Prediction of slurry operating temperature and biogas production rate using ambient temperature forecast as input parameter for underground brick-built biogas digesters

V Nekhubvi¹ and D Tinarwo²

Abstract: The operational temperature of the biogas digester is the most critical parameter for optimum biogas production. Most household digesters are operated at ambient temperatures throughout the year. Biogas production rate increases with the increase of digester operational temperature. The present work focuses on developing a mathematical model to predict operating temperature from ambient temperature for underground built fixed dome Deenbandhu model digester. The operating or slurry temperature would then estimate the daily biogas production. Three fixed-dome underground brick-built biogas digesters of bulk size 6.0 m³ constructed following a fixed-dome Deenbandhu model in India were used to study the operational temperature. Thermocouples were fitted in each digester to measure operational temperature data. The statistical tool R-studio was then used to establish the relationship between the operational and air temperature based on this arrangement. The results of this work provide information on the prevailing operating temperature for underground biogas digester systems and hence biogas production rate. The results from the study have shown that there is a strong correlation between bio-slurry temperature and ambient air temperature. Second, the biogas production was computed based on the data of the predicted slurry temperature. It was found that as the temperature increases, the production rate also increases.

Subjects: Environmental Sciences; Biotechnology; Applied Physics; Environmental Physics; Experimental Physics; Heat Transfer; Renewable Energy; Energy & Fuels

Keywords: Biogas digester; Operational Temperature; Fixed dome; Household digester; Deenbandhu model

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The Authors are part of renewable energy technologies researchers -Renewable Energy Research Group (RERG) at the University of Venda working together with some national and local government departments, national and international research institutions, other institutions of higher education within the country, including Universities, Technical Vocational Education and Training (TVET) and Agricultural Colleges around the Limpopo Province to foster multidisciplinary in dealing with the most topical issues of the green economy. Already research is taking place in biogas technology. Since 2013 we’ve been engaged in research projects in the surrounding communities to establish innovative strategies suitable to unlock the full potential of biogas technology in the province. As part of the strategies to raise acceptance and popularisation of biogas technology in the area, the group formulated topics such as “Prediction of slurry operating temperature and Biogas Production Rate using Ambient Temperature Forecast as Input Parameter for Underground Brick-Built Biogas Digesters”.

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PUBLIC INTEREST STATEMENT
Improper waste disposal has enormous social costs due to the spread of infectious diseases, increased treatment costs for pollutants. Worldwide, there is untapped biogas potential from organic materials in many areas that can be utilised to prevent improper waste disposal. Many governments are implementing biogas technology to improve the standard of living and mitigate greenhouse gases that are causing climate change. In rural areas, underground, brick, and mortar built fixed dome-type digesters are the most deployed for harnessing biogas because of low initial costs and long helpful lifespan, no moving or rusting parts involved compared to most prefabricated fixed dome plastic digesters. However, the digester gas production is not predictable using ambient temperature variations—the unpredictable gas production results in negative perceptions affecting biogas acceptance in Limpopo Province. This work, therefore, was designed to develop a locally applicable model for predicting the bio-slurry operating temperature of underground brick-built household biogas digesters.

1. Introduction
Several types of digesters, including family-type small scale and industrial-scale biogas systems for electricity generation, have been designed and constructed in many countries (Shukla et al., 2018). Family-type small-scale household biogas digester has three types: fixed dome digester, floating drum digester, and plastic tubular bio-digester (Ho et al., 2015). Biogas technology has vast potential benefits for humanity, but its use is minimal. Low acceptance of biogas technology in many African countries has been a technology barrier and limitation in technical skills (Prasad, 2012), (Kornelius & Msibi, 2017), (Sime, 2020). Some installed household digesters systems have been abandoned due to the lower production of biogas. Failure of these household digesters may be caused by the storage time of the manure prior to anaerobic digestion (AD) or poor feeding or structural failure or low digester operating temperature (Liebetrau et al., 2021, Gebreeziabher et al., 2014; Kornelius & Msibi, 2017; Rastogi et al., 2008). Rennuit and Sommer (2013) showed that, among other factors, the operational temperature of biogas digester is the most critical parameter for optimum biogas production. Dhaked et al. (2010), Mane et al. (2015), and Ramaswamy and Vemareddy (2015) showed that there are three temperature ranges for the AD process: thermophilic (40–70 °C), mesophilic (20–40 °C), and psychrophilic (<20 °C) although in principle, an AD process can occur between 3°C and approximately 70 °C (Rabbi et al., 2015). Thermophilic fermentation is characterised by rapid digestion, high gas yield and short retention time. Mesophilic fermentation has the added advantage of a slower death rate for bacteria resulting in better stability of the waste in the digester (Uzodinma et al., 2007). Singh et al. (2017) showed that the mesophilic bacteria could withstand a temperature change of ±3°C, influencing biogas production slightly. While thermophilic bacteria can only withstand a temperature change of ±1°C, affecting biogas production. The anaerobic digestion (AD) technology has been applied worldwide. The importance of heat transfer in the AD plants in continental climate has been studied by (Merlin et al., 2012). Digesters that are not artificially heated depend on the ambient air temperature and thus often experiences seasonal fluctuations in methane production (Meegoda et al., 2018)

1.1. Importance of predicting operational temperature using ambient temperature
Most 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 (Westerholm et al., 2018). Predicting operational temperature using ambient air temperature has many advantages in biogas production studies. For example,
cumulative methane production (CMP) can be predicted using as a function of operating temperature (Almomani, 2020). Biogas production rate increases with the increase of slurry temperature, as shown by Eq (1.1; Guo et al., 2019).

$$Y = -0.00090629X^2 + 0.01604X + 0.03032$$ \hspace{1cm} (1.1)

where $Y$ and $X$ are biogas production rate (m$^3$ m$^{-3}$ d$^{-1}$) and slurry temperature ($^\circ$C), respectively. The study results by Mukumba et al. (2015) on an assessment of the performance of a biogas digester when insulated with sawdust show that when the biogas digester is not insulated, there is an increase in temperature fluctuations. The relationship between ambient temperature and the slurry temperature was developed by Mukumba et al. (2015), as shown in Eq (1.2).

$$T_s = 0.6221 T_a + 9.4007$$ \hspace{1cm} (1.2)

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 effect on slurry temperatures for biogas with insulation. Castano et al. (2014) showed 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 meaningful results was that biogas in the methanogenic phase kept relatively higher levels at temperatures ranging from 25 - 35°C, with the CH$_4$ content of biogas production higher than 50 %. Nevertheless, Wang et al. (2019) emphasised that the methanogenic phase at temperatures less than 20°C could significantly decrease. In addition, ambient temperature can lower the thermal energy needed to keep the AD operational temperature (Wen et al., 2016). Therefore, researchers used various digester systems for their anaerobic digestion studies to develop a biogas digester that produces the required biogas throughout the year. However, of these systems, a report or analysis of a brick-built fixed dome biogas digester system, more particularly unstirred, unheated, uninsulated, and fully covered Deenbandhu model, is not available. The lack of information on this type of model makes it necessary to develop a mathematical model suitable for the conditions of the location where the biogas digester has been installed. The main reason for the model would be to plan in case low temperatures are detected since this may restrict biogas production in the winter and cold days.
2. Method and material

2.1. Experimental approach
This section presents the approach used to predict the digester’s slurry temperature and identify the model’s corresponding parameters. Suresh et al. (2013) showed that the temperature is regarded as a physical quantity in heat transfer problems that are not known. The study focused on a fixed dome Deenbandhu model digester. Three fixed-dome brick-built biogas digesters of bulk size 6.0 m³ constructed in 2015 were used to study the operational temperature (Cheng et al., 2013). Each digester was fed with 35 kg of cow dung and 35 L of water per day, giving the loading rate of 70 L/day. The experiment was conducted in 2015. Cow dung was used in this study because research on AD of cow dung to produce biogas has been mature (Li, Xu, Wang, Liu, & Zhang, 2020).

2.2. Assumption statement
The fundamental principle used in this study was to develop an equation to predict slurry temperature inside the biogas digesters. Thermocouples were fitted in each digester to measure slurry temperature data. The mathematical model was developed using an R-Studio tool utilising data of measured air temperature ($T_a$) and slurry temperature ($T_s$). The inputs to the model were designed to suit a specific design, a brick-built fixed dome. Figure 1 below shows a schematic diagram of the digester investigated. The uniqueness of a mathematical model is justified based on the following significant assumptions:

- The model assumes that cow dung temperature does not significantly contribute to the variation of the slurry temperature inside the digester.

- The slurry in the digester is not stirred, heated and the temperature is not constant.

- Uniform soil properties (specific heat, thermal conductivity, and density) are assumed through the soil depth.

- Heat flow through the digester is 1-D, meaning that a single temperature represents each system element.

- The digester walls are made of composite materials with different thermal properties.

- Properties of the feedstock added to the system are assumed to be equivalent to the slurry properties in the biogas digester except for temperature, which is supposed to be equal to ambient temperature.

- The pH is constant and equals 6.07

2.3. Statistical modelling approach
Data containing a total of 20,220 observations and two variables collected in pairs were categorised by the notation;

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

(1.3)

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 $T_a$, the air temperature, and $T_s$, the slurry temperature, represent $Y$. The pairs of data were uploaded to the statistical software (R studio) to enable the start-up of the modelling process. The data were graphically represented with variables subjected to building a model to predict slurry temperature by showing a mathematically meaningful relationship with
air temperature and slurry temperature using the observed values. A typical scatter plot was drawn to visualise the linear relationship between the two variables. The next step was to develop a linear model in the form of a mathematical formula represented by Eq (1.4) to predict slurry temperature as a function of air temperature.

\[ E(T_s | T_a = x) = \beta_0 + \beta_1 x \]  

(1.4)

The unknown parameters \( \beta_0 \) and \( \beta_1 \) determine the theoretical \( T_s \) -intercept and the slope of the specific straight line.

2.4. 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. It means that the linear model predicted values for the 25% data (test) and the actuals (from the original dataset).

3. Results and discussion correlation between slurry and air temperature variables

Looking closely at the three comparatively plots in Figure 2 , 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.
Table 2. Summary of observed and predicted slurry temperature

| Digester 1 | Digester 2 | Digester 3 |
|------------|------------|------------|
| T\(_{\text{observed}}\) (°C) | T\(_{\text{predicted}}\) (°C) | T\(_{\text{observed}}\) (°C) | T\(_{\text{predicted}}\) (°C) | T\(_{\text{observed}}\) (°C) | T\(_{\text{predicted}}\) (°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 |

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.

Applying the central limit theorem, the distribution of the means is normally distributed.

From the summary, Table 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, both intercept and theoretical slope have the three most significant stars. The predicting models for digesters 1, 2, and 3 are given by;

\[ T_{\text{slurry}} = 6.6 + 0.77T_{\text{Air}} \]  \hspace{1cm} (1.5)

\[ T_{\text{slurry}} = 4.91 + 0.81T_{\text{Air}} \]  \hspace{1cm} (1.6)

\[ T_{\text{slurry}} = 4.56 + 0.81T_{\text{Air}} \]  \hspace{1cm} (1.7)

3.1. Model validation

Figure 3 shows the plot in the upper left shows the residual errors plotted versus their fitted values. The residuals are randomly scattered, and a bit more spread 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 standardised residuals (sort of 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 3.

residuals versus point leverage.
Figure 3. Residuals errors plotted versus their fitted values, normal Q-Q, Cook’s distance and.

![Residuals vs Fitted](image1)

![Scale-Location](image2)

![Normal Q-Q](image3)

![Residuals vs Leverage](image4)

Table 3. Linear model summary of derivatives descriptor dataset

|          | Adjusted R² | Multiple R² | 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 *** |

Figure 4. Performance of observed and predicted model of Slurry Temperature derivatives descriptor dataset for digester.

![Temperature Plot](image5)

(a) digester1  (b) digester 2  (c) digester 3
3.2. Model testing

Table 2 below shows the observed and predicted slurry temperature, confirming the two relations. Thus, both the observed and the predicted slurry temperatures are closely related. For this reason, the three equations are valid.

Thus, both the observed and the predicted slurry temperatures are closely related. For this reason, the three equations are valid.

From the graph in Figure 4 and summary Table 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
Table 4. Biogas production rate for biogas plant of rated gas storage capacity of 2.0 m³ and digester volume 6 m³ fed with 35 kg cow dung and 35 L of water per day

| Ambient air temperature Ta (°C) | Estimated biogas production rate (m³/day) | Estimated biogas production volume (m³/m³/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                                     |

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. Moreover, a comparison between predicted slurry and air temperatures was also conducted. It is shown in Eq. (1.1) to Eq. (1.7) that the air temperature could be used to predict the slurry temperature for the three digesters. The three models have been developed and tested to predict the slurry temperature and agree with the measured data. Therefore, it was crucial to average the three models to get the general model to predict slurry temperature, which represented the temperature of each digester system as shown in Eq. (1.8).

\[ T_{\text{slurry}} = 0.79T_a + 5.35 \]  \( (1.8) \)

where \( T \) and \( T_{\text{slurry}} \) are slurry and ambient temperature, respectively.

3.3. Biogas digester performance

3.3.1. 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. (1.1). Thus, the fermentation process was more stable concerning biogas production. However, the methane content of biogas was not measured daily but was measured during the first stage.

Figure 5 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 5, 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 Nm³ d⁻¹. May was characterised by a daily average biogas production rate as low as 0.31 Nm³ d⁻¹ at 21.0 °C with a maximum of 0.36 Nm³ d⁻¹ at 27.0 °C. July and August were also very cold, recording biogas production rates as low as 0.27 Nm³ d⁻¹ at 16.0 °C and with a maximum of 0.35 Nm³ d⁻¹ and 0.37 Nm³ 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$^{-1}$.

The digester’s biogas production rate varies because of the average ambient temperature. The figure presents the values of average ambient temperature ranges with their biogas production rate per day. Figure 6 shows that for a day, the biogas production rate increases 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 $R^2 = 0.99$. The figure is crucial to users to predict daily biogas production using ambient air temperature as input using Eq. (1.9).

$$Y = 0.019X + 0.1929$$ (1.9)

where $Y$ and $X$ are biogas production rate (Nm$^3$/day) and ambient temperature (°C), respectively. Table 4 shows how biogas production rate ranges with the ranges of ambient temperature. We have put production rate in the table because Biogas meter readings displays m$^3$ and not Nm$^3$.

4. Conclusions

In conclusion, we draw our attention to the aim of the study to present the results of the research undertaken. This research aimed to study the relationship between bio-slurry temperature and ambient air temperature for a completely covered and unheated brick-built household size Deenbandhu biogas digester.

Firstly, a data acquisition system to investigate the operational temperature of biogas digester fermenting slurry was set up. The finding shows that the average daily operating temperature of the digesters studied ranged between psychrophilic and mesophilic regimes.

Second, the operational temperature was successfully predicted and evaluated. The ambient air temperature influences the temperature of the fermenting bio-slurry inside the digester studied. The results from the study have shown that there is a strong correlation between bio-slurry temperature and ambient air temperature. The study also shows the strong correlation of both measured and predicted temperature of the fermenting slurry inside the digester. Therefore, the models could accurately estimate the fermenting bio-slurry temperature inside the digester using local ambient air temperature data. Lastly, the biogas production was computed based on the data of the predicted slurry temperature. It was found that as the temperature increases, the production rate also increases.

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David Tinarwo holds a Ph. D. in Electrical Engineering (2008) from the University of Kassel in Germany, M.Sc. in Renewable Energy (2003), and a B.Sc. Hons. (Physics) (2001), from The University of Zimbabwe, a researcher in Renewable Energy, supervised several postgraduate theses and has led over ten national and international projects on domestic waste-to-energy conversion and low wind speed technologies and solar photovoltaics and thermal system design and optimisation. Nekhubvi Vhutshilo holds an MSc degree in Physics - Photovoltaic Power Systems from the University of Venda. Nekhubvi researched sizing, installing, checking PV array systems, measuring operating temperature under outdoor
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References
Almomani, F. (2020). Prediction of biogas production from chemically treated co-digested agricultural waste using artificial neural network. Fuel, 280. Retrieved from 10.1016/j.fuel.2020.118573

Castano, J. M., Martin, J. F., & Ciota, A. (2014). Performance of a small-scale, variable temperature fixed dome digester in a temperate climate. Energies, 7(9), 5701–5716. https://doi.org/10.3390/en7095701

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, 28 (1), 738–748. https://doi.org/10.1016/j.rser.2013.08.030

Dhakel, R., Singh, P., & Singh, L. (2010). Biomethanation under psychrophilic conditions. Waste Manage, 30(12), 2490–2496. https://doi.org/10.1016/j.wasman.2010.07.015

Gebreeziabher, Z., Naik, L., Melamu, R., & Balana, B. B. (2014). Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa. Biomass and Bioenergy, 70 (1), 130–140. https://doi.org/10.1016/j.biombioe.2014.02.036

Guo, P., Zhou, J., Mo, R., Yu, N., & Yuan, Y. (2019). Biogas production and heat transfer performance of a multiphase flow digester. Energies (10), 12 https://doi.org/10.3390/en12101960.

Ho, T. B., Roberts, T. K., & Lucas, S. (2015). Small-scale household biogas digesters as a viable option for energy recovery and global warming mitigation—vietnam case study. Journal of Agricultural Science and Technology, 5 (1), 387-395 doi:10.17265/2161-6256(2015).06.002.

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), 2117–2153. https://doi.org/10.1080/10643389.2019.1607441

Kornelius, G., & Mabi, S. S. (2017). Potential for domestic biogas as household energy supply in South Africa. Journal of Energy in Southern Africa, 28(2), 1–13. https://doi.org/10.17159/2413-3051/2017v28i2o1754

Liebetrau, J., O’Shea, R., Wesslisch, M., Lyng, K.-A., Bochmann, G., McCabe, B. K., & Murphy, J. D. (2021). Potential and utilization of manure to generate biogas in seven countries. IEA Bioenergy Task 37, 6.

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), 489–500.

Meegoda, J. N., Li, B., Wong, L. B., & Patel, K. (2018). A review of the processes, parameters, and optimization of anaerobic digestion. International Journal of Environmental Research and Public Health 15 (10), 1–16 doi:10.3390/ijerph15102224.

Merlin, G., Kohler, F., Bouvier, M., Lissola, T., & Boileau, H. (2012). Importance of heat transfer in an anaerobic digesting plant in a continental climate context. Bioresource Technology, 124 (1), 59–67. https://doi.org/10.1016/j.biortech.2012.08.018

Mukumbo, P., Makoka, G., & Shonhwi, C. (2015). An assessment of the performance of a biogas digester when insulated with sawdust. International Journal of Energy and Power Engineering, 4(2), 24–31. https://doi.org/10.11648/j.ijepe.20150402.12

Perriquita, T., Weatherford, V., Marti-Herreroa, J., & Poggio, D. (2012). Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. Bioresource Technology, 124(21), 259–268. https://doi.org/10.1016/j.biortech.2012.08.019

Prasad, R. D. (2012). Empirical study on factors affecting biogas production. JSRN Renewable Energy, 2012, 1–7. https://doi.org/10.5402/2012/136959

Rabbii, S. M., Biswas, S., & Solam, B. (2015). Biogas from mesophilic anaerobic digestion of cow dung using silica gel as catalyst. Procedia Engineering, 105 (1), 652–657. https://doi.org/10.1016/j.proeng.2015.05.064

Ramaseswamy, J., & Vernareddy, 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), 1–4. https://doi.org/10.1186/s40807-015-0006-0

Rastogi, G., Ranade, D. R., Tulshiram, Y. Y.,Patole, M. S., & Shouche, Y. S. (2009). Investigation of methanogen population structure in biogas reactor by molecular characterization of methyl-coenzyme M reductase (mcrA) genes. Bioresource Technology, 99(13), 5317–5326. https://doi.org/10.1016/j.biortech.2007.11.024

Rennunti, C., & Sommer, S. G. (2013). Decision support for the construction of farm-scale biogas digesters in developing countries with cold seasons. Energies, 6 (10), 5314–5332. https://doi.org/10.3390/en6105314

Shukla, P. R., Ahlgren, E. O., & Mittal, S. (2018). Barriers to biogas dissemination in India: A review. Energy Policy, 112 (1), 361–370. https://doi.org/10.1016/j.enpol.2017.10.027

Siene, G. (2020). Technical and socioeconomic constraints to the domestication and functionality of biogas technology in rural areas of southern Ethiopia. Cogent Engineering, 7(1). 10.1080/23311916.2020.2153669

Singh, G., Jain, V. K., & Singh, A. (2017). Effect of temperature and other factors on anaerobic digestion process, responsible for biogas production. International Journal of Theoretical and Applied Mechanics, 12(3), 637–657.

Suresh, B., Pudassini, S. P., Khanal, S. N., & Gurung, D. B. (2013). Mathematical modelling, finite element simulation and experimental validation of biogas-digester slurry temperature. International Journal of Energy and Power Engineering, 3(2), 128–135 doi:10.11648/j.ijepe.20130203.17

Uzodimma, E. O., Ofoedu, U. I., Eze, J. I., & Onwuka, N. D. (2007). Optimum mesophilic temperature of biogas production from blends of agro-based wastes. Trends in Applied Sciences Research, 2(1), 39–44. https://doi.org/10.3923/tras.2007.39.44
Wang, S., Ma, F., Ma, W., Wang, P., Zhao, G., & Lu, X. (2019). Influence of temperature on biogas production efficiency and microbial community in a two-phase anaerobic digestion system. Water, 11(1), 1–13. https://doi.org/10.3390/w11010033.

Wen, L. Y., 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), 245–254. https://doi.org/10.1016/j.nbt.2015.07.001

Westerholm, M., Isaksson, S., Lindsjö, O. K., & Schnürer, A. (2016). Microbial community adaptability to altered temperature conditions determines the potential for process optimisation in biogas production. Applied Energy, 226 (1), 838–848. https://doi.org/10.1016/j.apenergy.2018.06.045