the specific straight line.

k , is the thermal conductivity of soil and the digester cover.

h, is the heat flux coefficient.

The thickness of the ground and the cover (δ)

$\sum R_{tot}$, is the total thermal resistance.

C_{slurry} , is the specific heat capacity.

m_{slurry} , is the mass of the slurry inside the digester.

Heat gained by the digester(Q_{gained})

The volumetric heat conductivity(k_s).

The soil surface or soil surface heat flux ($G(t)$)

Soil surface temperature(T_{ss})

D_0 i a constant thermal diffusivity

S_o is the concentration of organic components in the cow dung

$\dot{Q}_{conv}$, is the heat transfer by convection

$\dot{Q}_{rad}$, *is* the heat transfer by radiation.

$\dot{Q}_{cond}$ s the heat transfer by conduction.

Ωs_2 is the sunset angle.

Ωs_1 *is* the sunrise angles.

$\bar{q}''$, is the average daytime solar radiation flux.

λ is the soil thermal conductivity.

U_{dw} is the average heat transfer coefficient.

U_{df} is the average heat transfer coefficient of the digester floor.

A_{dw} is the area of the digester wall.

A_{df}, is the area of the digester floor.

A_m, is the manure surface area.

T, is manure temperature.

T_b , is the biogas temperature.

CHAPTER 1: INTRODUCTION

1.1. Background

1.1.1. Anaerobic digestion technology for bio-energy

Poverty has been seen in most African countries as a barrier to economic growth, especially in rural areas. Nations around the globe need energy for economic, social, cultural, and technological development. With the increasing concern about harmful fossil energy sources, countries worldwide are implementing renewable energy sources (Assabumrungrat et al., 2010). The anaerobic digestion (AD) technology is traced back to the 17th century, when Volta noted that biogas production is a function of decomposing plant material (Prathmika & Patel, 2014). One of the AD product sources is biogas. Efforts to implement biogas technology to enhance energy supply and poverty eradication have been witnessed in many developing countries (Bha et al., 2001; Laichena & Wafula, 1997; Msibi & Gerrit, 2017; Mulu et al., 2016, Tewelde et al., 2017). Biogas energy plays a vital role in improving the living standard in communities. Scientific knowledge associated with biogas production and risk management, such as low gas production, is still lacking to reach the end-user in a more simplified manner.,

1.1.2. Scientific understanding of biogas

1.1.2.1. Formation of biogas

Biogas is a composition of gases generated from the AD of organic degradable material such as above-ground biomass wood, agricultural and forest wastes, human and animal excreta, and food waste (Nichols et al., 2019; Wright et al., 2019). Livestock farming has become the most significant anthropogenic source of global methane since 1983, contributing 113.1Tg methane in 1994 (Zhou et al., 2007). Ruminant animals (cattle, buffalo, sheep, goats, and camels) produce significant amounts of methane as part of their normal digestive process (Tauseef et al., 2013). The methane production rate from above enteric fermentation is affected by the quantity and quality of the animal feed, body weight, age, and exercise. It varies among individuals and animal species (Zhou et al., 2007). The methane (CH_4) that the ruminant animals exhale is impossible to capture. However, a large proportion of CH_4 produced by the manure of these animals can be captured. Waste deposited on fields and pastures also has significant amounts of CH_4. Agricultural wastes such as cow manure represent the second-largest source of greenhouse gases. Cow dung as a feedstock produces efficient biogas production (Baba & Nasir, 2012; Caruso et al., 2019; Prayoonkhama et al., 2017). It is estimated that fresh cow dung contains 28% water (Sruthy et al., 2017). For an AD to generate biogas, raw material such as fresh cow dung is mixed with water at a widely used ratio of 1:1 (Baba & Nasir, 2012). The mixture undergoes biological and physical stages that have been well-studied (Appels et al., 2008). In all steps mentioned above, responsible bacteria decompose the mixture with little or no oxygen (Rabbi et al., 2015). Alfa et al. (2014) and Bove & Lunghi (2005) indicated that biogas production also depends on the physical and chemical properties of the feedstock type used. There are four stages of the digestion process, as shown in Figure 1-1 (Sarker et al., 2019).

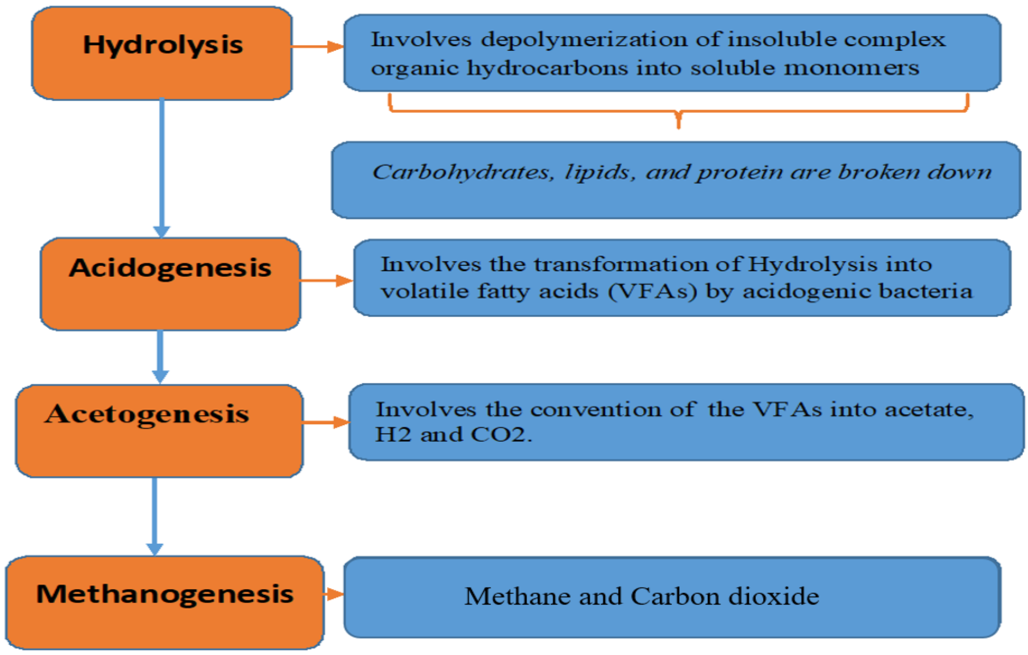


Figure 1-1. Biological and chemical stages of the digestion process.

Biogas is one of the most sustainable fuels and environmentally friendly if used responsibly and is intended to power cooking stoves and generate electricity from small watts to megawatts and as transport fuel (Bhat et al., 2001; Gaby et al., 2017). Anaerobic digestion occurs within distinct types of physical structures. The quality of biogas and quantity of biogas are essential in evaluating the success of the process.

1.1.2.2. Hydrolysis

Hydrolysis disintegrates complex carbohydrates, fats, and proteins into soluble monomers and dimers such as sugars (glucose, sucrose, and fructose), fatty acids, and amino acids (Rajendran et al., 2012). The hydrolysis process is described as a simple first-order process due to extensive variations in substrate composition and is not applicable in all circumstances (Mani & Sundaram, 2016). Park et al. (2005) identified hydrolysis of particulate matter as the rate-limiting step in AD when particulate matter is not readily degradable or in systems with high loading rates (Mani & Sundaram, 2016). It is crucial to maintain the uniform mixing and temperature and concentrated organic substrate and the microbial population inside the digester system during the hydrolysis process so that extracellular hydrolytic enzymes produced by the bacteria can have intimate contact with complex organics without limiting the overall stabilization reaction (Mani & Sundaram, 2016). The hydrolysis process rate depends on particle size and pH (Ziemiński & Frąc, 2012). The size of solids negatively affects the rate of the hydrolysis process, influencing the performance of the whole process. To avoid disadvantages due to the size of solids, expensive pre-treatments aimed at disintegrating and solubilizing substrates are conducted before AD. Pre-treatments to improve hydrolysis account for 20–40% of total process costs (Menzel et al., 2020). However, some organic substrates, although particulate, once immersed in water, tend to solubilize immediately (Panico et al., 2014). Hydrolytic microorganisms favour a slightly acidic pH of around 5.0–6.0 (Menzel et al., 2020). Myint et al. (2007) studied a mathematical model for the hydrolysis and acidogenesis reactions in the anaerobic digestion of cattle manure. Still, they did not consider the effect of pH on the hydrolysis rate due to the poor statistically significant dependence of the linear regression. Hydrolysis can be viewed from a chemical perspective by (Anukam et al., 2019);

$$(C_6H_{10}O_5)n + n\, H_2O \;\rightarrow\; n\, C_6H_{12}O_{\,6} + \; nH_2 \qquad (1.1)$$

Where, $C_6H_{10}O_5$ represents cellulose via the addition of water (H_2O) to form glucose $C_6H_{12}O_{\,6}$ as the primary product and giving off hydrogen (H_2). The concentration of degradable organic materials can be simulated using a first-order kinetics model (Mani & Sundaram, 2016).

$$\frac{dS}{dt} = -k_{hyd}S \qquad (1.2)$$

where S is the volatile solids (VS) concentration, k_{hyd} is the first-order coefficient and t is time in days. Eq. (1.2) shows that the observed solids conversion rate depends on the solid substrate concentration and the first-order hydrolysis rate constant (Guo et al., 2021). Integrating Eq. (1.2) will lead to the following solution.

$$InS = -k_{hyd}t + b \qquad (1.3)$$

Where b is the constant of the integration. $\ln S$ can be plotted against t to find the slope $-k_{hyd}$ and intercept (b). Luo et al. (2012) show that the hydrolysis rate constant increases with a rising temperature:

$$Ink = \frac{E_a}{RT} + InA \qquad (1.4)$$

Where A is the pre-exponential factor, E_a(Jmol^{-1}) is the reaction activation energy,$T(K)$ is the absolute temperature, and R is the gas constant(J·K^{-1}·mol^{-1}). The plot of Ink and $\frac{1}{T}$ can be used to find the activation energy since the linear relationship predicted by the Arrhenius equation gives a slope equal to $-\frac{E_a}{RT}$. (Kothari et al., 2018) shows that the expression can find the activation enthalpy.

$$\Delta H = Ea - RT \tag{1.5}$$

Where enthalpy $\Delta H (Jmol^{-1})$ is enthalpy, $T(K)$ is the absolute temperature, and R is the gas constant($J \cdot K^{-1} \cdot mol^{-1}$), respectively. We have found that hydrolysis represents a bottleneck stage, which requires higher temperatures to increase the degradation rate.

1.1.2.3.Composition of biogas

Biogas is a mixture of various gases besides CH_4, such as hydrogen sulphide (H_2S) and carbon dioxide (CO_2) (Jiang et al., 2011). Methane in biogas constitutes 40-75%. However, when conditions are best, some organic materials can produce biogas containing up to 80% volume of CH_4 (Huang & Crookes, 1998; Msibi & Kornelius, 2017; Yang et al., 2019). Methane (CH_4) is the most desired gas for energy supply. Compounds such as H_2S and CO_2 are removed using different methods, such as absorption and adsorption, as shown in Figure 1-2. The energy content of biogas is directly proportional to the CH_4 concentration (Jiang et al., 2011); Torii & Rashed Al Mamun, 2017).

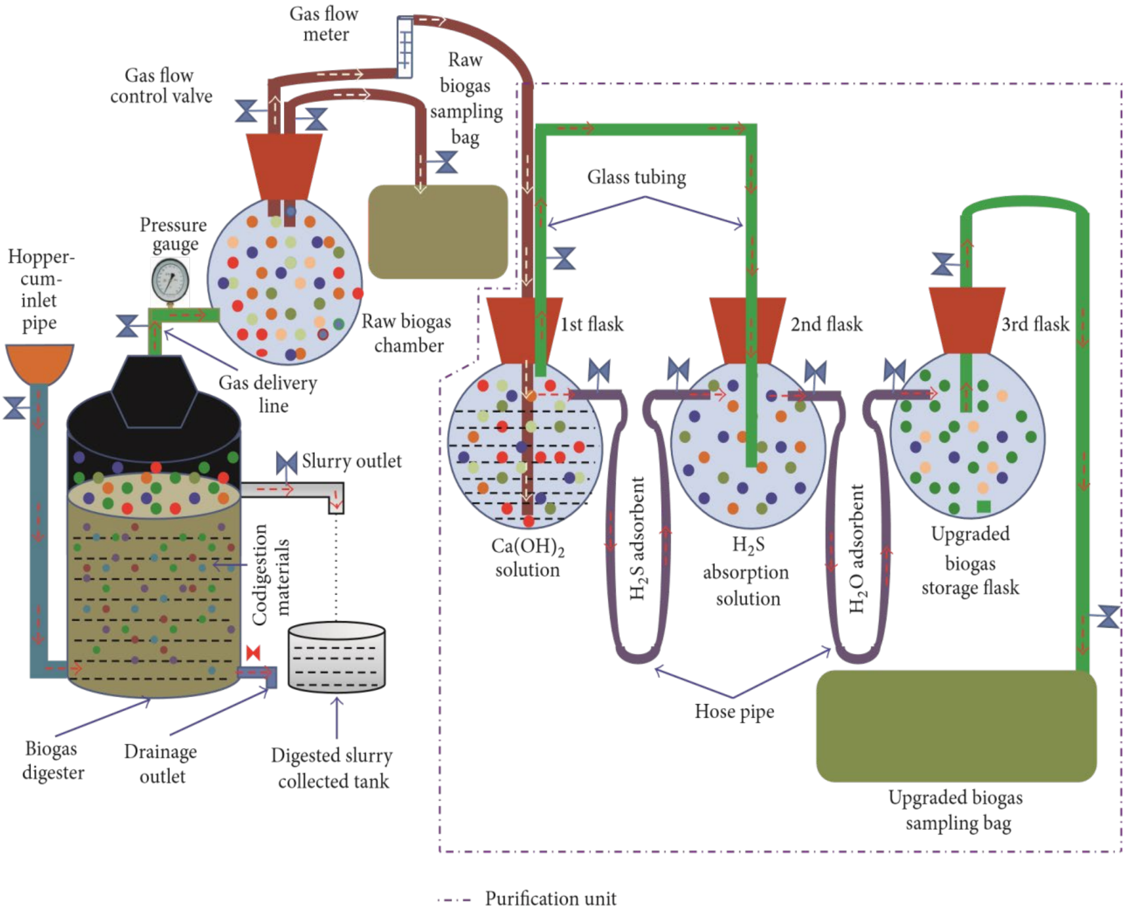


Figure 1-2. Purification of raw biogas *(Torii & Rashed Al Mamun, 2017)*

1.1.3. Household biogas digesters

Biogas digesters range from small-scale systems primarily found in rural areas to industrial-scale biogas systems for electricity generation (Shukla et al., 2018). As for the family-type small-scale biogas digester or household biogas digester, there exist many types: fixed dome digester, floating drum digester, and plastic tubular bio-digester (Ho et al., 2015). The disadvantages and advantages of household fixed dome digesters, floating drum digesters, and plastic tubular bio-digester systems are shown in Table 1-1.

Table 1-1: Advantages and disadvantages of three types of household biogas digester systems.

Digester type	Advantages	Disadvantages

Fixed dome digester	Low initial cost Long useful lifespan No moving parts Less land is required if built underground Low maintenance	Requires high technical skills. Difficult to repair in case of leakage. Requires heavy construction materials The amount of gas produced is not immediately visible.
Floating drum digester	Simple and easy to understand Visible stored gas volume Constant gas pressure Relatively easy construction	High material costs because of the extra steel drum Short lifespan because of steel drum corrosion High maintenance because of the regular painting of drum
Plug flow digester	Low cost. Ease of transportation Low construction sophistication Uncomplicated maintenance Less subject to climatic variations for fixed dome type (Kalia, 1988)	Short lifespan High susceptibility to damage Low gas pressure Limited creation of local employment High impact on the environment, less environmental-friendly (Pérez et al., 2014)

The fixed dome digester types are the most deployed small-scale biogas technology in sub-Sahara Africa (SSA). However, little or no literature on this type's actual field operation and performance within the SSA context because monitoring anaerobic digestion is difficult and complex (Mane et al., 2015). However, the monitoring complexity should not increase the cost of the investigation (Schievano et al., 2016). The development of the first biogas digesters in South Africa (SA) dates to the 1950s. Since their introduction, the number of digesters installations has been about 700 (Amigun & Blottnitz, 2010; Mutungwazi et al., 2018)

1.1.4. Anaerobic digestion process evaluation.

Like any other existing technology, specific measures ensure its success. The metrics to evaluate the AD process, such as Biochemical Oxygen Demand (BOD), provide an estimate of biodegradable organics present in sludge and, in turn, can be used for the overall effectiveness of an anaerobic digester. Chemical Oxygen Demand (COD) measures the oxygen in a sludge sample. The general gas equation to find a theoretical molar and volumetric output of CH_4 is given by (Buswell & Mueller, 1952).

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 \qquad (1.6)$$

Eq. (1.6) shows that only CH_4 and CO_2 are produced.

1.1.5. Operational Challenges affecting Household biogas digester system

Biogas digester has vast potential in many rural areas and can generate environmental, health, and social benefits with a net positive impact on energy access but its use are minimal (Pilloni & Hamed, 2021). Low acceptance of biogas technology in many African countries has been a technology barrier (Msibi & Kornelius, 2017; Prasad, 2012). Some installed household digesters system has been abandoned due to expected lower biogas production. Failure of these household digesters may be caused by poor feeding due to water unavailability, lack of technical knowledge, or low digester operating temperature (Gebreegziabher et al., 2014; Kornelius & Msibi, 2017; Rastogi et al., 2008). Rennuit & Sommer (2013) indicated that, among other factors, the operational temperature of the biogas digester is the most critical parameter for optimum biogas production. Dhaked et al. (2010), Mane et al. (2015), and Ramaswamyy & Vemareddy (2015) showed that there are four temperature ranges for the AD process: thermophilic (>40–70 °C), mesophilic (30 – 40 °C), and Psychrotrophic (20 – 30°C) and psychrophilic (<20 °C) although in principle an AD process can take place between 3 °C and approximately 70 ºC (Rabbi et al., 2015). Thermophilic fermentation is characterized by rapid digestion, high gas yield, and short retention time. Mesophilic fermentation has the advantage of a slower death rate for bacteria (Uzodinma et al., 2007). Singh et al.(2017) indicated that the mesophilic bacteria could withstand a temperature change of ±3℃. The mesophilic temperature change influences biogas production a little, unlike the Thermophilic type bacteria, which can only withstand a temperature change of ±1℃, affecting biogas production. The temperature regimes and the methanogenic microorganism growth rate are shown in Figure 1-3.

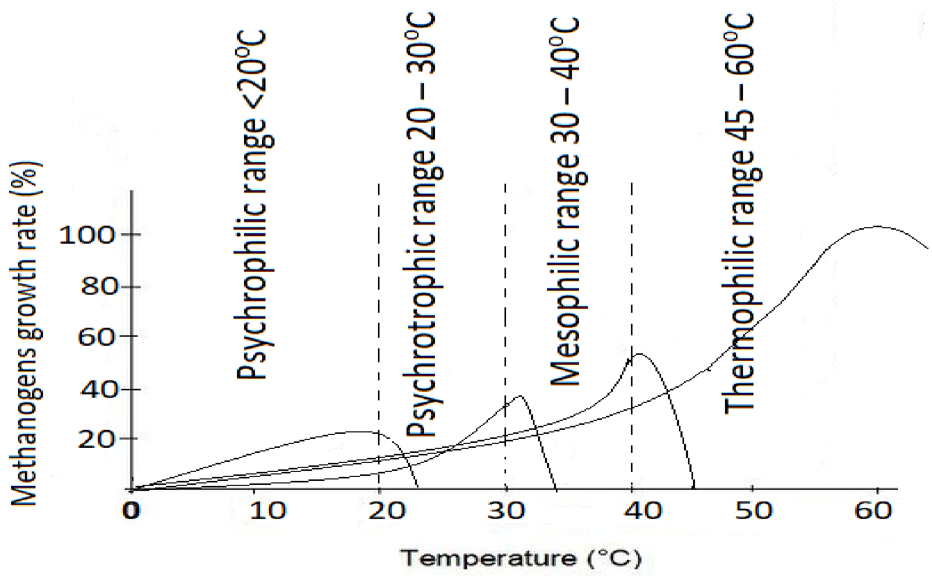


Figure 1-3.The temperature regimes and the methanogenic microorganism growth rate.

Anaerobic digestion in the digester is a slow process, especially under unheated conditions, and it requires a long hydraulic retention time (HRT) (>30 days). Ezekoye et al. (2011) reported HRT varying between 10 to 30 days, depending on the temperature. Gaby et al. (2017) said that HRTs lower than 8–10 days might lead to instability of the methanogenic process. Hydraulic retention time (HRT) refers to the mean length of time liquids remain in a digester. HRT can be calculated using the equation (Cooper, 2014);

$$\theta = \frac{V_d}{Q_d} \quad (1.7)$$

The equation is a quotient of active digester volume, V_d, and volume flow rate of feed of a digester, Q_d which often appears as θ,

The AD technology has been applied worldwide, and its associated heat transfer has been studied (Merlin et al., 2012). Ambient temperature is regarded as the independent variable because the heat transferred to the digester comes from the sun and no other heating except the internal energy of the feedstock due to the presence of bacteria. The decrease in biogas production during the winter makes it difficult for cold countries to adapt to this technology, especially without heating. Some digesters depend on the ambient air temperature, requiring no heating; these digesters often see seasonal fluctuations in methane production (Meegoda et al., 2018).

1.1.6. Fuelwood usage in household

According to (STATSSA, 2012), the number of households with energy sources for cooking and heating using firewood in Limpopo province is 616312 and 541947. These are the most significant numbers compared to other regions. Research on the use of firewood for thermal energy uses shows that firewood largely contributes to GHG emissions and other environmental problems (Montoya et al., 2008; Sesan, 2012; Verma et al., 2010). Indicators show that cutting trees may be accelerated by poverty, lack of knowledge, unemployment, unclear land policy, law enforcement, traditional practices, and economic gains (MDM, 2011). People in rural areas continue to use a range of energy sources like wood to meet their needs, irrespective of whether their houses are electrified or not (MDM, 2011). In the Mopani District municipality alone, 89.1% of the population of 1 068 569 in the Greater Giyani Local Municipality earns less than $R800$ per month. According to (MDM, 2011), the situation is worse in Greater Letaba, where the earning population makes less than $R800$ per month.

1.1.7. Fuelwood usage in educational institutions

The department of basic education nationally introduced the National School Nutrition Programme (NSNP) to secondary schools in 2009 (DOE, 2009). The NSNP guide indicated that there had been improved punctuality, regular school attendance, concentration, and the general well-being of participating learners in many schools. In addition, the NSNP guide also indicated that each school should have three - liquid petroleum gas burners' gas stoves and three twenty litres pots (DOE, 2009). However, most schools do not have those facilities for learners, and their alternative energy source is fuelwood. Hamilton's (2008) report shows primary schools in Vhembe, Capricon, and Sekhukhune districts with learners taking part in the school feeding scheme in 2008. The report also indicated that in most rural schools, the communities deliver firewood to schools as their contributions.

In contrast, in semi-urban schools, parents contribute minimal amounts of money, such as R10.00 a month, towards purchasing firewood (Hamilton, 2008). Makhado et al. (2009) show that a household of seven uses 7.8 kg of wood to cook daily meals. The primary schools, with 722087 learners, consumed about 804611 kg of fuelwood per day, equivalent to 1472438,54 kilograms of CO_2 in 2008. These calculations assumed that 1kg of firewood emits 1.83 kg CO_2 (Khanal, 2010). However, it should be noted that different trees emit more CO_2 when burnt due to their carbon content.

1.1.8. Untapped biogas in the agricultural sector

According to (NDA, 2013), Limpopo province had a lot of livestock. The statistical data published by (VDM, 2013) shows that the whole district has 180673 cattle. Furthermore, Wang et al. (2011) assumption is that the estimated dung produced per day is 10286 tons and 1043 tons of volatile solids. This estimation only leads to the total estimated methane production of 130 896 500 (130896.5 m^3) to 173 450 900 (1734 50.9 m^3) per day in Vhembe District Municipality. Assuming that 1m^3 of biogas is equivalent to 5.0 kWh/day, the herd of 180673 cattle is estimated to produce 6.54 to 8.67 GWh/day of heating (Wahyuni et al., 2018). However, this potential is not realized because of economic and socio-cultural barriers. Implementation of biogas technology requires high investment costs. Biogas plants are disregarded due to the usage of waste materials for cooking

1.2. Problem statement

Few organizations took the initiative to install biogas digester systems in Limpopo province. The motive was to show their environmental friendliness and potential to improve the province's energy and waste management status. Existing demonstration biogas digesters in Limpopo province are crucial for guiding interested communities, government departments, private sectors, farmers, and funders (regionally, nationally, and internationally) on the technology. However, there still exist constraints to technology development and specific and easy-to-understand operational issues for predictable performance. The more each multi-factor dependence is understood and controllable, the better the performance of the digester system is predicted and the enhanced trust in the technology. In Limpopo, the most deployed digester type is underground brick-built and fixed-dome because they have a long lifespan, no moving or rusting parts, and the basic design is compact, saving space. These small-scale household digester types are unheated, receiving only heat from solar radiation flux striking the soil surface and transmitted through the biogas digester's cover. The digester is relatively cheap and easy to build, and materials are locally available, with low maintenance compared with the prefabricated fixed-dome plastic digester and tube digester. Most of the installed digesters are 6 m^3, with expected daily gas production of 2 m^3. Only 13% of the incoming solar radiation is transmitted into the soil, with approximately 27% reflected with plants and soil absorbing about 60% (Ayata et al., 2011). The absorbed and transmitted solar energy into the ground is essential for raising soil temperature, allowing the biogas digester system to heat up and increase the slurry temperature. With all other factors in the rightful ranges, correct quantity and quality of daily, and proper mixing ratios with water and pH, slurry temperature determines the maximum specific growth rate of microorganisms and biogas production rate. The digester gas production is not predictable due to ambient temperature variations. The unpredictable gas production results in negative perceptions affecting biogas acceptance in Limpopo Province. Therefore, predicting the slurry temperature inside the digester under ambient air becomes important for proper digester systems and performance prediction. The average ambient temperature is one of the most easily accessible parameters, even in rural areas without weather stations through weather reports on televisions and radios. In numerous studies involving slurry temperature inside the digester, such as those reported by (Axaopoulos et al., 2001; Perrigaulta et al., 2012 and Wu et al., 2009), little information is available about heat transfer problems related to unheated brick-built fixed-dome household size biogas digesters, especially Deenbandhu model. The gap that this research intends to fill in the biogas digester technology is the development of an accessible, user-friendly calculator to predict the daily biogas production rate for unheated brick-built fixed-dome household size biogas digesters fed with cow dung under ambient air temperature.

1.3. Aim and objectives of the study

1.3.1. Aim of the Study

The study aimed to determine the relationship between bio-slurry and ambient air temperature and subsequent biogas production for completely covered and unheated brick-built household size Deenbandhu biogas digester. Studying the heat transfer and hence temperature correlations between ambient and digester slurry of these unheated underground buried brick-built biogas digesters can make new recommendations for innovative design and construction to improve their gas production efficiency. Weatherford & Zhai (2015) noted that people in colder climates and higher altitudes could not take advantage of AD due to low inside digester slurry temperatures. However, they reached this conclusion by investigating a tubular bio-digester.

1.3.2. Objectives of the Study

The work was arranged to study heat transfer through underground, unstirred, and unheated biogas digesters fed with cow dung to;

1. Develop and validate a direct relationship between slurry and ambient air temperature.
2. Compute the daily biogas production rate based on the predicted slurry temperature and ambient temperature data.

1.4. Research questions

- Can we promote/improve the uptake of biogas digester technology in Limpopo province by improving beneficiaries' technical knowledge and operational conditions of the systems?
- How does the slurry digester temperature vary with ambient air temperature?
- Can a heat transfer model be used to predict slurry temperature based on local ambient air temperature as an input?
- Can we predict biogas production rate using ambient air temperature?

1.5. Thesis arrangement

The thesis comprises five chapters, with Chapter 1 giving the introductory background and justification for the research work, clearly showing the research problem and, therefore, the research objectives. Chapter 2 provides a literature review of research related to the current study showing its limitations to fill the existing gap in the physical operation of AD technology more significantly in the fixed dome brick-built model and their gas production predictability with ambient temperature. Chapter 3 presents the methods and materials to gather the information and data needed to answer the research questions. It also provided a detailed description of the methods and how they have been executed. Chapter 4 presents the results of the measurements and processing data captured for this research. The chapter presents the developed linear regression equation to forecast slurry temperature from daily ambient temperature variation even though the soil temperature is unavailable. Finally, the correlation between slurry temperature and ambient air temperature, model validation, and model testing are reported and discussed. In Chapter 5, the overall work is concluded, and recommendations and future scope are presented.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

A few studies about Deenbandhu fixed dome digester types are in the literature. Verma et al. (2010) studied the cost analysis of this type of digester and the KVIC digester. They found that Deenbandhu fixed dome generated more profit compared to KVIC. A similar study on the economics of different biogas digester models, including the Deenbandhu fixed dome model for Punjab, India, showed that the annual profit for the Deenbandhu fixed dome model is higher than the rest of the digesters (Singh & Sooch, 2004). The profitability depends on how the produced CH_4 is used (Axaopoulos & Panagakis, 2003). Although profitability is not a concern in developing countries like South Africa, as this technology improves human life in these areas, poor performance is a concern due to technical limitations (Khan & Martin, 2016; Michal & Mark Mba, 2020). Lack of technical knowledge during an operation led to failed biogas digesters (Nevzorova & Kutcherov, 2019). During the process of a biogas digester, several factors such as temperature inside the digester, hydraulic retention time, organic loading rate, the composition of the feedstock, PH, Volatile fatty acids (VFAs), Pressure inside the digester, the ratio of content carbon and nitrogen (C/N), mixing, ammonia (NH_3), salinity, trace element supplementation affects the efficiency of biogas production (Dobre et al., 2014; Nevzorova &

Kutcherov, 2019; Rajendran et al., 2012; Spyridonidis et al., 2020). Since this research focuses on ambient, slurry temperature, and biogas production rate, other factors were not reviewed in detail. The temperature inside the digester is the principal factor influencing microbial activity and growth or microbial consortia's survival (Mir et al., 2016; Sabbir et al., 2021). By its nature, AD is a temperature-sensitive process with three different temperatures regions: psychrophilic (<30 ◦C), mesophilic (30–40 ◦C), and thermophilic (50–60 ◦C) (Sabbir et al., 2021).

2.2. The link between hydraulic retention time, organic loading rate, and temperature

Rajendran et al. (2012) noted some observations that the amount of biogas produced by high temperature (mesophilic) and low HRT is comparable to those produced with low (psychrophilic) temperature and high HRT. However, shorter HRT is desirable as it directly reduces capital costs (Shi et al., 2017). Shi et al. (2017) studied the effect of HRT on the anaerobic digestion of wheat straw in semi-continuous stirred-tank reactors at a controlled temperature of 35^{o}C. Their results show that the average biogas production with HRT of 20, 40, and 60 days was 55.2, 94.3, and 105.2 mL/g volatile solids, respectively. The digestion with HRT of 20 days showed lower stability than those with 40- and 60-days HRT. HRT is an important operational parameter for determining the organic loading rate (OLR) (Feng et al., 2019). Spyridonidis et al. (2020) showed that increasing OLR reduces HRT, which requires a higher temperature for best biogas production. The thermophilic digester achieved a greater biogas yield when run at a 5-day HRT than at a 7.5-day HRT (6.3 versus 4.7 L/L)/day). In contrast, the mesophilic digester had a stable biogas yield of about ((1.0 L/L)/day) (Wen et al., 2016). The OLR is an essential parameter for the AD process since it shows the daily number of Volatile solids (VS) fed into the digester. VS concentrations give helpful information about biogas yield that can be expected and process efficiency (Orhorhoro et al., 2017). Volatile solids (VS) reduction is an indirect measurement of organic matter utilization (Castano et al., 2014). The biogas production may decrease if the feeding rate in the reactor is beyond the best level. Then, system failures can occur due to overloading (Pramanik et al., 2019). At different temperature conditions, the HRT can significantly affect the metabolic rate of anaerobic microorganisms (Feng et al., 2019).

2.3. Heat transfer in small scale anaerobic digesters

Real-time digesting temperature affects biogas production rate, especially in winter, since this low-temperature condition increases the retention period (Karimov & Abid, 2012; Yang et al., 2019). Estimating the impact of heat transfer is crucial since this may help answer significant changes in the biogas production caused by temperature fluctuations in the AD (Merlin et al., 2012). Research shows several approaches to computing heat transfer through the AD biogas digester. The studies include experimental, theoretical, and simulation models. Some studies compute heat transfer by solving equations without considering the ambient temperature. In addition, since these studies also do not involve brick-built digesters covered with soil, their results may be suitable only for limited conditions. The following studies address various aspects of heat transfer in AD systems and are in the order of years they were carried out (Axaopoulos et al., 2001; Gebremedhin et al., 2005; Guo et al., 2019; Mukumba et al., 2015; Perrigaulta et al., 2012; Shaheen & Nene Anita, 2014; Terradas-III et al., 2014; Wu & Bibeau, 2006). These studies have both similarities and differences. The differences found were the digester type studied, environmental conditions, exposure of the digester cover, physical parameters employed, and the model assumption for a chosen method.

Axaopoulos et al. (2001) investigated AD's dynamic behavior and employed ambient, biogas, and slurry temperature parameters. However, the study did not show the relationship between slurry temperature response to ambient temperature. Later (Gebremedhin et al., 2005) developed a one-dimensional model for predicting energy requirements for a plug and flow AD digester to run at a specified temperature. The study includes solar energy, soil properties as well as weather conditions. The setup of this study resembles the study of (Axaopoulos et al., 2001), which used hot water pipes to heat the slurry inside the digester. Wu & Bibeau (2006) studied the three-dimensional heat transfer model to predict the heat losses for underground digesters under cold weather conditions considering the constant ambient temperature. Perrigaulta et al. (2012) developed a 1-D thermal model with input data for fixed dome digesters that are not heated, stirred, or insulated. Shaheen & Nene Anita (2014) studied thermal simulation to understand the heat transfer from the slurry and the gas holder to the surrounding earth and air. Terradas-III et al. (2014) developed a simple 1-D thermal model with input data for a fixed dome, unheated, unstirred, uninsulated fiberglass digester. They predicted temperatures in the dome cover, biogas, and inside the digester resulting in biogas production.

The model was validated using data from a fixed-dome digester with a total volume of 7 m^3 and a working capacity of 5 m^3 fed with pig slurry. The model was well able to estimate the temperature inside the digester. Terradas-III et al. (2014) study is helpful, although the feedstock used and digester type and size differ from what is used in the present study. Mukumba et al. (2015) assessed the performance of a biogas digester first without insulation and later with insulation. The digester was not underground. The results for biogas digester without insulation show that biogas and slurry temperatures depend entirely on ambient temperature. When the biogas digester is not insulated, there is an increase in temperature fluctuations because of heat transfer from the environment into the digester through the double wall brick structure of the biogas digester. The relationship between ambient temperature and the slurry temperature was developed for the insulated digester following the fluctuation in slurry temperature due to the lack of insulation of the digester. Guo et al. (2019) developed a multiphase flow anaerobic digester to improve the biogas production rate and keep constant temperature digestion during winters. The slurry temperature, slurry flow rate, ambient air temperature, and biogas production were measured, among other parameters. As a result of the study, a relationship between slurry temperature and biogas production rate was established.

2.4. Equations for computing heat transfer for different digesters

Axaopoulos et al. (2001) conducted a simulation and experimental performance of a solar-heated anaerobic digester and employed the following equations;

$$\dot{Q}_d = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{2.1}$$

where, $\dot{Q}_d$, $\dot{Q}_{conv}$, and $\dot{Q}_{rad}$ represent heat transferred to the digester, convection, and radiation heat losses. $\dot{Q}_{conv}$ is given by

$$\dot{Q}_{conv} = h_c(T - T_b)A_m \tag{2.2}$$

where h_c is the convection heat transfer coefficient, T is manure temperature T_b is the biogas temperature and A_m is the (slurry-biogas interface) manure surface area, $\dot{Q}_{rad}$ can be calculated using the following equation;

$$\dot{Q}_{rad} = \varepsilon\delta(T^4 - T_b^4)A_m \tag{2.3}$$

where ε is the manure emissivity averaged over the infrared spectrum (IR) and δ is the Steffan-Boltzman constant. The following equation computes the heat losses through the digester walls and floor;

$$\dot{Q}_W = (U_{dw}A_{dw} + U_{df}A_{df})(T - T_a) \tag{2.4}$$

where U_{dw} is the average heat transfer coefficient of the digester wall of the area, A_{dw}, U_{df} is the average heat transfer coefficient of the area's digester floor A_{df}, and T_a is the ambient temperature. The average heat transfer coefficient of the digester wall was calculated using the equation;

$$U_{dw} = \frac{2\lambda}{\pi H} In(1 + \frac{\pi H}{2\lambda R}) \tag{2.5}$$

where λ is the soil thermal conductivity, H is the depth of the digester, and R is the thermal resistance of the digester wall. (Gebremedhin et al., 2005) study where the top surface may be covered with synthetic or concrete material is exposed to ambient air. The solar radiation distributed to the digester cover is computed using the following equation;

$$Q_{solar} = \bar{q}'' A_{cover} \tau(\lambda) \tag{2.6}$$

where $\tau(\lambda)$ and A are transmitivity and the area of the digester covering material. $\bar{q}''$ is the average daytime solar radiation flux and is calculated by the equation;

$$\bar{q}'' = q''_{solar}/(\Omega s_2 - \Omega s_1) \tag{2.7}$$

where, Ωs_2 and Ωs_1) represent sunset hour and sunrise angles. The heat exchange between the digester cover material and ambient air is by conduction and is given by equation;

$$\dot{Q}_{cover} = \dot{Q}_{cond} = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{2.8}$$

where, $\dot{Q}_{conv}$ and $\dot{Q}_{rad}$ represent heat transfer by convection and radiation, respectively. $\dot{Q}_{cond}$ is the heat transfer by conduction. Eq. (2.8) is the same as Eq. (2.1); the only difference is the definition of $\dot{Q}_{conv}$ and $\dot{Q}_{rad}$ as well as $\dot{Q}_{cond}$ *and* $\dot{Q}_d$.

Perrigaulta et al. (2012) used the following equations to find the solar radiation heat flux absorbed by the gas holder and the slurry. Since the model accounts for solar gains and heat transfer with the ground, the air inside the greenhouse, the plastic greenhouse cover, the greenhouse walls, the ambient air, and mass transfer via the influent and effluent flows.

$$S_{gh} = \tau_{gc}\alpha_{gh}F_{gh}A_{gh}I_{gh,T} \quad (2.9)$$

and

$$S_s = \tau_{gh}.\alpha_s.F_s.A_sI_{s,T} \quad (2.10)$$

where, S_{gh}, S_s $\tau_{gc}\alpha_{gh}F_{gh}A_{gh}I_{gh,T}\tau_{gh}.\alpha_s.F_s.A_sI_{s,T}$ represent solar radiation heat flux absorbed by the greenhouse cover, slurry, and shading factors.

2.4. Importance of predicting operational temperature using ambient temperature

Household digesters are operated at ambient temperatures throughout the year, with temperatures in the range of $20°C - 25°C$ in most developing countries (Jegede et al., 2019). Perrigaulta et al. (2012) assumed that the mean monthly air temperature represents the mean monthly operational digester temperature. The operating temperature in anaerobic digestion strongly affects biogas yield, process stability, and process optimization potential (Westerholm et al., 2018). Biogas production rate increases with slurry temperature, as shown by (Guo et al., 2019);

$$Y = -0.000090629X^2 + 0.01604X + 0.03032 \quad (2.11)$$

where Y and X are biogas production rate and slurry temperature, respectively. Mukumba et al. (2015) showed that when the biogas digester is not insulated, there is an increase in temperature fluctuations. Because of heat transfer from the environment into the digester through the double wall brick structure. Following the change in slurry temperature due to the lack of insulation of the digester, the relationship between ambient temperature and the slurry temperature was developed and is as follows;

$$T_s = 0.6221\, T_a + 9.4007 \quad (2.12)$$

where T_s and T_a are slurry and ambient temperature, respectively. On the other hand, the effect of insulation on slurry and ambient temperatures was noted. It was found that ambient temperature had a minor impact on slurry temperatures for biogas with insulation. (Castano et al. (2014) indicated that insulating and burying the digester increases the digester temperature above the ambient winter temperatures. Wang et al. (2019) studied the influence of temperature on biogas production efficiency and microbial community in a two-phase anaerobic digestion system. One of the most significant results was that biogas in the methanogenic phase is maintained at temperatures ranging from $25 - 35°C$. Wang et al. (2019) emphasized that the methanogenic phase could significantly decrease at temperatures less than 20ºC. Pham et al. (2014) investigated the main factors influencing the temperature of digesters in Northern Vietnam and identified ways to keep the temperature high during the winter. More specifically, insulating the digesters affects the temperature inside the digester. The results showed that insulation and ambient air temperature significantly influenced digester temperature. The AD at the ambient temperature can lower the thermal energy needed to keep the AD operational temperature (Wen et al., 2016). The operating temperature plays a significant role in determining the maximum specific growth rate (µm (T_s)) of the microorganism, which is given by the equation;

$$\mu m(T_s) = 0.013T_s - 0.129 \quad (2.13)$$

and

$$\mu m(T_s) = 0.0039e^{0.118(T_s)} \quad (2.14)$$

where (T_s) is the slurry temperature. Eq. (2.13) holds for temperature (T_s) between 20°C and 60°C. Equation (2.14) holds for temperature (T_s) in the temperature interval from 10°C to 30°C. The maximum specific growth rate is, in turn, used to compute methane yield given by

$$\gamma = \left(\frac{B_0 S_0}{HRT}\right)\left(1 - \frac{k}{HRT * \mu_m - 1 + k}\right) \tag{2.15}$$

where B_o is the overall production yield, S_o is the concentration of organic components in the cow dung; HRT is the hydraulic retention time; (μm) the maximum specific growth rate of microorganisms of cow dung as a function of the temperature (T_s) of the slurry inside the digester and k represents the kinetic constant. Nielsen et al. (2017) indicated that an increase in slurry temperature correlated positively with methane yield.

2.5. Conclusions

Researchers used various biogas digester types for their AD studies to develop biogas digesters that produce the required biogas throughout the year. Sometimes lack of technical knowledge during an operation leads to failed biogas digesters due to factors affecting the efficiency of biogas production. The temperature inside the digester is regarded as the principal factor affecting biogas efficiency. The temperature inside the digester has been thoroughly studied; However, further study of the temperature, specifically, the temperature inside the digester, will better understand why some biogas digesters fail. Studies associated with the temperature inside the digester were reviewed to see if they could be used in the current study. From the literature reviewed, the study of the fixed dome, unheated, unstirred, uninsulated digester, and prediction of temperatures in the dome cover, biogas, and inside the digester resembled the present study's design. Still, it differed in the material used to build the digester and the feedstock type used to feed it. The lack of information on a brick-built fixed dome biogas digester fed with cow dung makes it necessary to develop a mathematical model suitable for where the biogas digester has been installed. The main reason for the model will be to plan if low temperatures are detected since this may restrict biogas production in the winter and cold days. Such restriction makes biogas a less reliable energy source and can often be a reason for choosing alternative sources (Bruun et al., 2014).

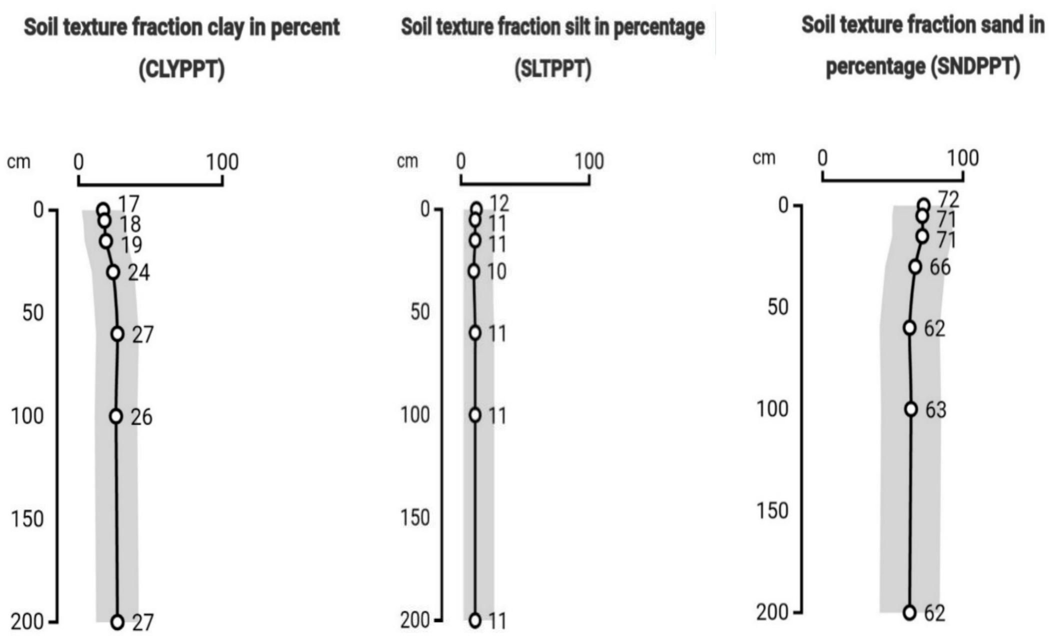
CHAPTER 3: METHODOLOGY

3.1. Introduction

The present chapter is made up of nine sections and five sub-sections. The arrangement of this chapter is in the following order. Section 3.1 is the introduction and gives an outline of the methods employed in the study. Section 3.2 describes the experimental site and the soil type where the study was conducted. Section 3.3 outlined how workshops were used to promote the uptake of biogas digester technology in Limpopo Province. Section 3.4 outlines the experimental design of the instrument used to collect data and how the system was activated. Data collection is described in Section 3.5, and data analysis in Section 3.6. Statistical modeling of data collected is conducted in section 3.7. Biogas digester performance is presented in section 3.8, where the method used to predict the biogas production rate is given. The conclusion is given in section 3.9.

3.2. Experimental Site and Soil type

Since the experience from one area can be helpful for others, the present research was confined to Vele Secondary School (geographical coordinates 22°45'56.08"S, 30°20'34.44"E) in rural Gogogo village due to insufficient funds to acquire measuring equipment. The school was chosen because they planned to construct a biogas digester and offered agricultural science subjects. In addition to that, the school consisted of a vegetable garden. The village is under Thulamela Local Municipality (TLM), situated in the Northern region of the Vhembe District of Limpopo Province in South Africa. The area's diverse range of soil types is shown in Figure 3-1. The most prominent soil is sandy soil, which warmed rapidly because of its low heat capacity and thermal conductivity (Akter et al., 2015).



(a) (b) (c)

Figure 3-1: Soil type (a) Clay (b) Silt (c) Sand *(*ISRIC - World Soil Information, 2016*)*.

3.3. Workshop research

3.3.1. Promoting the uptake of biogas digester technology in Limpopo province

The workshops as a research method were used to investigate what could support the technology uptake and accelerate the utilization of biogas technology in Limpopo province. The technique employed community-based approaches, which in the end, allowed rural communities to understand biogas digester systems. Training workshops on biogas digester technology have been conducted in communities since 2012 targeting between 20 to 50 participants per workshop. Technical knowledge and operational conditions of the designs where the two main aspects considered the most crucial tools that could be used to promote the uptake of the technology.

3.4. Experimental design

The current work aimed to study heat transfer problems associated with an underground brick-built biogas digester to understand the temperature inside and outside the digester. To achieve the above, three fixed-dome brick-built biogas digesters of bulk size 6.0 m^3, each shown in Figure 3-2, were constructed following a fixed-dome Deenbandhu model in India (Cheng et al., 2013). The outlet chamber was covered with rectangular slabs to avoid substantial heat loss and protect against the possible danger of animals and children falling in. The bottom part of the dome is where the bio-slurry is stored to initiate the fermentation process. The upper part is where the generated gas by the fermenting slurry is stored before utilization. The upper part is also known as the gas chamber, and its volume is equivalent to the capacity of the outlet tank. The digesters were built using the following materials:

• Standard sand and cement bricks $(0.20 \text{ m} \times 0.10 \text{ m} \times 0.065 \text{ m})$ usually used for building houses in the area, each with thermal conductivity of 0.8 W/mK, a value that agrees with the thermal conductivity of a brick in the study of

• A 0.20 m concrete slab at the bottom of the digester and the inner and outer walls of the digester were plastered and only painted with waterproofing paint inside the digester to prevent gas and water leakage.

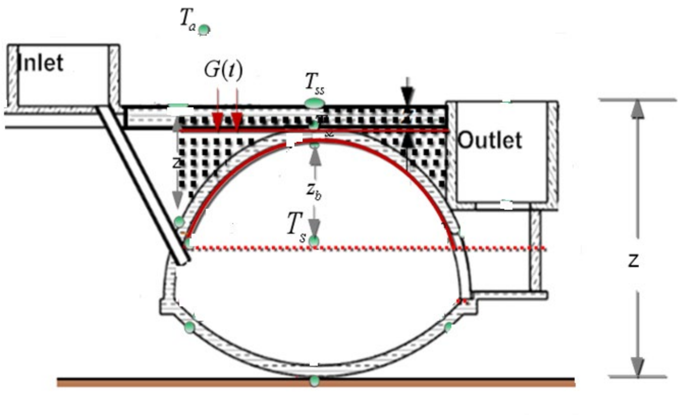


Figure 3-2. Schematic diagram of the Deenbandhu digester with model components built at Vele Secondary School.

The digesters were filled with 2500 L of clean water and 2500 kg of cow dung to initiate the process with a pH of 6.07. A compressor was used to pressurize the digesters to check for leakages. A maximum of 10 kpa was pumped into each digester through the gas outlet pipe, and the change in pressure was observed for nine hours. When it was confirmed that there was no change in pressure, fresh cow dung was collected from local cattle owners and feedlots around the village. Cow dung was chosen because it is the best input to digesters at room temperature (Prasad, 2012). The digesters were continuously fed with 35 kg (or 4,6kgVS/m^3/day) cow dung mixed with 35 L of water to allow them to completely close the opening at the outlet side of the digester. The organic loading rate calculations were done using Ramaswamy & Vemareddy (2015) and Nsair et al. (2020). The properties (specific heat capacity, thermal conductivity, and density) of the daily feed were assumed to be equivalent to the properties of the mixture throughout any location inside the digester.

3.5. Data collection

Just after detecting methane gas($> 51\ \%\ CH_4$) by a hand-held Riken Niken gas detector of model GLX 2012 after 42 days, measurement of slurry temperature, soil temperature, and air temperature commenced. The fermenting slurry temperatures inside each digester were measured using a MultiCon CMC-141 data logger (Simex Sp, 2015). The data logger was fitted with three K-type NiCr-Ni temperature sensors of sensitivity of approximately $41\mu V/$ °C and response time of $0.8s$ in liquids. The temperature sensors were connected to the logger using wires of about $10m$ in length to measure soil temperature, ambient air temperature, and slurry temperature. The sensors to measure slurry temperature were located at each digester's center (Baral et al., 2013). The choice of measuring the slurry temperature at one point within the digester assumed that there is no significant gradient in slurry temperature inside the digester at any depth (Sabbir et al., 2021). Terradas-III et al. (2014) showed that the average slurry temperature related to depths was 24.80 °C at 1m, 24.50 °C at 1.4 m, and 24.40 °C at 1.8 m, and the mean and standard deviation of the temperature at the three depths were 0.5 °C. The measurements of temperature started on 01 May 2015. The data were recorded every second, while the logging device automatically measured hourly and daily averages.

3.6. Data analysis

The data was retrieved and imported to the Matlab and R studio to study heat transfer problems and model temperature variation.

3.6.1. Heat transfer to the slurry through the digester

Eq. (3.1) was used to determine the heat transferred to the soil where the digester is buried (Wang & Brass, 1999);

$$\frac{\partial T}{\partial t} = D_0 \frac{\partial^2 T_{ss}}{\partial z^2} \tag{3.1}$$

Where T_{ss} represents soil temperature, z is the soil depth and D_0 is a constant thermal diffusivity. Hence, the soil heat flux equation obtained from the diffusion equation was used to compute the soil surface heat flux. The heat supplied to the digester equals the soil surface heat flux since solar influx calculations do not consider soil properties. The expression developed by (Wang & Brass, 1999) to compute soil surface heat flux is applied and is given by the following;

$$Q_{\sup} = G(t) = \sqrt{\frac{k_s C_s}{\pi}} \int_0^t \frac{dT_s(s)}{\sqrt{t-s}} \tag{3.2}$$

where $G(t)$ and k_s, and C_s represents the soil surface heat flux, volumetric heat conductivity, and the soil material's heat capacity. T_{ss} is the soil surface temperature over the period *t,* and s is the variable of integration. Eq. (3.2) is a time series of soil surface temperature. Heat gained (Q_{gained}) by the slurry inside the digester is given by the equation;

$$Q_{gained} = \frac{m_{slurry} C_{slurry} dT}{dt} = \frac{m_{slurry} C_{slurry} \sum_{i=0}^{N} T_{i+1} - T_i}{(t_{i+1} - t_i)} \tag{3.3.}$$

m_{slurry} is the mass of the slurry inside the digester, C_{slurry} is the specific heat capacity of the slurry inside the digester, $\Delta T_s = T_{i+1} - T_i$ is the temperature of the slurry, t represents the period when the temperature starts to rise from minimum until the maximum value of temperature is reached. Calculations of soil surface heat flux and heat gained by the slurry were carried out using hourly average temperatures each month. Analyses of soil surface heat flux and heat acquired by the slurry were conducted using hourly average temperatures each month.

3.6.1. Model for determining slurry temperature inside the digester

The ambient air temperature T_a causes temperature changes in the soil. The changes are driven by transient one-dimensional heat conduction given by the heat diffusion Eq. (3.1). Eq. (3.1) is applied for isotropic and homogenous media with uniform properties. The physical structure in Figure 3-3 comprises three media (i.e., soil., cement plaster, and bricks). The above equation can only determine ground heat flux near the soil's surface. When heat is transferred to the digester, convective and conductive heat transfer exists between air and soil surface and from the soil surface to the digester wall to the slurry.

The two sides at the top of the digester in Figure 3-3 are exposed to two fluids at temperature T_{Air} and T_{ss}. The heat is assumed to flow to and from the digester wall by convection and conduction. We apply the convective heat transfer equation to compute the heat flux to the near surface of the soil from mixed air.

$$\dot{\Phi}_o = h_{air-soil}(T_{Air} - T_{ss})$$

(3.4.)

The conduction heat flux from through the soil cover to the top outer surface of the digester is,

$$\dot{\Phi}_{soil-digester} = \left(\frac{k}{\delta}\right)(T_{ss} - T_d) \quad (3.5.)$$

Where ,$\delta = (\delta_{ss} + \delta_d)$ is the thickness of the soil and the cover and $k = (k_{ss} + k_d)$ the soil's thermal conductivity and the digester cover. The convective heat flux from the inner top of the digester cover to the near surface of slurry, which is in contact with enclosed biogas is.

$$\dot{\Phi}_i = h_{digester-slury}(T_d - T_s) \quad (3.6.)$$

Combining the three equations in Eq. (3.4), (3.5), and (3.6), we get

$$T_s = T_{Air} - \dot{\Phi}_{o-i}\left(\frac{1}{h_0} + \frac{\delta}{k} + \frac{1}{h_i}\right)$$

$$T_s = T_{Air} - \dot{\Phi}_{o-i}\sum R_{tot} \quad (3.7)$$

where $\sum R_{tot}$ is the total thermal resistances of the air-soil, digester cover, or outer and inner fluid. Eq. (3.7) can be solved for T_s provided that the heat flux and T_{Air} , as well as the thermal resistance parameters δ,k,$h_o h_i$, are known. Again Eq. (3.7) also shows that the slurry temperature is the difference between ambient air temperature and heat flux to the digester.

The model shown in Eq. (3.7) is comprehensive to account for all relevant parameters of heat transfer associated with the selected biogas digester system. The goal of this study was to establish a direct relationship between T_s and T_{Air} with the minimum of restrictions. It turns out that both T_s and T_{Air} may need to be checked for their relationship.

3.7. Statistical modeling

Data containing a total of 20220 observations and two variables collected in pairs were categorized by the notation;

$$(x_1, y_1), (x_2, y_2), \ldots\ldots\ldots, (x_n, y_n) \qquad (3.8)$$

Where x_1 is the first value of the X variable, and y_1 is the first value of the Y variable. In this study, the variable X is denoted by $T_{Air,}$ the air temperature, and Y, represents the slurry temperature denoted by Ts,. The pairs of data were uploaded to the statistical software (R studio) to enable the start-up of the modeling process. The data were graphically represented with variables subjected to building a model to predict slurry temperature by showing a mathematically meaningful relationship between air temperature and slurry temperature using the observed values. A typical scatter plot was drawn to visualize the linear relationship between the two variables. The next step was establishing a linear model using a mathematical formula represented by Equation (3.9.) to predict slurry temperature as a function of air temperature.

$$E(T_s|T_{Air} = x) = \beta_0 + \beta_1 x \quad (3.9.)$$

Where the unknown parameters β_0 and β_1 determine the theoretical T_s-intercept and the theoretical slope of the specific straight line.

3.7.1. Model testing

The original dataset was randomly split into a 75:25 sample (training: test). The linear model was then built on the 75% sample. The linear model was constructed thus to predict the slurry temperature variable on test data. The linear model predicted values for the 25% data (test) and the actuals (from the original dataset).

3.8. Biogas digester performance

3.8.1. Prediction of biogas production rate

This section aimed to predict the daily biogas production rate using slurry temperature averaged for the three digesters. The rate of biogas produced per the rated volume of biogas storage is one of the most crucial measures of digester performance. Predicting the biogas production helps users plan since the exact cooking time is hard to predict when using biogas. By doing so, the daily biogas production rate was computed using Eq. (2.11). Thus, the fermentation process was more stable concerning biogas production. However, the methane content of biogas was not measured daily but during the first stage.

3.9. Conclusions

The focus of this chapter was to outline the methodology used in this study. Firstly, information on research approaches and the type of biogas digester was given. Secondly, the method for data collection and analysis was provided. Thirdly, the technique used for modeling data collected was presented. Lastly, the section on biogas performance was outlined.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Introduction

To complete this research correctly, it is necessary to discuss the data collected to answer the research questions outlined. The following chapter comprises the presentation and interpretation of the results.

4.2. Promoting the uptake of biogas digester technology in Limpopo province

4.2.1. Impact assessment of initial biogas uptake study

A review of barriers to the broader implementation of biogas as a source of energy revealed that the unavailability of local biogas technologies could challenge the deployment of biogas as a source of energy (Nevzorova & Kutcherova, 2019). Looking at the African context, Bensah & Hammond (2010) showed that biogas technology dissemination has been unsuccessful in Africa due to poor dissemination strategies. In Africa, biogas installations are family-sized or domestic digesters that generate heat for cooking (Kemausuor et al., 2018; Mengistu et al., 2015). However, Gosens et al. (2013) and Berhe et al. (2017) indicated that the dissemination of household biogas digester is one of the strategies used to determine biogas' use and adoption in rural areas of developing countries. The construction of a digester is essential for disseminating biogas technology. The investment cost cannot be ignored since many rural people are within or below the low-income level (Osei-Marfo et al., 2018).

In Limpopo province, active harnessing and development of biogas energy began in 2007 in rural villages by a non-profit organization (NPO) called the Mpfuneko Community Support organization in conjunction with the Netherlands Wild Goose Dutch Development Organisation. The aim was to promote socio-economic development in rural areas (Hlungwani, 2009). The organization installed fixed dome, brick-built design models since they play a significant role in disseminating household biogas technology in Africa (Mulinda et al., 2013). Later, the project attracted local and national institutions to develop a biogas program. The South African National Energy Development Institute (SANEDI) helped the Mpfuneko Community Support organization construct more digesters in the area. The NPO targeted the low-income group willing to sign a contract with a minimum of three households nearby and allowed them to use an unlimited gas supply for a collective amount of R125 per month. There was no information in the literature about the amount of daily biogas production that households were paying for since no gas meters were installed. Surprisingly, the group could not pay monthly fees to the organization in the end. Financial constraint is one of the most often cited challenges limiting the expansion of biogas technology (Mengistu et al., 2015). Many households stopped feeding the digester due to cost implications since cow dung is the province's primary feedstock for biogas digester. Most beneficiaries of these digesters do not own any cattle, and those with cattle were selling cow dung which was not the case before. Kabir et al. (2013) indicated that adopting new technology requires incentives for encouraging potential adopters. Among other things was ownership, which resulted in the operational failures of many installed digesters and negatively impacted the image of biogas technology in the province.

4.2.2. Accelerating the dissemination of biogas technology through research

Five years of appreciation of biogas technology and the lack of research on maximizing the uptake of biogas technology in Limpopo Province paved the way for research institutions to get involved in research work. Biogas technology is a new concept in many rural communities. Social acceptance and demonstration of new technologies are necessary to understand potential barriers to uptake (Smith & Everson, 2016). Mulinda et al. (2013) highlighted that where there are contributions from various scientists and engineers, there is a promising startup in developing household digesters. A collaboration between the University of Cape Town and the

University of Venda introduced a biogas innovators workshop in 2012 to promote the implementation of biogas technology in Limpopo province. Educational awareness in schools, colleges, and community centers was conducted to improve biogas energy in the region. Education increases information acquisition ability, thereby understanding innovative technologies and beneficial practices (Mwirigi et al., 2018). The awareness was made since biogas technology, and implementation is not taught in colleges and schools' technical courses.

Active stakeholders were set up to solve the prevailing constraints in accelerating biogas technology in the province, as shown in Figure 4-1. Political representatives were included since literature shows that a lack of political support can also hinder the promotion of biogas technology (Nevzorova & Kutcherova, 2019). Mwirigi et al. (2018) indicated that customers might reject some technologies because technologies are not in line with their values, beliefs, and past experiences. Through formal presentation, participants were informed that the implementation of biogas technology comes with benefits such as;

1. Reducing and re-using waste through agricultural recycling,
2. Reducing the GHG emission of gases implicated in causing global warming.
3. Biogas technology helps the Department of Environmental, Forestry, and Fisheries (DEFF) to control deforestation.
4. Alleviate poverty by creating job opportunities during the biogas plant construction and operational phase.
5. Have a Positive impact on Eskom electricity if many digesters are rolled out. The load shedding will be minimal if local people promote the technology. Furthermore, dissemination of the systems' technical knowledge and operational conditions resulted in many meetings about biogas technology, as shown by (Univen, 2020).

Figure 4-1. Field trip for active stakeholders at Maila.

4.2.3. Technical knowledge and operational conditions of the system

Shane et al. (2015) indicated that sometimes biogas digesters operators lack technical knowledge on repairing and maintaining biogas digesters. It was thus necessary to conduct workshops related to the technicality of a biogas digester. Community members contributed to the developmental planning process of the technology. It was vital to allow participants to share their views of biogas technology. Amongst other statements, the following were pivotal knowledge sharing for regional-scale dissemination of biogas technology.

- **Quality of the biogas produced**: Technical error such as poor feeding of the digester was observed during the site visit. A beneficiary feeds a biogas digester using cow dung and water directly from the pipe in Figure 4-2 below. Whether the beneficiary added the required water to the mixing tank is questionable. Such an essential requirement was addressed since it is well-known that the quality of the feedstock mixture affects the biogas produced, and beneficiaries did not consider that. The proportion of water and cow dung is essential. Berhe et al. (2017) indicated that a well-functioning plant is the best possible promotional tool, and the satisfied user is the best potential promoter for biogas technology.

Figure 4-2. Possible technical error when feeding a biogas digester.

- **Safety of biogas**: As far as safety is concerned, we discussed the health hazard of biogas. Montoya et al. (2008) indicated that little information is available in the published work on in-home monitoring studies of carbon monoxide (CO) levels. However, these studies are not shared with rural communities due to the lack of communication. Monitoring the levels of CO assisted in advising biogas end users on what they inhale in their kitchens when using poor-quality biogas. Broken digester caps and gas valves that are not airtight can cause significant environmental problems, such as gas escaping into the atmosphere, as depicted in Figure 4-3. There is the potential for a fire outbreak since mixtures of biogas and air in specific concentrations (6 - 12 % CH_4) could be explosive. It may cause damage to human life and property (Bensah & Hammond, 2010).

Figure 4-3. Biogas digester corrosive valve caused by H_2S.

4.3. Temperature profile inside the digester

The results are presented and discussed based on the first digester because no significant differences were observed between temperature values. Five graphs were plotted and presented for better graphical analysis to compare slurry and ambient air temperature, average daily temperature, average monthly temperature, monthly minima, maxima, and average hourly temperature.

The graph in Figure 4-4. represents the bio-slurry temperature across the period of eight months. It is evident from the chart that weather conditions played a significant role in the heat transferred to the digester. This feature observes fluctuating temperatures and might be due to the lower absorption of heat by the bio-slurry. The figure shows the daily average bio-slurry temperature profiles inside the digester varying from as low as 10.20 °C during winter to only about 28.80 °C during summer.

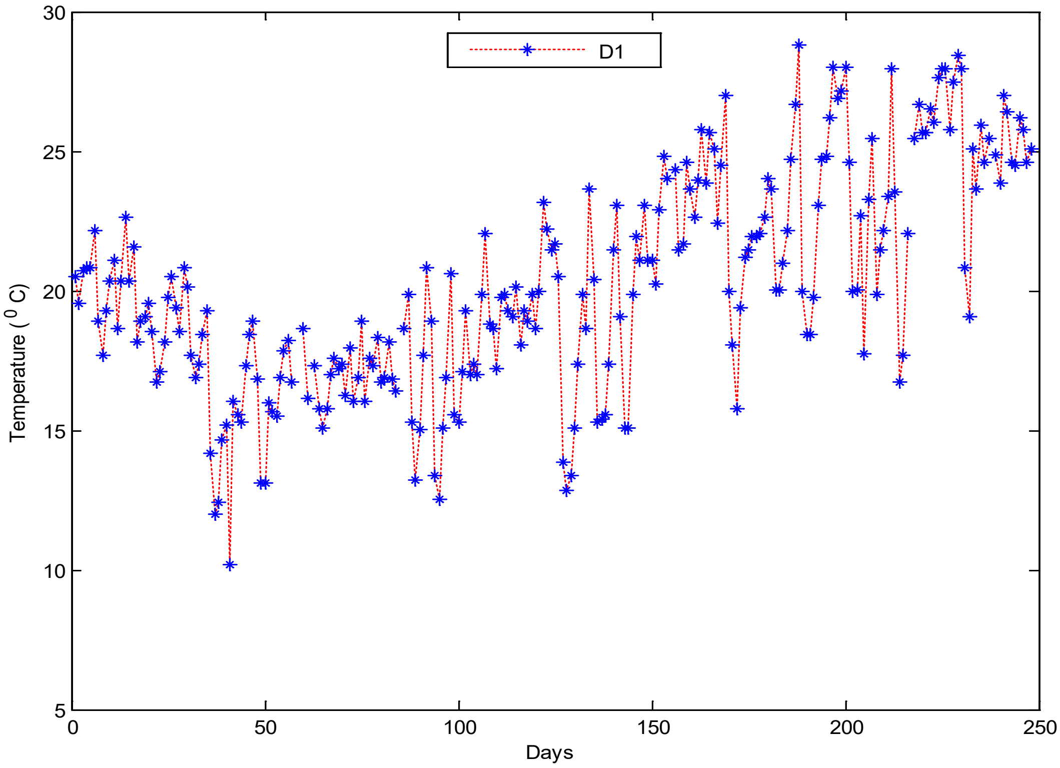


Figure 4-4. Bio-slurry temperature profile for the combined daily average for eight months.

The graph in Figure 4-5. represents both slurry and ambient air temperature across five days during May. The days are 11(A) ,12 (B), 13(C) ,14(D) and 15(E) May 2015. The graph shows that the slurry temperature was mostly higher than the ambient air temperature. On the 11th day, the temperature reading showed that the maximum ambient air temperature was 22.69 °C at 15h51 and the maximum slurry temperature was 24.00 °C at 16h34, giving the thermal time lag of 0.7h and a decrement factor (DF) of 0.9.The thermal time lag of 0.7h which shows the time delay of heat transfer to the slurry through the digester and is defined as the difference between the time of maximum inner temperature (hr) and the time of maximum ambient air temperature(hr) (Quagraine et al., 2020). On the 15th, the maximum for the day was 26.46 for the air temperature at 13h10, and the corresponding maximum slurry temperature recorded was 27.20 °C at 13h53 giving a time lag of 0.7h and a DF of 0.6. The dependency of slurry temperature is also shown for the remaining days, as depicted in Fig 4-4. Like the study (Qiu et al., 2016), ambient air temperature is usually less than the slurry temperature. Similar results were obtained in the study by (Sabbir et al., 2021)

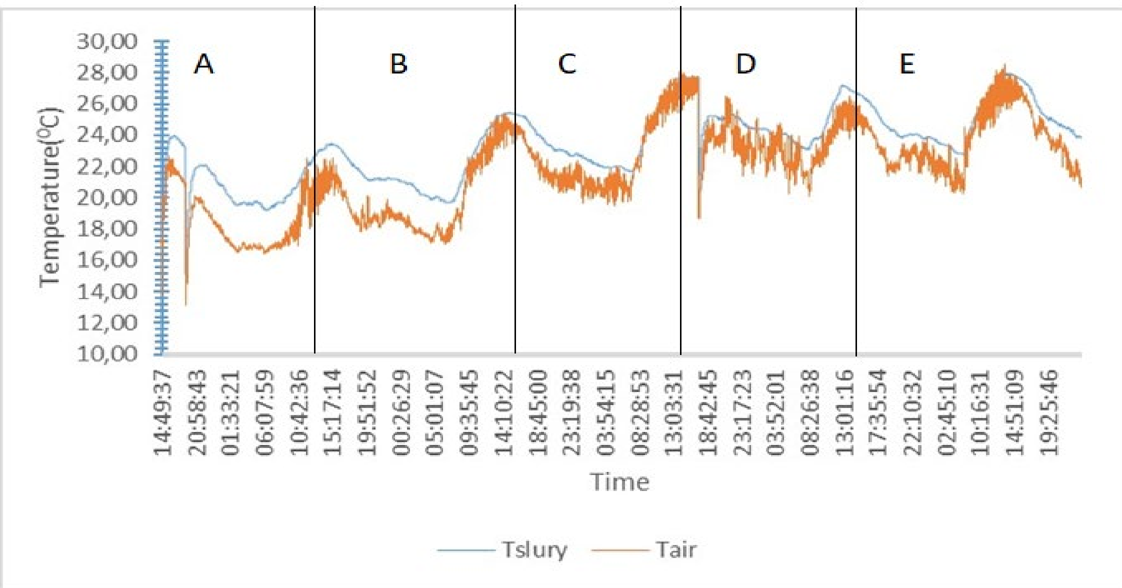


Figure 4-5. Comparison of ambient air temperature and bio-slurry air temperature.

Figure 4-6. represents the monthly average bio-slurry temperature profile. May was characterized by a daily average temperature as low as 16.70 °C with a maximum of 22.90 °C and a standard deviation of 4.38°C. June saw a daily average temperature down to 10.20 °C, rising to a maximum of 19.30 °C with a standard deviation of 6.43°C. July and August were also very cold, recording slurry temperatures ranging between 13.20 °C and 20.80 °C and 12.50 °C to 23.20 °C, respectively. The warmer months of September, October, November, and December recorded, as expected, relatively higher daily average temperatures inside the digester bio-slurry, ranging from 12.80 °C to just above 24.80 °C, between 15.80 °C and 27.00 °C, from 16.70 to 28.8 and from 19.10 °C to 28.40 °C. It shows that during May, which marks the beginning of the winter season, the average temperature was 19.80 °C. June had a monthly average of 14.75 °C, and July and August recorded 17.0 °C and 17.85 °C, respectively. The warmer months of September, October, November, and December recorded a relatively higher monthly mean of 18.18 °C, 21.40 °C, 22.75 °C, and 23.75 °C, respectively. The standard deviation, which measures the diversity of the data set from the mean, was slight, meaning that the data were close to the mean. The standard deviation for July, August, September, October, November, and December are 5.37°C,7.5°C, 8.48°C,7.9°C, 8.5°C, and 6.5°C, respectively, which shows that data were most spread in November and tightly packed in May.

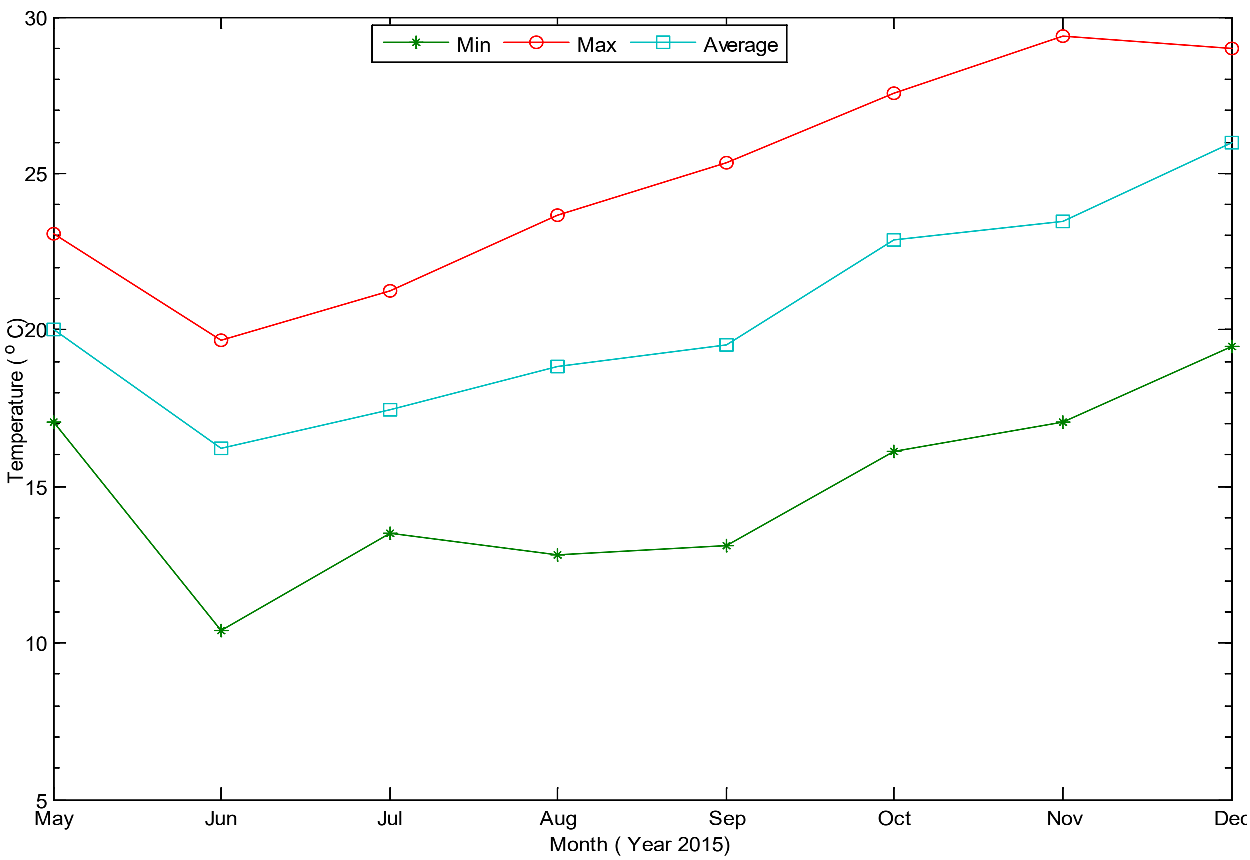


Figure 4-5. A monthly minimum, maximum and average bio-slurry temperature.

Figure 4-7 shows the measured bio-slurry temperature on the coldest and hottest days. Day 10 of June was recorded as the coldest, with a monthly average temperature of 15.90 °C. On the coldest day of June, the temperature rises and attains a maximum of 18.81°C for three hours between 14H00 and 16H00. The minimum was 4.70 °C, around 07H00. There was a substantial difference between the coldest and hottest temperatures. The temperature difference was from a minimum of 5.05 °C at 05H00 on 10 June to 38.76 °C at 13H00 on 2 November. The graph also shows that the temperature was above 30.00 °C from 08H00 until 17H00 on 2 November.

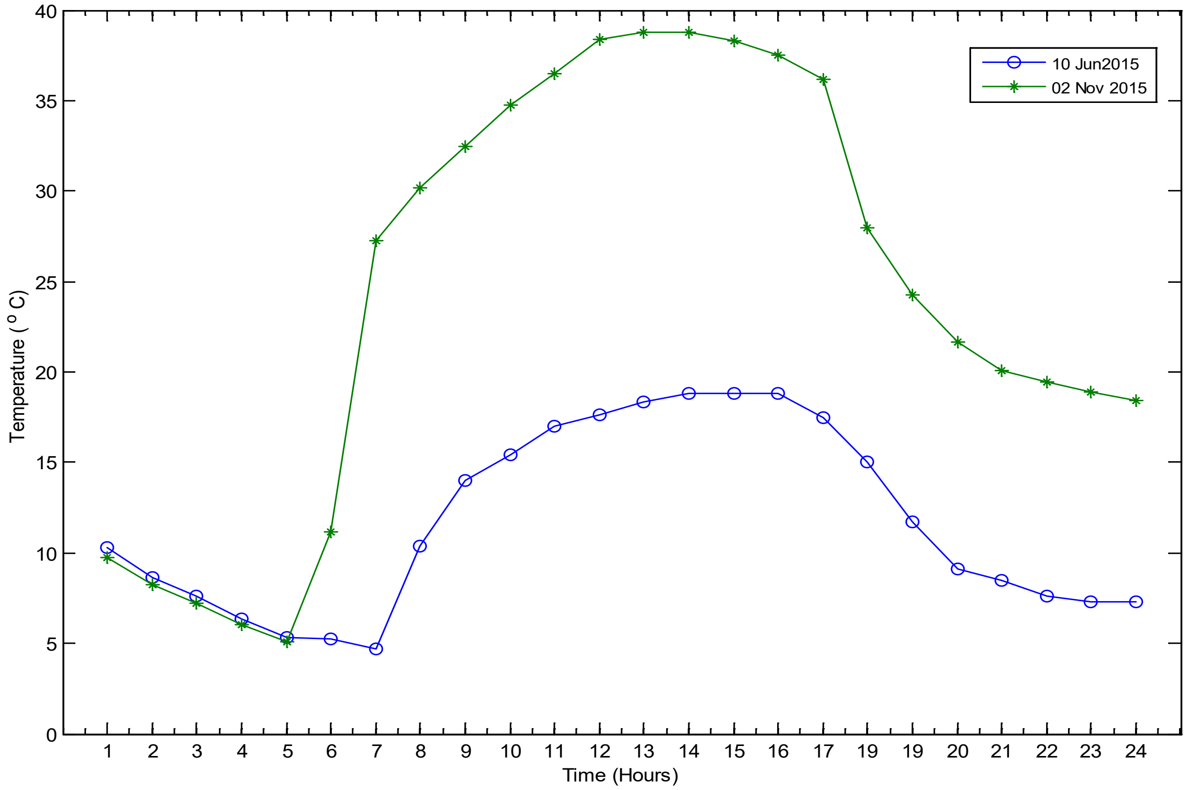


Figure 4-6. Slurry temperature profile for the hourly average for the winter and summer peaks.

4.4. Heat transfer to the slurry through the digester

Figure 4-8 shows the total monthly energy accumulated by the slurry inside the digester. It can be seen from the bar graph that the slurry acquired more heat during December compared to the other months (November, September, October, July, August, and June, May) .

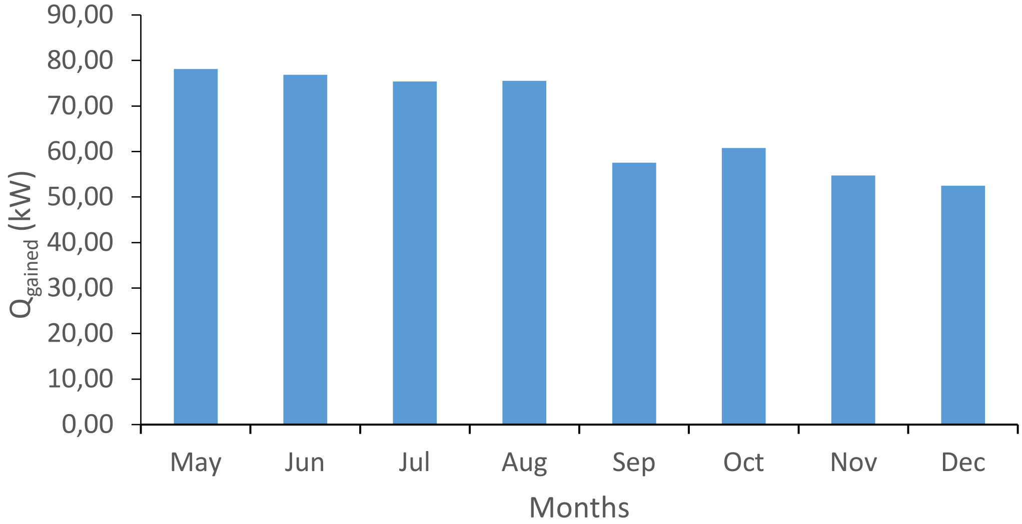


Figure 4-8. Total heat gained by the fermenting slurry.

While still focusing on the information presented in Figure 4-8, the increment of the heat gained values by the fermenting slurry was found using Equation 3.3. The heat gained was found to be 52.46 kW, 54.76 kW, 57.53 kW, 60.75 kW, 75.37 kW, 75.56 kW, and 76.85 kW during December, November, September, October, July, August, and June, then 78.09 kW during May. However, looking at the averages of the slurry temperature over nine hours of each month, the increment is in the order of 20.90 °C, 21.26 °C, 23.01 °C, 23.08 °C,2 4.38 °C, 26.56 °C, 27.20 °C, and 29.25 °C during June, July, August, September, May, October November, and December. From this observation, it can be emphasized that the warmest months (e.g., December and November) warrant the possibility of low heat requirement of the digester. This study investigated why the warmer month (December) yields the lowest heat requirement than the colder month (June). It was found that during the colder month, the minimum temperature is 5.00°C, and the maximum temperature is 30.65 °C. During

December, the minimum temperature is 19.95 ℃, and the maximum temperature is 38.75 ℃ Hence the temperature difference on an hourly basis was higher during colder months than in warmer months. Another point to note is that as the difference between the cold and hot temperatures in each period increases, the total heat also increases, which helps keep warm digesters. This is beneficial to the biogas operators to harness more biogas because if the dissipated energy from the digester is less than that absorbed from the sun, the digester can experience a temperature drift, which can endanger the stability of the biomethane process in the biomass substrate (Matteo et al., 2014).

Figure 4-9 shows the estimated results of soil heat flux. The horizontal axis presents the days, and the vertical axis shows soil heat flux. The starting time of the integration was set to 07h00am and ended at 16h00pm of each day to enable soil heat flux estimates. The daily sums of the soil heat flux depend on the temperature difference of the soil at its surface.

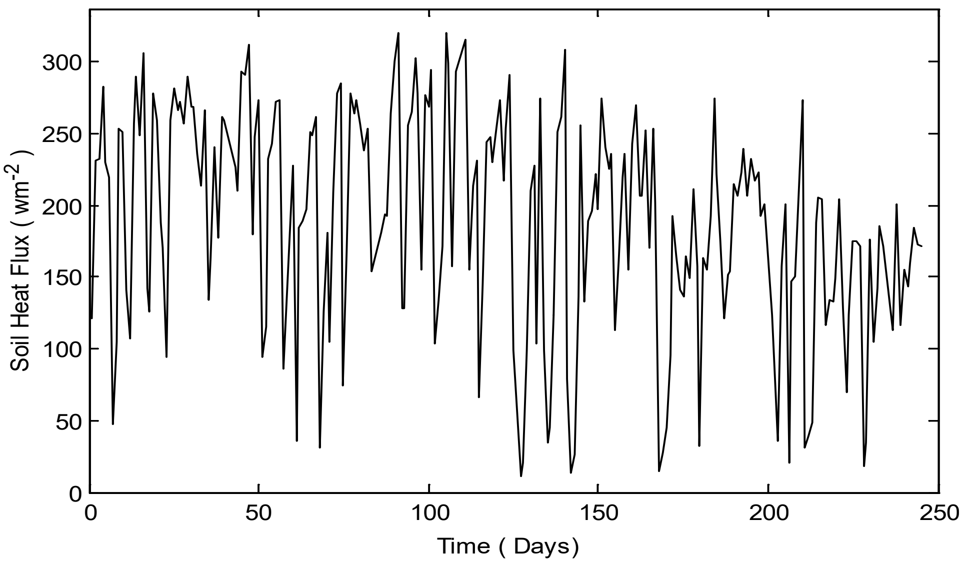


Figure 4-9. Results of soil surface heat flux

Figure 4-10 shows the relationship between the total heat gained for 245 days and soil surface heat flux. The figure shows that the horizontal axis presents the heat gained, and the vertical axis shows soil heat flux. The variation of heat acquired by the slurry was in good agreement with the soil surface heat flux variation. The linear polynomial curve obtained a linear slope nearly to 1 and the RMSE of 5.33 x10^{-6}. The relation obtained from the linear fit in Figure 4-10 suggests that the heat gained by the slurry may be obtained from the soil surface heat flux given by Equation 4.1.

$$Q_{gained} = 0.358G(t) + 3.44e^{-13} \tag{4.1}$$

Where G(t) is soil heat flux in W/m^{-2} and can be measured directly using any soil heat flux detector.

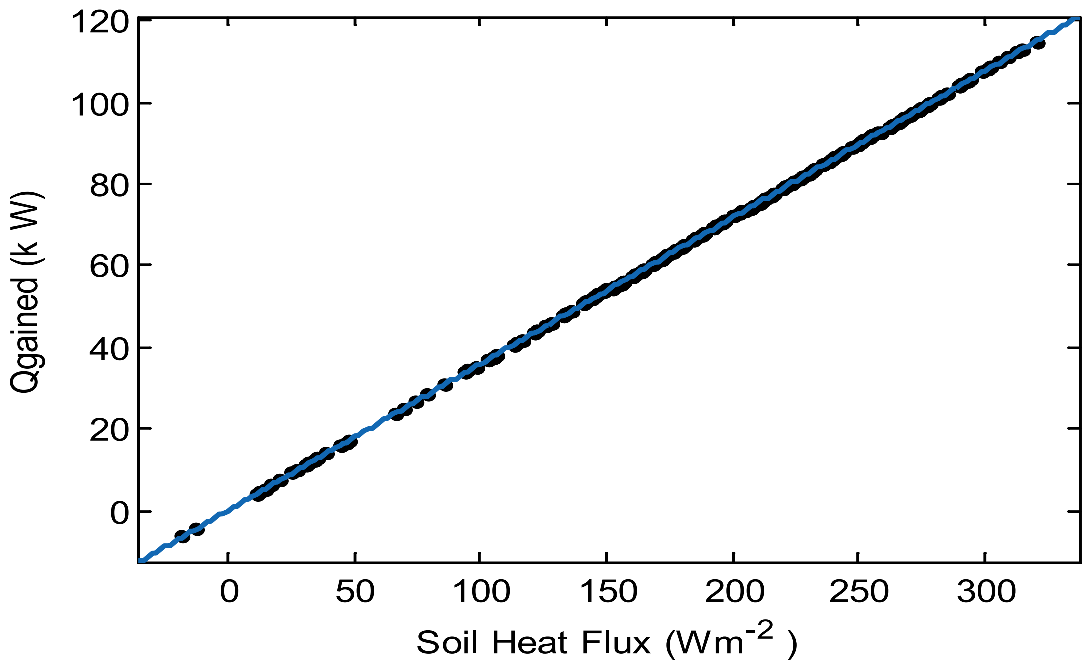


Figure 4-10. Relationship of heat gained by the slurry and soil surface heat flux.

Figure 4-11 shows the relationship between the average slurry temperature for 245 days and the soil surface temperature. The figure shows that the horizontal axis presents the soil surface temperature, and the vertical axis shows the slurry temperature. Figure 4-11 shows that slurry and soil surface temperature are closely related (R^2=0.949), leading to a linear regression Equation.

$$T_s = 1.13T_{ss} + 0.18 \tag{4.2}$$

Using the Equation (Kätterer & Andrén, 2009) to express T_{slurry} in Eq. (4.2) leads to the extended regression equation.

$$T_s = 1.13\{T_{Air}[\left(s_1 + (1 - s_1)e^{\left(-s_2(LAI - LAI_{ref})\right)}\right]\} + 0.18 \tag{4.3}$$

LAI denotes the leaf area index, and LAI_{ref} is the standard leaf area. Eq. (4.3) suggests that ambient air temperature could be a substitute for predicting slurry temperature even if soil surface temperature data are unavailable. The Eq. (4.3) holds for $T_{air\geq}0$ for non-standard conditions $(LAI \neq LAL_{ref})$. T_{ss} differs from T_{air} to an extent governed by estimated parameters values for the general model where $s_1 = 0.95$ and $s_2 = 0.40$ for mineral soils .The meaning of s_1 is that soil surface temperature is 95% of air temperature, and s_2 is that soil surface is 40% of air temperature (Kätterer & Andrén, 2009).

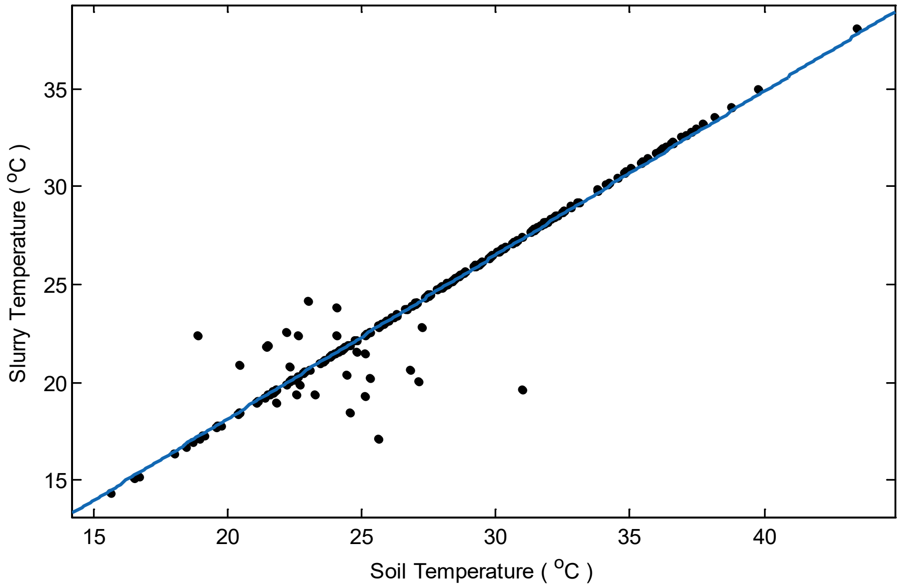
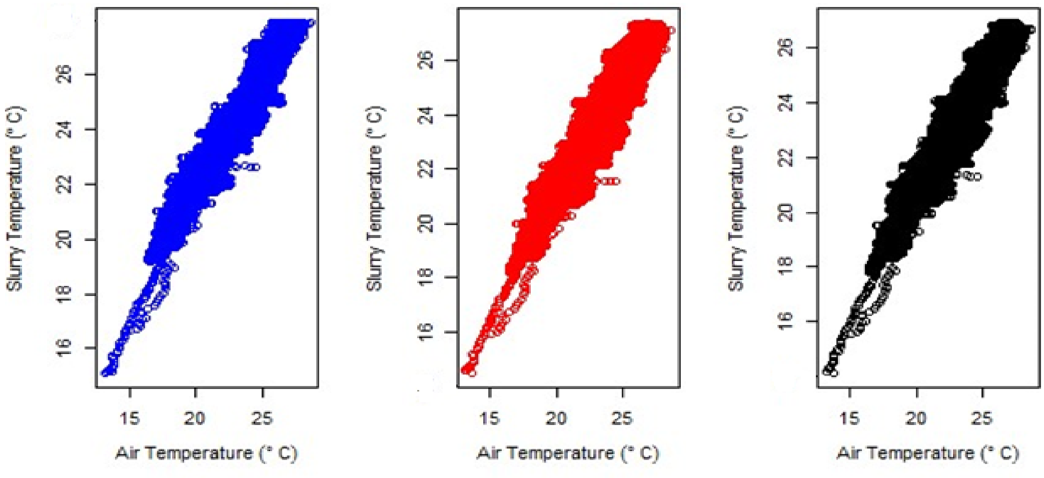


Figure 4-11 Relationship of slurry temperature and soil temperature.

4.5. Statistical modelling

4.5.1. Correlation between slurry and air temperature variables

Looking closely at the three comparatively plots in Figure 4-12 below, we see that for most instances where air temperature increases, the slurry temperature also increases along with it. The increased pattern of both variables shows a high positive correlation between them. Therefore, the correlation between them could be closer to 1. For example, the computed correlation between the slurry temperature of digester one and the air temperature was 0.967. For digesters 2 and 3, the correlation was 0.954 and 0.955. Thus, the two variables are correlated.



(a) digester 1 (b) digester 2 (c) digester 3

Figure 4- 7. Relationship of bio-slurry temperature and air temperature.

Table 4-1:Linear model summary of full data.

Digester	Adjusted R^2	Multiple R^2	Pr(>|t|)
1	0.9365	0.9365	<2e-16 ***
2	0.9102	0.9102	<2e-16 ***
3	0.9126	0.9126	<2e-16 ***

In summary, Table 4-1 shows that for digester 1, multiple R-squared values are 0.9365. The Adjusted R-squared value is 0.9365, which is remarkably high. Multiple R-squared values and Adjusted R-squared values for digester 2 are 0.9102 and 0.9102, which is also extremely high. Multiple R-squared values and Adjusted R-squared values for digester 3 are 0.9126 and 0.9126, which is also extremely high. The other thing to notice is that both values are non-zero for all digesters, influencing the prediction model. As for the Pr(>|t|) values, intercept and theoretical slope have the three most significant stars. The predicting models for digesters 1, 2, and 3 are given by;

$$T_s = 6.6 + 0.77T_{Air} \tag{4.4}$$

$$T_s = 4.56 + 0.81T_{Air} \quad (4.5)$$

$$T_s = 4.91 + 0.81T_{Air} \quad (4.6)$$

4.5.2. Model diagnostic

Figure 4-13 shows the plot in the upper left shows the residual errors plotted versus their fitted values. The residuals are randomly scattered and spread more to the right than to the left. The plot in the lower left is a standard Q-Q plot, which shows that the residual errors are normally distributed. The scale location plot in the upper right shows the square root of the standardized residuals (a square root of relative error) as a function of the fitted values. Finally, the plot in the lower right shows each point leverage, which measures its importance in determining the regression result. A smaller distance means that removing the observation has an insignificant effect on the regression results. Spaces larger than 1 are suspicious and suggest the presence of a possible outlier or a poor model. Hence in our case, the spaces are less than one, as shown in Figure 4-13.

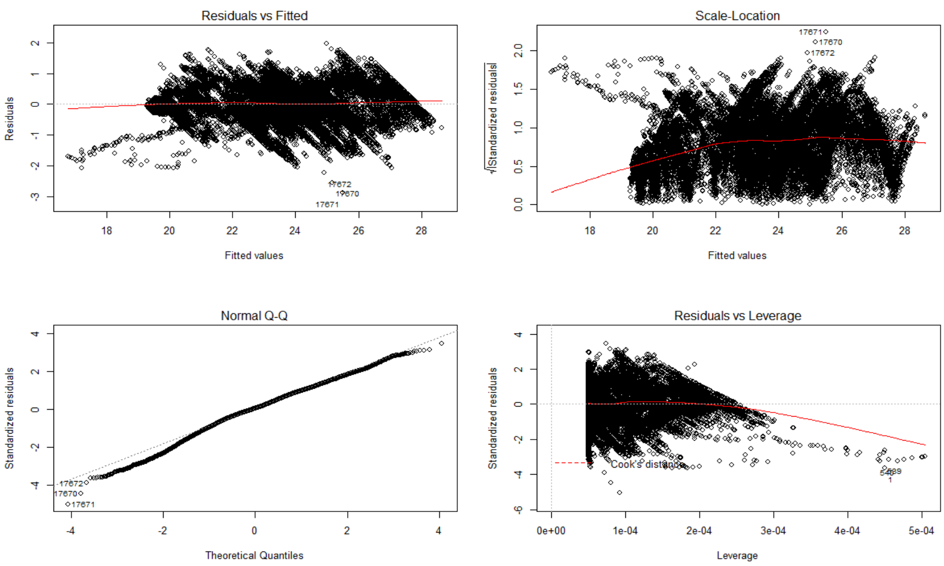


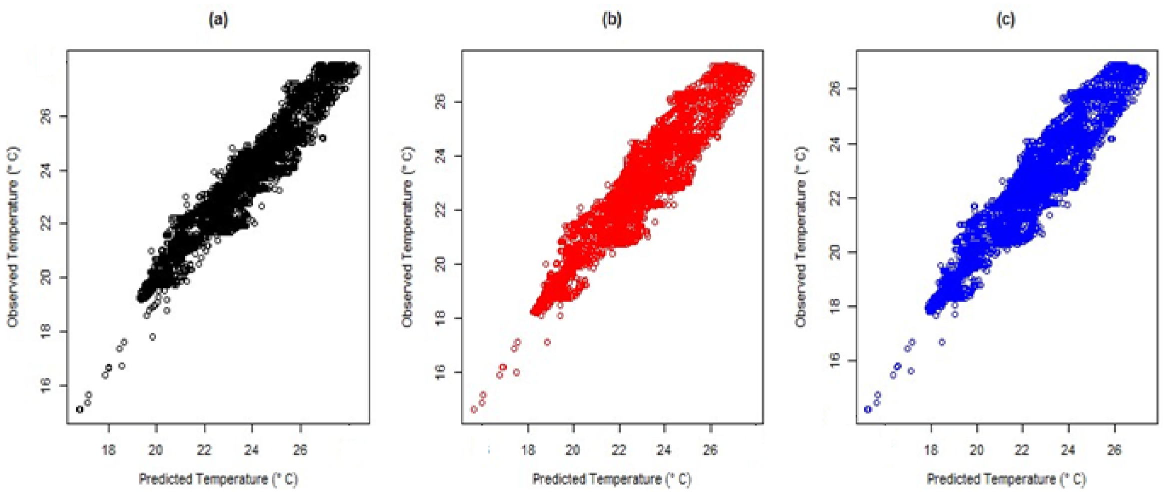
Figure 4-8. Residuals errors plotted versus their fitted values, normal Q-Q, Cook's distance and residuals versus point leverage.

4.5.3. Model testing

In summary below, we found that the Multiple R-squared values, Adjusted R-squared values, and $\Pr(>|t|)$ values are close to each other. Again, Table 4-2 shows the observed and predicted slurry temperature, confirming the two relations. Thus, both the experimental and the predicted slurry temperatures are closely related. For this reason, the three equations are valid despite some discrepancies in the model, which can be improved by installing more temperature sensors with a data logger.

Table 4-2: Summary of observed and predicted slurry temperature.

No of Trial	Digester 1		Digester 2		Digester 3	
	$T_{observed}$ (°C)	$T_{Predicted}$ (°C)	$T_{observed}$ (°C)	$T_{Predicted}$ (°C)	$T_{observed}$ (°C)	$T_{Predicted}$ (°C)
3	16.73	18.59	16.00	17.51	15.60	17.12
14	17.81	19.86	18.10	19.43	16.71	18.46
23	18.80	20.42	18.10	19.43	17.70	19.04
27	19.16	20.42	18.46	19.43	18.06	19.04
29	19.35	19.60	18.65	18.57	18.25	18.18
33	19.75	20.76	19.05	19.79	18.65	19.40



(a) digester1 (b) digester 2 (c) digester 3

Figure 4-14. Performance of trained and tested model of Slurry Temperature and air temperature derivatives descriptor dataset.

Table 4-3:Linear model summary of derivatives descriptor dataset.

	Adjusted R^2	Multiple R^2	Pr(>|t|)
Digester 1	0.9364	0.9364	<2e-16 ***
Digester 2	0.9100	0.9100	<2e-16 ***
Digester 3	0.9123	0.9123	<2e-16 ***

From the graph in Figure 4-14 and Table 4-3, for digester 1, multiple R-squared values are 0.9364. The Adjusted R-squared value is 0.9364, which is remarkably high. Multiple R-squared values and Adjusted R-squared values for digester 2 are 0.9100 and 0.9100, which is also extremely high. Multiple R-squared values and Adjusted R-squared values for digester 3 are 0.9123 and 0.9123, which is also remarkably high. As for the Pr(>|t|) values, both intercept and theoretical slope have the three most significant stars

4.6. Biogas digester performance

4.6.1. Prediction of biogas production rate

This section aimed to predict the daily biogas production rate using slurry temperature averaged for the three digesters. The rate of biogas produced per the rated volume of biogas storage is one of the most crucial measures of digester performance. Predicting the biogas production helps users plan since the exact cooking time is hard to predict when using biogas. The three models have been developed and tested to predict the slurry temperature and agree with the measured data. It was crucial to average the three models to get the general model to predict slurry temperature, representing the temperature of each digester system as shown in Eq. (4.7).

$$T_s = 0{,}79\mathrm{T}_{Air}+5{,}35 \quad (4.7)$$

By doing so, the biogas production rate was computed using Eq. (2.11). The fermentation process in the biogas digester was stable concerning biogas production. The methane content of biogas was not measured daily but was measured after 42 days of initial feeding. Figure 4-15 shows the daily rate of biogas production of the fermentation of cow manure. The difference between the biogas production rate shows the influence of a temperature slurry on the process. Looking closely at the plot in Figure 4-15, we see that for most instances where slurry temperature increases, the biogas production rate increases along with it. For example, when the slurry temperature is the lowest at 15.0 °C during June, the biogas production rate varies from as low as 0.24 Nm^3 d^{-1}. May was characterized by a daily average biogas production rate as low as 0.31 Nm^3 d^{-1} at 21.0 °C with a maximum of 0.36 Nm^3 d^{-1} at 27.0°C. July and August were also very cold, recording biogas production rates as low as 0.27 Nm^3 d^{-1} at 16.0 °C and with a maximum of 0.35 Nm^3 $d^{-1}$and 0.37 Nm^3 d^{-1}, respectively. The warmer months of September, October, November, and December recorded a higher biogas production rate, ranging from 0.25 Nm^3 d^{-1} to 0.41 Nm^3 d^{-1}.

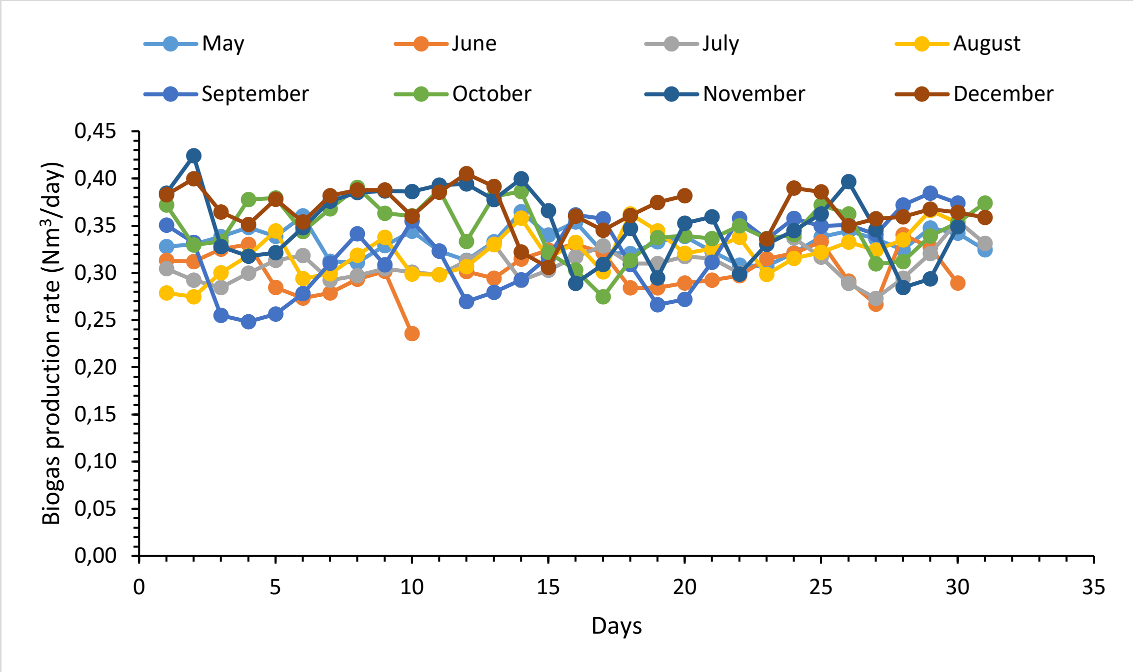


Figure 4-15. Daily Predicted biogas production rate.

The digester's biogas production rate varies because of the average ambient temperature. Figure 4-16 presents the values of average ambient temperature ranges with their biogas production rate per day. Figure 4-16 below shows that the biogas production rate increases for a day as the average ambient air temperature increases and vice versa. There is a strong relationship between the biogas production rate and the ambient air temperature with R^2=0.99. Figure 4-16 is crucial for users to predict daily biogas production using ambient air temperature as input using Eq. (4.8).

$$Y = 0.019T_{Air} + 0.1929 \quad (4.8.)$$

Where Y and T_{Air} are biogas production rate (Nm^3/day) and ambient temperature, respectively. Equation 4.8 is valid for temperatures ranging from 10°C to temperatures 40°C. Table 4-4 below shows how biogas production rate varies with the change of ambient temperature. We put the production rate in the table because Biogas meter readings display m^3 not Nm^3.

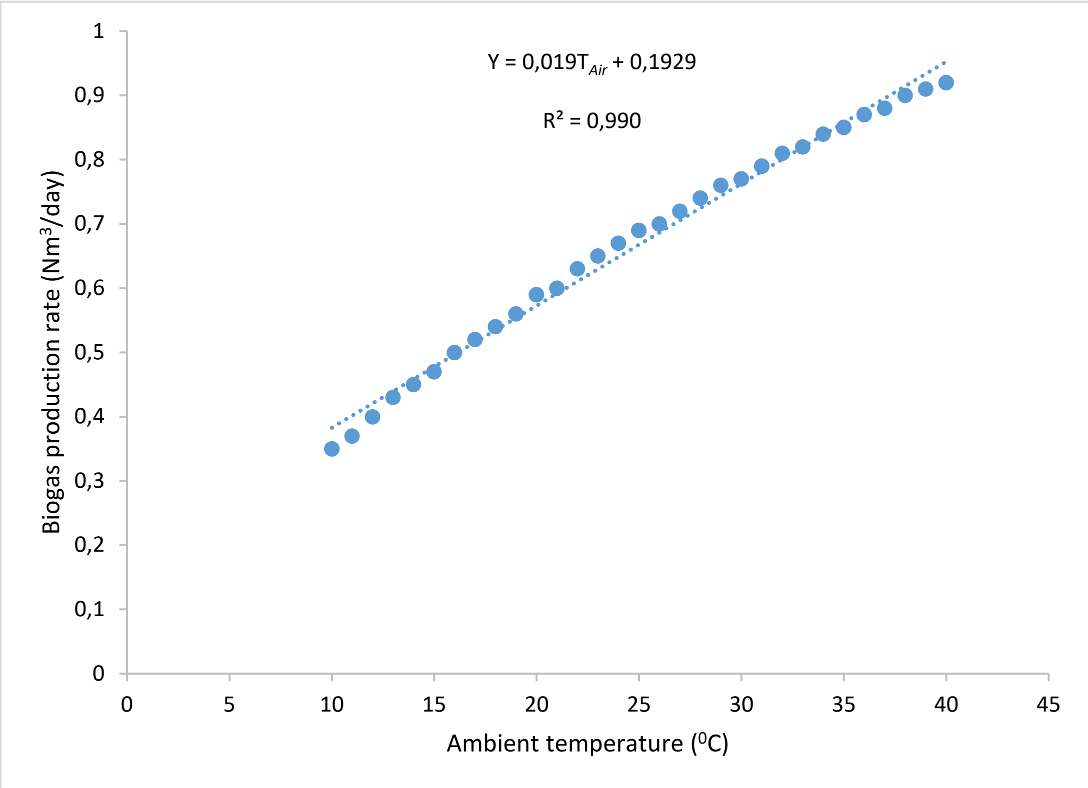


Figure 4-16. Relationship of biogas production rate and ambient temperature.

Table 4-4: Biogas production rate for biogas plant of rated gas storage capacity of 2.0 m^3 and digester volume 6 m^3 fed with 35 kg cow dung and 35 L of water per day.

Ambient air temperature T*Air* (°C)	Estimated biogas production rate (m^3/day)	Estimated biogas production (m^3/m^3/day)
10-15	0.36 - 0.50	0.18 - 0.25
16-20	0.53 - 0.63	0.26 - 0.31
21-25	0.65 - 0.75	0.33 - 0.37
26-30	0.77 - 0.86	0.39 - 0.44
31-35	0.88 - 0.96	0.44 - 0.48
36- 40	0.98 - 1.05	0.49 - 0.53

4.7. Conclusions

Firstly, workshops conducted with biogas digester beneficiaries revealed that active harnessing and developing of small-scale biogas digester technology in Limpopo province began in 2007. It was also found that there was a lack of research on maximizing the uptake of biogas technology in Limpopo Province paved the way for research institutions to get involved in research work. During workshops, technicality surrounding biogas digester technology, such as the quality of biogas produced, was discussed. Secondly, the chapter reported the monitored operational temperature of fermenting slurry inside an underground, unheated, unstirred Deenbandhu model biogas digester by orientating a temperature sensor at the center of a digester.

The emphasis was on showing how important it is to conduct a long-term study of the slurry temperature profile at the local level. Based on the obtained results, the average daily operational temperature of the digester at Vele Secondary School ranged between 10.32 °C and 29.80 °C. Again, the biogas digesters sometimes operated at an optimum mesophilic temperature range in summer hours. For example, in the hottest month (November), the system's temperature was over 35.00 °C for seven hours, between 11H00 and 17H00. Thirdly, the results of the calculations of the heat absorbed by the digester over a given period were discussed. Using the soil layer as an insulator of the cover was to avoid implications on digester economics. The forecast of slurry temperature depending on the daily ambient temperature variation, even though the soil temperature is unavailable, was developed. However, a more reliable model was then developed using the measured data of slurry temperature and ambient air temperature. Lastly, the biogas production was computed based on the data of the predicted slurry temperature. It was found that the production rate also increases as the temperature increases.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In conclusion, we draw our attention to the aim of the thesis to present the results of the research work undertaken. This research aimed to study the relationship between bio-slurry temperature and the ambient air temperature for a completely covered and unheated brick-built household size Deenbandhu biogas digester, relevant at a local level. Numerous studies on household biogas digester systems in the literature focused more on biogas digesters that are heated, stirred, and not covered with soil. Therefore, it appeared appropriate to conclude this work by providing answers to the research questions formulated. Firstly, the rigorous selection of suitable locations and potential stakeholders for biogas digester facilities is of utmost importance in Limpopo province and must be approached with renewed interest. We have also found that biogas projects fail whenever organizations choose locations for biogas projects without the involvement of key research institutions such as universities, technical colleges, and SANEDI.

Secondly, a background check was conducted on household biogas digesters installed in Limpopo province. The study found that many were unstirred, unheated, brick-built systems. Some were not operational due to low gas production, especially during winter and rainy days. The background check study enabled us to set up a data acquisition system to investigate the operational temperature of biogas digester fermenting slurry. The study shows that the average daily operating temperature of the digesters studied ranged between psychrophilic and mesophilic regimes.

Thirdly, the bio-slurry temperature was successfully predicted and evaluated. The temperature of the fermenting bio-slurry inside the digester studied is influenced by the ambient air temperature. The study showed a strong correlation between bio-slurry and ambient air temperature. The study also shows a strong correlation between the measured and predicted temperature of the fermenting slurry inside the digester. The two developed models could estimate the temperature of the fermenting bio-slurry inside the digester. In addition, the biogas production was computed based on the data of the predicted slurry temperature. It was found that the production rate also increases as the temperature increases.

5.2. Recommendations and future scope

Many things can be improved in the future study of heat transfer using temperature as one of the significant input parameters. Data loggers and temperature sensors can improve the sophistication level to reduce inconvenience. Since the digesters were operating at three different temperature ranges. I recommend the following future studies.

- Field study on Hydrolysis rate at three temperature ranges (Mesophilic, Psychrotrophic and Psychrophilic).
- Validation of the biogas production rate using experimental measurement
  Field study of effect of soil moisture, thermal conductivity on bio-slurry temperature.
- Validation of slurry temperature predictions using ambient temperature, heat flux and thermal resistance of the soil, digester cover, biogas.
- Characterization of organic materials for biogas optimization during three temperature ranges (Mesophilic ,Psychrotrophic and Psychrophilic).

References

Ahring, B. K., Ibrahim, A. A. & Mladenovska, Z., 2001. Effect of temperature increase from 55 to 65 degrees C on performance and microbial population dynamics of an anaerobic reactor treating cattle manure. *Water research,* 35(10), p. 2446–2452.

Akter, M. et al., 2015. Textural Influence on Surface and Subsurface Soil Temperatures under Various Conditions. *Journal of Environmental Sciences & Natural Resources,* 8(2), pp. 147-151.

Alfa, I. M. et al., 2014. Comparative evaluation of biogas production from Poultry droppings,Cow dung and Lemon grass. *Bioresource Technology,* Volume 157, p. 270–277.

Amigun, B. & Blottnitz, H., 2010. Capacity-cost and location-cost analyses for biogas plants in AfricaResources. *Resources , Conservation and Recycling,* 55(1), p. 63–73.

Anukam, A., Mohammadi, A., Naqvi, M. & Granström, K., 2019. A Review of the Chemistry of Anaerobic Digestion:Methods of Accelerating and Optimizing Process Efficiency. *Processes,* Volume 7, p. 504.

Appels , L., Baeyens, J., Degre`ve, J. & Dewil , R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science,* Volume 34, p. 755–781.

Assabumrungrat, S. et al., 2010. Thermodynamic analysis of calcium oxide assisted hydrogen production from biogas. *Journal of Industrial and Engineering Chemistry,* 16(5), p. 785–789.

Axaopoulos, P. & Panagakis, P., 2003. Energy and economic analysis of biogas heated livestock buildings. *Biomass and Bioenergy,* 24(3), pp. 239-248.

Axaopoulos, P., Panagakis, P., Tsavdaris, A. & Georgakakis, D., 2001. Simulation and experimental performance of a solar heated anaerobic digester. *Solar Energy,* 70(2), p. 155–164.

Ayata, T., Tabares-Velasco, P. C. & Srebric, J., 2011. An investigation of sensible heat fluxes at a green roof in a laboratory setup. *Building and Environment,* 46(9), pp. 1851-1861.

Baba, S. U. I. A. & Nasir, I., 2012. Anaerobic Digestion of Cow Dung For Biogas Production. *Journal of Engineering and Applied Sciences,* 7(2), pp. 1819-6608.

Baral, S., Pudasaini , S. P., Khanal, S. N. & Gurung, D. B., 2013. Mathematical model, finite element, simulation, and experimental validation of biogas-digester slurry temperature. *International Journal of Energy and Power Engineering,* 2 (3), pp. 128-135.

Mensah, E. C. & Hammond, A. B., 2010. Biogas technology dissemination in Ghana: history, current status, future prospects, and policy significance. *International Journal of Energy and Environment,* 1(2), pp. 277-294.

Berhe, T. G., Tesfahuney, R. G., Desta, G. A. & Mekonnen, L. S., 2017. Biogas Plant Distribution for Rural Household Sustainable Energy Supply in Africa. *Energy and Policy Research,* 4(1), pp. 10-20.

Bhat, P. R., Chanakya, H. N. & Ravindranath, N. H., 2001. Biogas plant dissemination: success story of Sirsi, India. *Energy for Sustainable Development,* Volume 1, p. 39–46.

Bhattacharjya, D. & Yu, J.-S., 2014. Activated carbon made from cow dung as electrode material for electrochemical double layer capacitor. *Journal of Power Sources,* Volume 265, pp. 224-231.

Bove, R. & Lunghi, P., 2005. Experimental comparison of MCFC performance using three different biogas types and methane. *Journal of Power Sources,* 145(2), p. 588–593.

Bruun, S., Jensen, L., Vu, T. & Sommer, S., 2014. Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb. *Renewable and Sustainable Energy Reviews,* Volume 33, p. 736–741.

Buswell, A. M. & Mueller, H. F., 1952. Mechanism of methane fermentation. *Industrial and Engineering Chemistry,* 44(3), p. 550–552.

Caruso, M. C. et al., 2019. Recent Updates on the Use of Agro-Food Waste for Biogas Production. *Applied sciences,* Volume 9.

Castano, J. M., Martin, J. F. & Ciotola, R., 2014. Performance of a Small-Scale, Variable Temperature Fixed Dome Digester in a Temperate Climate. *Energies,* Volume 7, pp. 5701-5716.

Chattopadhyay, S., Dutta, A. & Ray, S., 2009. Municipal solid waste management in Kolkata, India – A review. *Waste Management,* 29(4), p. 1449–1458.

Cheng, S., Huba, E. M., Li , A. Z. & Mang, H. P., 2013. A review of prefabricated biogas digesters in China. *Renewable and Sustainable Energy Reviews,* Issue 28, p. 738–748.

Cooper, C. D., 2014. *Introduction to Environmental Engineering, ISBN,* Long Grove, IL, Waveland Press.

Das, A. & Mondal, C., 2015. Comparative Kinetic Study of Anaerobic Treatment of Thermally Pretreated Source-Sorted Organic Market Refuse. *Journal of Engineering,* p. http://dx.doi.org/10.1155/2015/684749.

Dhaked, R., Singh, P. & Singh, L., 2010. Biomethanation under psychrophilic conditions. *Waste Manage,* 30(12), p. 2490–2496.

Dobre, P., Nicolae, F. & Matei, F., 2014. Main factors affecting biogas production - an overview. *Romanian Biotechnological Letters,* 19(3), pp. 9283-9296.

DOE, 2009. *NSNP, Guidelines for secondary schools national nutrition program,* Pretoria: Department of education.

Feng, Q. et al., 2019. Influence of the temperature and hydraulic retention time in bioelectrochemical anaerobic digestion of sewage sludge. *International Journal of Hydrogen Energy,* 44(4), pp. 2170-2179.

Gaby, J. C., Zamanzadeh, M. & Horn, S. J., 2017. The effect of temperature and retention time on methane production and microbial community composition in staged anaerobic digesters fed with food waste. *Biotechnology Biofuels,* Volume 10.

Gebreegziabher, Z., Naik, L., Melamu, R. & Balana, B. . B., 2014. Prospects and challenges for the urban application of biogas installations in Sub-Saharan Africa. *Biomass and Bioenergy,* Volume 70, pp. 130-140.

Gebremedhin, K. G. et al., 2005. Heat Transfer Model for Plug-Flow Anaerobic Digesters. *American Society of Agricultural Engineers,* 48(2), p. 777−785.

Gosens, J. et al., 2013. Sustainability effects of household-scale biogas in rural China. *Energy Policy,* Volume 54, p. 273–287.

Guo, H. et al., 2021. Reconsidering hydrolysis kinetics for anaerobic digestion of waste-activated sludge applying cascade reactors with ultra-short residence times. *Water Research,* Volume 202.

Guo, P. et al., 2019. Biogas Production and Heat Transfer Performance of a Multiphase Flow Digester. *Energies,* Volume 12.

Hamilton, C., 2008. *Report on the Evaluating of the National School Nutrition Programme (NSNP),* Pretoria: Creda Communications.

Hlungwani, V., 2009. *Use of biogas energy a first for Limpopo.* [Online].

Huang, J. & Crookes, R. J., 1998. Assessment of simulated biogas as a fuel for the spark ignition engine. *Fuel,* 77(15), p. 1793–1801.

ISRIC - World Soil Information, 2016. *SoilInfo App — global soil data on your palm.* [Online]
Available at: http://www.isric.org/explore/soilinfo
[Accessed December 2017].

Jegede, A. O., Zeeman, G. & Bruning, H., 2019. A review of mixing, design and loading conditions in household anaerobic digesters. *Critical Reviews In Environmental Science And Technology,* 49(22), p. 2117–2153.

Jiang, J. et al., 2020. Effect of Organic Loading Rate and Temperature on the Anaerobic Digestion of Municipal Solid Waste: Process Performance and Energy Recovery. *Frontiers in Energy Research,* Volume 8.

Jiang, X., Sommer, S. G. & Christensen, K., 2011. A review of the biogas industry in China. *Energy Policy,* 39(10), p. 6073–6081.

Kabir, H., Yegbemey, R. N. & Baue, S., 2013. Factors determinant of biogas adoption in Bangladesh. *Renewable and Sustainable Energy Reviews,* Volume 28, pp. 881-889.

Kalia, A. K., 1988. Development and evaluation of a fixed dome plug flow anaerobic digester. *Biomass,* Volume 16, pp. 225-235.

Karimov, S. K. & Abid, M., 2012. Biogas digester with simple solar heater. *IIUM Engineering Journal,* 13(2), pp. 109-119.

Kassongo, J., Shahsavari, E. & Ball , A. S., 2022. Substrate-to-inoculum ratio drives solid-state anaerobic digestion of unamended grape marc and cheese whey. *PLoS ONE,* 17(1).

Kätterer, T. & Andrén, O., 2009. Predicting daily soil temperature profiles in arable soils in cold temperate regions from air temperature. *Acta Agric. Scand., Sect. B,* 59(1), p. 77−86.

Kemausuor, F., Adaramola, M. S. & Morken, J., 2018. A Review of Commercial Biogas Systems and Lessons for Africa. *Energies,* Volume 11.

Khanal, R. C. & Bajacharya, L., 2010. Improved cooking stove(ICS) and its impact on Firewood Consumptions and Reducing Carbon Dioxide Emission: A Case Study from TMJ Area, Nepal. *IUCN Nepal,* Volume 26, pp. 1-3.

Khan, E. U. & Martin, A. R., 2016. Review of biogas digester technology in rural Bangladesh. *Renewable and Sustainable Energy Reviews,* Volume 62, pp. 247-259.

Kothari, R. et al., 2018. Experiment-based thermodynamic feasibility with co-digestion of nutrient-rich biowaste materials for biogas production. *3Biotechnology,* 8(34), pp. 2-8.

Laichena, J. K. & Wafula, J. C., 1997. Biogas technology for rural households in Kenya. *OPEC Energy Review,* 21(3), p. 223–244.

Luo, K. et al., 2012. Hydrolysis kinetics in anaerobic digestion of waste activated sludge enhanced by - amylase. *Biochemical Engineering Journal,* Volume 62, pp. 17-21.

Makhado, R. A., Von Maltitz, G. P., Potgieter, M. J. & Wessels, D. C., 2009. Contribution of woodland products to rural livelihoods in the northeast of Limpopo, South Africa. *South African geographical journal,* pp. 46-53.

Mane, A. B., Rao, B. & Rao, A. B., 2015. Characterization of fruit and vegetable waste for maximizing the biogas yield. *International Journal of Advanced Technology Engineering and Science,* 3(1), pp. 489-500.

Mani, S. & Sundaram, J., 2016. Process simulation and modeling: Anaerobic digestion of complex organic matter. *Biomass and Bioenergy,* Volume 93, pp. 158-167.

Matteo, B. et al., 2014. Thermal stabilization of digesters of biogas plants by means of optimization of the surface radiative properties of the gasometer domes. *Energy Procedia,* Volume 45, pp. 1344-1353.

MDM, 2011. *Mopani District Municipality, Integrated Development Plan, 2011-2016,* Polokwane: Mopani District Municipality.

Meegoda, J. N., Li, B., Wang, L. B. & Patel, K., 2018. A Review of the Processes, Parameters, and Optimization of Anaerobic Digestion. *International Journal of Environmental Research and Public Health 2018,* Volume 15.

Mengistu, M. G., Simane, B., Eshete, G. & Workneh, T. S., 2015. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. *Renewable and Sustainable Energy Reviews,* Volume 48, p. 306–316.

Menzel, T., Neubauer, P. & Junne, S., 2020. Role of Microbial Hydrolysis in Anaerobic Digestion. *Energies,* Volume 13.

Merlin, G. et al., 2012. Importance of heat transfer in an anaerobic digestion plant in a continental climate context. *Bioresource Technology,* Volume 124, pp. 59-67.

Michal, L. & Mark Mba., W., 2020. A review of biogas and an assessment of its economic impact and future role as a renewable energy source. *Reviews in Chemical Engineering,* 36(3), pp. 401-421.

Mir, M. A., Hussain, A. & Verma, C., 2016. Design considerations and operational performance of anaerobic digester: A review. *Cogent Engineering,* Volume 3.

Msibi, S. S. & Gerrit, K., 2017. Potential for domestic biogas as household energy. *Journal of Energy in Southern Africa,* 28(2), pp. 1-13.

Mukumba, P., Makaka, G., Mamphweli, S. & Misi, S., 2013. A possible design and justification for a biogas plant at Nyazura Adventist High School, Rusape, Zimbabwe. *Journal of Energy in Southern Africa,* 24(4), pp. 12-21.

Mukumba, P., Makaka, G. & Shonhiwa, C., 2015. An assessment of the performance of a biogas digester when insulated with sawdust. *International Journal of Energy and Power Engineering,* 4(2), pp. 24-31.

Mulinda, C., Hu, Q. & Pan, K., 2013. Dissemination and Problems of African Biogas Technology. *Energy and Power Engineering,* Volume 5, pp. 506-512.

Mulu, G. M., Belay, S., Getachew, E. & Tilahum, W. S., 2016. The environmental benefits of domestic biogas technology in rural Ethiopia. *Biomass and Bioenergy,* Volume 90, pp. 131-138.

Mutungwazi, A., Mukumba, p. & Makaka, G., 2018. Biogas digester types installed in South Africa: A review. *Renewable and Sustainable Energy Reviews,* Volume 81, p. 172–180.

Mwirigi, E. K., Kirubi, G. & muriuki, S., 2018. Key Factors Influencing Adoption of Biogas Technology in Meru County, Kenya. *Journal of Environmental Science, Toxicology and Food Technology,* 12(3), pp. 57-67.

Myint, M., Nirmalakhandan, N. & Speece, R. E., 2007. Anaerobic fermentation of cattle manure: Modeling of hydrolysis and acidogenesis. *Water Research,* 41(2), pp. 323-332.

NDA, 2013. *cattle,* Pretoria: National department of agriculture.

Nevzorova, T. & Kutcherova, V., 2019. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. *EnergyStrategyReviews,* Volume 26.

Nichols, D. J., Glencross, K., Vanclay, K. J. & Flore, G. L., 2019. Developing biomass estimation models for above-ground compartments in Eucalyptus dunnii and Corymbia citriodora plantations. *Biomass and Bioenergy,* Volume 130.

Nie, E. et al., 2021. How does temperature regulate anaerobic digestion. *Renewable and Sustainable Energy Reviews,* Volume 150.

Nielsen, M. et al., 2017. Small temperature differences can improve the performance of mesophilic sludge-based digesters. *Biotechnology Letter,* Volume 39, p. 1689–1698.

Nsair, A. et al., 2020. Operational Parameters of Biogas Plants: A Review and Evaluation Study. *Energies,* 14(15).

Orhorhoro, E. K., Ebunilo, P. O. & Sadjere, G. E., 2017. Experimental Determination of Effect of Total Solid (TS) and Volatile Solid (VS) on Biogas Yield. *American Journal of Modern Energy,* 3(6), pp. 131-135.

Osei-Marfo, M., Awuah, E. & de Vries, N. K., 2018. Biogas technology diffusion and shortfalls in the central and greater Accra regions of Ghana. *Water Practice and Technology,* 13(4), pp. 932-946.

Panico, A. et al., 2014. The Effect of Substrate-Bulk Interaction on Hydrolysis Modeling in Anaerobic Digestion Process. *Sustainability,* Volume 6, pp. 8348-8363.

Park, C. et al., 2005. Upgrading of Anaerobic Digestion by Incorporating Two Different Hydrolysis Processes. *Journal of Bioscience and Bioengineering,* 100(2), p. 164–167.

Pérez, I., Garfí, M., Cadena, E. & Ferrer, I., 2014. Economic and environmental assessment of household biogas digesters for rural communities. *Renew Energy,* 2(Renew Energy), pp. 13-18.

Perrigaulta, t., Weatherfordb, V., Martí-Herreroa, J. & Poggioc, D., 2012. Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. *Bioresource Technology,* 124(21), p. 259–268.

Pham, C. ,. H., Triolo, J. M. & Sommer, S., 2014. Predicting methane production in simple and unheated biogas digesters at low temperatures. *Applied Energy,* Volume 136, pp. 1-6.

Pilloni, M. & Hamed, T. A., 2021. Small-Size Biogas Technology Applications for Rural Areas in the Context of Developing Countries. In: A. Sikora, ed. *Anaerobic Digestion in Built Environments.* United Kingdom: IntechOpen Limited.

Pramanik, S. K., Suja, F. B., Porhemmat, M. & Pramanik, B. K., 2019. Performance and Kinetic Model of a Single-Stage Anaerobic Digestion System Operated at Different Successive Operating Stages for the Treatment of Food Waste. *Processes,* Volume 7.

Prasad, R. D., 2012. Empirical Study on Factors Affecting Biogas Production. *ISRN Renewable Energy.*

Prathmika, D. & Patel, N., 2014. Biogas Production from Different Waste Materials in India. *The international journal of science and technology,* 2(6), pp. 105-109.

Prayoonkhama, S., khanthi, K. & Sukasem, N., 2017. Biomethane Recovery from Fresh and Dry Water Hyacinth Anaerobic Co-Digestion with Pig Dung, Elephant Dung, and Bat Dung with Different Alkali Pretreatments. *Energy Procedia,* Volume 138, p. 294–300.

Qiu, L., Amro, A. M. H. & Asli, A., 2016. New Factor (Quality of Temperature) Affecting Directly the Biogas Production and Solved by Solar Heating Models. *Nature Environment and Pollution Technology,* 15(2), pp. 761-766.

Quagraine, K. A., Ramde, E. W., Fiagbe, Y. A. & Quansah, D. A., 2020. Evaluation of time lag and decrement factor of walls in a hot, humid tropical climate. *Thermal Science and Engineering Progress.*

Rabbi, S. M., Biswas, S. & Salam, B., 2015. Biogas from Mesophilic Anaerobic Digestion of Cow Dung Using Silica Gel as Catalyst. *Procedia Engineering,* Volume 105, p. 652–657.

Rajendran, K., Aslanzadeh, S. & Taherzadeh, M. J., 2012. Household Biogas Digesters—A Review. *Energies,* Volume 5, pp. 2911-2942.

Rajendran, K., Aslanzadeh, S. & Taherzadeh, M. J., 2012. Household Biogas Digesters—A Review. *Energies,* Volume 5, pp. 2911-2942.

Ramaswamy, J. & Vemareddy, P. S., 2015. Production of biogas using small-scale plug flow reactor and sizing calculation for biodegradable solid waste. *Renewables: Wind, Water, and Solar,* 2(6), pp. 1-4.

Rennuit, C. & Sommer, S. G., 2013. Decision Support for the Construction of Farm-Scale Biogas Digesters in Developing Countries with Cold Seasons. *Energies,* Volume 6, pp. 5314-5332.

Sabbir, Y. B. A. S. M. et al., 2021. Effects of Seasonal Temperature Variation on Slurry Temperature and Biogas Composition of a Commercial Fixed-Dome Anaerobic Digester Used in Bangladesh. *Sustainability 2021, 13,* Volume 13.

Sarker, S., Lamb, J. J., Hjelme, D. R. & Lien, K. M., 2019. A Review of the Role of Critical Parameters in the Design and Operation of Biogas Production Plants. *Applied Sciences,* Volume 9.

Schievano, A., Adani, F., Colombo, E. & Mungwe, J. N., 2016. The fixed dome digester: An appropriate design for the context of SubSahara Africa. *Biomass and Bioenergy,* Volume 95, pp. 35-44.

Sesan, T., 2012. Lessons from the promotion of improved cooking technologies in Kenya Energy Policy. *Navigating the limitations of energy poverty,* Volume 47, p. 202–210.

Shaheen, S. M. & Nene Anita, A. A., 2014. Thermal Simulation of Biogas Plants Using Mat Lab. *International Journal of Engineering Research and Applications,* 4(10), pp. 24-28.

Shane, A., Gheewala, S. H. & Kasali, G., 2015. Potential, Barriers and Prospects of Biogas Production in Zambia. *Journal of Sustainable Energy & Environment,* Volume 6, pp. 21-27.

Shi, X.-S., Dong, J.-J. & Yu, J.-H., 2017. Effect of Hydraulic Retention Time on Anaerobic Digestion of Wheat Straw in the Semicontinuous Continuous Stirred-Tank Reactors. *BioMed Research Internationa.*

Shukla, P. R., Ahlgren, E. O. & Mittal, S., 2018. Barriers to biogas dissemination in India: A review. *Energy Policy,* Volume 112, p. 361–370.

Singh, G., Jain, V. K. & Singh, A., 2017. Effect of Temperature and other factors on Anaerobic Digestion Process, responsible for Bio Gas Production. *International Journal of Theoretical and Applied Mechanics,* 12(3), pp. 637-657.

Singh, J. K. & Sooch, S. S., 2004. Comparative study of the economics of different models of family size biogas plants for state of Punjab, India. *Energy Conversion and Management,* 45(9), pp. 1329-1341.

Singh, L., Maurya, M. S., Ramana, K. V. & Alam, S. I., 1995. Production of biogas from night soil at psychrophilic temperature. *Bioresource Technology,* Volume 53, pp. 147-149.

Smith, M. & Everson, T., 2016. *Improving rural livelihoods through biogas generation using livestock manure and rainwater harvesting,* s.l.: Guideline Report. Report to the Water Research Commission.

Spyridonidis, A., Vasiliadou, I. A., Akratos, C. S. & Stamatelatou, K., 2020. Performance of a Full-Scale Biogas Plant Operation in Greece and Its Impact on the Circular Economy. *Water,* Volume 12.

Sruthy, B., Anisha, G. K., Gibi, M. M. & Sruthi, G. . R., 2017. An Experimental Investigation on Strength of Concrete Made with Cow Dung Ash and Glass Fibre. *International Journal of Engineering Research & Technology,* 6(3), pp. 492-495.

STATSSA, 2012. *census 2011, census, in brief,* Pretoria: Statistics South Africa.

Suresh, B., Pudasaini, S. P., Khanal, S. N. & Gurung, D. B., 2013. Mathematical modeling, finite element simulation, and experimental validation of biogas-digester slurry temperature. *International Journal of Energy and Power Engineering,* 3(2), pp. 128-135.

Tauseef , S. M., Premalatha , M., Abbasi , T. & Abbasi , S. A., 2013. Methane capture from livestock manure. *Journal of Environmental Management,* Volume 117, pp. 187-207.

Terradas-III, G. et al., 2014. Thermic Model to Predict Biogas Production in Unheated Fixed Dome Digesters Buried in the Ground. *Environ. Sci. Technol,* Issue 48, pp. 3253-3262.

Tewelde, G. B., Rahwa, G. T., Grmanesh, A. D. & Lemlem, S. M., 2017. Biogas Plant Distribution for Rural Household Sustainable Energy Supply in Africa. *Energy and Policy Research,* 4(1), pp. 10-20.

Torii, S. & Rashed Al Mamun, M., 2017. Enhancement of Methane Concentration by Removing Contaminants from Biogas Mixtures Using Combined Method of Absorption and Adsorption. *International Journal of Chemical Engineering,* pp. 1-9.

Univen, 2020. *UNIVEN partners with UNIDO, GEF, CDM, and the Department of Environment, Forestry, and Fisheries to empower Limpopo youth.* [Online]
Available at: https://www.univen.ac.za

Uzodinma, E. O., Ofoefule, A. U., Eze, J. I. & Onwuka, N. D., 2007. Optimum Mesophilic Temperature of Biogas Production from Blends of Agro-Based Wastes. *Trends in Applied Sciences Research,* Volume 2, pp. 39-44.

VDM, 2013. *The integrated development plan,* Polokwane: Vhembe District Municipality.

Verma , T. S., Chimidza , S. & Molefhi, T., 2010. Study of indoor air pollution from household fuels in Gaborone, Botswana. *Journal of African Earth Sciences,* 58(4), p. 648–651.

Wahyuni, S. et al., 2018. Application of small digester biogas for energy supply in rural. *Earth and Environmental Science,* Volume 141, pp. doi:10.1088/1755-1315/141/1/012035.

Wang, H., Aguirre-Villegas, H. A., Larson, R. A. & Alkan-Ozkaynak, A., 2019. Physical Properties of Dairy Manure Pre- and Post-Anaerobic Digestion. *Applied Science,* 9(13), pp. 1-10.

Wang, J. & Brass, L. R., 1999. Ground heat flux estimated from surface soil temperature. *Journal of Hydrology,* Volume 216, p. 214–226.

Wang, Q. et al., 2010. Economic feasibility of converting cow manure to electricity: A Case study of the CVPS Cow power program in Vermont. *Journal of Dairy Science,* 94(10), pp. 4937-4949.

Weatherford, V. C. & Zhai, Z. . J., 2015. Affordable solar-assisted biogas digesters for cold climates: Experiment, model, verification and analysis. *Applied Energy,* Volume 146, p. 209–216.

Wen, L. V., Wenfei , Z. & Zhongtang, Y., 2016. Volume ratios between the thermophilic and the mesophilic digesters of a temperature phased anaerobic digestion system affect their performance and microbial communities. *New Biotechnology,* 33(1), pp. 245-254.

Westerholm, M., Isaksson, S., Lindsjö, O. K. & Schnürer, A., 2018. Microbial community adaptability to altered temperature conditions determines the potential for process optimisation in biogas production. *Applied Energy,* Volume 226, p. 838–848.

Wright, P. C. et al., 2019. Alcoholic fermentation of thermochemical and biological hydrolysates derived from Miscanthus biomass by Clostridium acetobutylicum ATCC 82. *Biomass and Bioenergy,* Volume 130.

Wu, B. & Bibeau, E., 2006. Development of 3D anaerobic digester heat transfer model for cold weather applications. *American Society of Agricultural and Biological Engineers,* 49(3), pp. 49-757.

Wu, B., Bibeau, E. & Gebremedhin, K., 2009. Three-dimension numerical simulation model of biogas production for anaerobic digesters. *Canadian Biosystems Engineering,* Volume 51, pp. 1-8.

Yang, H. et al., 2019. An optimal self-excited heating method for biogas production under a cold climate. *The Journal of Engineering,* pp. 5094-5098.

Zhou, J. B., Jiang, M. M. & Chen, G. Q., 2007. Estimation of methane and nitrous oxide emission from livestock and poultry in China during 1949–2003. *Energy Policy,* 35(7), p. 3759–3767.

Ziemiński, K. & Frąc, M., 2012. Methane fermentation process as anaerobic digestion of biomass: Transformations, stages, and microorganisms. *African Journal of Biotechnology Vol. 11(18),* pp. 4127-4139.

APPENDICES 1: List of Published Articles

V Nekhubvi and D Tinarwo. Methane Capturing Using Anaerobic Digestion Technology: A Way Towards Mitigating Green House Gases in Limpopo Province, South Africa. *Nature Environment and Pollution Technology*. Vol.16 No. 4 2017

V Nekhubvi and D Tinarwo. Long-term temperature measurement: Biogas digesters fermenting slurry. *Journal of Energy in Southern Africa*. Vol 28 No. 3 2017

V Nekhubvi and D Tinarwo. The investigation of heat transfer associated with Deenbandhu brick-built anaerobic digester covered with single-layer soil type. *Nature Environment and Pollution Technology*. Vol.17 No. 1 2018

V Nekhubvi and D Tinarwo. Prediction of slurry operating temperature and Biogas Production Rate using Ambient Temperature Forecast as Input Parameter for Underground Brick-Built Biogas Digesters. *Cogent Engineering.* Vol.9 No.1 2022

Annexure 1: Gas monitor specifications

GX-2012 <TIIS specifications>

Detection principle	Galvanic cell type (OS)	New ceramic type (NC) /Thermal conductivity type (TE)(*)	Electrochemical type (ES)	Electrochemical type (ES)
Gas to be detected	Oxygen (O2)	Combustible gas (HC/CH4)	Hydrogen sulfide (H2S)	Carbon monoxide (CO)
Detection range <Service range>	0 to 25 vol% <-40 vol%>	0 to 100% LEL(NC) /-100 vol%(TE)(*)	0 to 30 ppm	0 to 150 ppm <-500 ppm>
Display resolution	0.1 vol%	1% LEL(NC)/1 vol%(TE)	0.1 ppm	1 ppm
Alarm setpoint value	19.5 vol%(L) 18.0 vol%(LL) 40.0 vol%(OVER)	10% LEL(1st) 50% LEL(2nd) 100% LEL(OVER)	1.0 ppm(1st) 10.0 ppm(2nd) 1.0 ppm(TWA) 5.0 ppm(STEL) 30.0 ppm(OVER)	25 ppm(1st) 50 ppm(2nd) 25 ppm(TWA) 200 ppm(STEL) 500 ppm(OVER)