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# **Design, fabrication and evaluation of bio-digester for generating bio-gas and bio-fertiliser for Auchi polytechnic demonstration farm**

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**A 4000 L bio-digester was designed and fabricated using 5 mm mild steel plate with the main purpose of generating biogas and bio-fertiliser for Auchi Polytechnic Demonstration Farm. To achieve this, a varying ratio of 1.155 m<sup>3</sup>: 2.310 m<sup>3</sup> mixtures of cow dung and water were anaerobically digested in the batch digester. The experiment lasted for 33 days during which the quantity of gas generated were evaluated. The volume of daily methane gas production ranged from 0 to 1.2 m<sup>3</sup>. The total volume of gas generated from the digestion was 21.68 m<sup>3</sup> and comprised of 58% CH<sub>4</sub>, 25% CO<sub>2</sub>, 15% H<sub>2</sub>S and 2% other impurities. The results of physiochemical properties of the feedstock revealed a progressive increase of 6.0-6.2 in pH value from Day 4 after which it dropped sharply in value to 5.5 on the second week of fermentation. The minimum and maximum ambient temperatures of 24 and 30°C were observed while the slurry temperatures varied from 27 to 35°C. The average pressure built up of the digester was about 214,000 N/m<sup>2</sup>. The results further showed that biogas production is sensitive to pH and cannot produce optimally below the pH of 6.5. To achieve optimum biogas generation, a temperature range within mesophilic condition of 25 to 40°C and pH values of 7 should be maintained.**

**Key words:** Biogas, mesophilic temperature, retention period, anaerobic digestion, digester.

## **INTRODUCTION**

Nigeria is endowed with a lot of natural resources which comprises fossil fuel e.g. natural gas and coal that is, (petroleum) for power generation and other enormous purposes. The production and utilization of these resources is facing critical challenges. Nigerian

government over the years have applied different technical approaches and as well invested huge amount of monies in the energy sector but substantial progress in solving the energy crisis in the country is yet to be made. The government of the day can no longer provide the

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required energy need and other agricultural input like fertilizers to her citizens. The rapid increase in population is suspected to have aggravated the situation.

Unlike other developed countries of the world, provision of adequate energy to her citizen is not a major problem. The major challenge is on how to harness the energy source which is environmental friendly and ecologically balanced. This need has forced the world to search for other alternative sources of energy since the energy sources like the solar, hydro, wind etc. require huge economical investment and technical power to operate, which is very difficult for the developing country like Nigeria.

According to Mshandete and Parawira (2009), Nigeria produces about 227,500 tons of fresh animal waste daily. This shows that Nigeria can potentially produce about 6.8 million m<sup>3</sup> of biogas every day from animal waste only if properly managed. Mitel (1996) also reported that the sludge obtained from bio-fermentation process contains high concentration of nutrients and organic matter. The application of this sludge at the rate equivalent to traditional chemical fertilizer increase the yield of maize up to 35.7%, wheat 12.5%, rice 5.9%, cotton 27.5%, carrot 14.9% and spinach 20.6%.

In the present economic recession in the country, biogas energy can be one of the most reliable, easily available and economically feasible sources of alternative and renewable energy which can be managed by locally available materials and simple technology for both urban and rural dwellers. The biogas system also provides a barrier protecting ground water from contamination with untreated waste (Ocwieja, 2010). Furthermore, with the enormous cattle population in the country, millions of tonnes of dung released daily emit a lot of methane gas to the atmosphere, which is 320 times more harmful to human health than carbondioxide (Thakur, 2006). A biogas plant is an anaerobic digester that produces biogas and natural fertilizer from animal, food waste or plant waste. Although, biogas plant is not a new technology to many developed and some few developing countries of the world, in Nigeria the technology is still on skeletal basis. Biogas can provide a clean, easily controlled source of renewable energy from organic waste materials for a small labour input. This will go long way to replace firewood or fossil fuels which are becoming more expensive as supply falls below demand. Biogas is generated when bacteria degrade biological material in the absence of oxygen, in a process known as anaerobic digestion. Since biogas is a mixture of methane (also known as marsh gas or natural gas, CH<sub>4</sub>), hydrogen sulphide (H<sub>2</sub>S) and carbon dioxide. It is a renewable fuel produced from waste treatment.

This system produces two extremely useful products from the waste: biogas and slurry. The use of biogas for cooking and lighting reduces the strain on the environment by decreasing the use of biomass and the production of greenhouse gases. The objective of this

study was to design, fabricate and evaluate batch biogas digester for generation of Biogas and natural fertilizer from cow dung for utilization in Auchi Polytechnic Agricultural Engineering Technology Demonstration Farm.

## MATERIALS AND METHODS

### Selection of site and fabrication materials for the digester

The project site was carefully selected, designed and constructed based on factors affecting digester installation and optimum gas generation among others according to the guidelines documented by Republic of Rwanda (2012). The material selected for the fabrication of the digester was a 5 mm galvanized steel sheet because it is cost effective and as well absorbs heat easily when compared to cement and brick. The material was folded and arc welding was carried out in order to fabricate fermentation digester and other component parts. The tank was pressure tested before taken to site for use, after coating with a black paint to aid heat retention within the walls of the digester. The major components of the digester (Plate 1) include:

**Inlet chamber:** It is a 75 mm diameter 5 mm galvanize steel pipe having half metre in length, which was fixed at an angle that allows the feedstock to move into the digester. A pipe reducer having an inner diameter of 8 mm and outer diameter of 150 mm was used as funnel.

**Outlet chamber:** This is the chamber through which the slurry after the digestion is moved out. It was made by a 75 mm diameter 5 mm galvanize steel pipe and placed at an angle that allows the slurry come out easily.

**Digester body:** This is the place where the anaerobic digestion takes place. The properly mixed feedstock was fed into the digester body and after the digestion process; slurry goes outside through the outlet or effluent chamber. The digester body was made of a 5 mm thick galvanized steel material.

**Gas holder:** The biogas formed after the anaerobic digestion was collected on the top of the plant, called gas holder. This was also made of the same material with the body of the digester.

**Gas outlet:** The biogas which was present in the gas holder was taken using the gas outlet, which was a gas valve connected with a reducer. The gas valve is opened when it is to be used. The gas valve was made of brass material.

**Stirrer:** It was fixed inside the digester through the top of gas outlet for intermittent stirring of the slurry to speed up fermentation and gas production.

**Compost pits:** These pits were also constructed to remove the spent slurry from the digester tank to the outlet chamber where it was finally used as bio fertilizer for crop use.

**Potassium hydroxide (KOH) and Potassium permanganate (KMnO<sub>4</sub>):** Both were used for absorbing carbon dioxide (CO<sub>2</sub>) and Hydrogen Sulphide (H<sub>2</sub>S) contained in the biogas respectively.

**Gas cylinder:** It was used for collection of purified methane gas.

**Thermometer:** The thermometer was employed to measure ambient and slurry temperature variations during digestion of the

substrate.

**Pressure gauge:** It was used to measure pressure built-up during gas fermentation.

**pH meter:** The instrument was used for measuring pH values.

#### Design calculation

Amount of Total Solid (TS) in the slurry

$$TS = 8.5\% \text{ of slurry} \quad (1)$$

#### Amount of Volatile Solid (VS) in the slurry

$$VS = 0.8TS \quad (2)$$

Where TS = amount of Total Solid in the slurry

#### Substrate input (S<sub>d</sub>)

$$S_d = B + w \text{ (m}^3\text{/d)} \quad (3)$$

Where S<sub>d</sub> = Substrate input  
B = Biomass (organic matter)  
w = water

#### Hydraulic retention time (HRT)

HRT was determined by chosen/given digesting temperature. Since the temperature of the environment varies from 25 to 35°C (mesophilic digestion). Therefore, HRT of 33 days was chosen. In a cattle-dung plant, the retention time was calculated by dividing total volume of the digester by volume of input added daily.

#### Digester volume (V<sub>d</sub>)

$$V_d = S_d \times R_T \text{ (m}^3\text{/day} \times \text{number of days)} \quad (4)$$

Where S<sub>d</sub> = daily substrate input quantity, R<sub>T</sub> = chosen retention time.

#### Daily gas production, G

The amount of gas generated each day, G (m<sup>3</sup>gas/d), was calculated on the basis of the specific gas yield, G<sub>y</sub> of the substrate and the daily substrate input, S<sub>d</sub>. The calculation was based on standard gas yield values per cattle unit

$$G = x \times y \times z \quad (5)$$

where G = Daily gas production, x = No. of cow that generate the biomass (organic matter) for the study, y = average wt. of dung (organic matter) estimated to be produced by each cow on daily basis (that is, cow produce 10 kg of manure).

#### Specific gas production G<sub>p</sub>

It was calculated according to the following equation

$$G_p = \frac{G}{V_d} \left( \frac{\text{m}^3}{\text{m}^3 \text{d}} \right) \quad (6)$$

Where G<sub>p</sub> = Specific gas production, G = daily gas production, V<sub>d</sub> = Digestive volume.

#### Digester loading, L<sub>d</sub>

The digester loading, L<sub>d</sub> was calculated from the daily total solid input:

$$L_{dT} = \frac{T_s}{V_d} \left( \frac{\text{kg}}{\text{m}^3 \text{d}} \right) \quad (7)$$

$$T_s/d = 8.5\% \text{ of slurry kg,}$$

Where L<sub>dT</sub> = Digester Loading,  $\frac{T_s}{d}$  = daily total solids input, V<sub>d</sub> = digestive volume.

#### Volume of gas holder V<sub>g</sub>

To minimize the size and to keep the cost as low as possible, the gasholder was not built to accommodate a full day gas production on the basis that the gas will be used throughout the day and the gasholder will never be allowed to reach full capacity. The gasholder was designed to hold between 60 to 70% of the volume of the total daily gas production, G. For the purpose of this research, the volume of gasholder, V<sub>g</sub> designed to hold the gas was 65% x daily gas production.

#### Gas holder capacity (C)

$$C = V_g / G \quad (8)$$

Where C = Gas holder capacity, V<sub>g</sub> = Gasholder volume, G = daily gas production.

#### Biogas yield

Biogas yield was determined using the equation reported by Arthur (2004), expressed as:

$$G_y = \frac{V_d}{F_s} \quad (9)$$

Where G<sub>y</sub> = Biogas yield (m<sup>3</sup>/kg), V<sub>d</sub> = Digestive volume (m<sup>3</sup>), and F<sub>s</sub> = Mass of feed stock (kg)

#### Volumetric capacity V<sub>d</sub>

$$V_d = \pi r^2 h \quad (10)$$





Plate 1. Gas collection set up.

Table 1. Design calculation for the digester plant.

Parameter	Symbols	Values(units)
Volume of the digester	$V_d$	4.0 m <sup>3</sup>
Volume of Gasholder	$V_g$	1 m <sup>3</sup>
Volume of Gas collecting chamber	$V_c$	0.21 m <sup>3</sup>
Volume of fermentation chamber	$V_f$	2.36 m <sup>3</sup>
Height of the digester	$H_D$	1.63 m <sup>3</sup>
Height of Gas collecting chamber	$H_C$	0.3 m
Height of fermentation chamber	$h_f$	1.33 m
Height of influent in the digester for 33 days	$H_I$	1.90 m
Diameter of cylinder	$D_c$	1.5 m

Where:  $V_d$  = volume (m<sup>3</sup>),  $r$  = radius (m),  $h$  = height (m) and  $\pi$  = 3.142

**Cylindrical volume of digester**

$$C_y = \pi r^2 h \tag{11}$$

**Conical volume of digester (Cd)**

$$V_{CD} = \frac{1}{3} (\pi r^2 h) \tag{12}$$

Where:  $r$  = radius (m),  $h$  = height (m) and  $\pi$  = 3.142

**pH**

Report from literature showed that a pH range of 6.8 to 7.2

gives optimum yield of biogas (Olaoye et al., 2014; Dobre et al., 2014; Mateescu, 2016). For the purpose of this research a pH value of 7 was maintained.

**Temperature regulation**

The temperature range between the mesophilic temperatures (20 to 40°C) is the best range for producing biogas (Olaoye et al., 2014; Sibiyi et al., 2014; Ukpai et al., 2015; Mir et al., 2016). For the purpose of this research, a temperature range of 20 to 35°C was maintained throughout the research to avoid the effect of ambient temperature influencing the temperature of the slurry. Summary of design calculation for the digester plant is shown in Table 1.

**Sample collection and experimental details**

A total quantity of 1155 kg (1.155 m<sup>3</sup>) fresh cow dung was collected from Aviele and Auchy abattoirs in sealed drums respectively for the experiment. This was further mixed with water in the ratio of 1:2 in the mixing tank to make an approximately final 3465 kg (3.465 m<sup>3</sup>) slurry that was fed into the digester through the inlet chamber as



**Plate 2.** Mixing and feeding of the slurry.

shown in Plate 2. When the digester was filled to 80% of its total volume, the introduction of slurry was stopped after mixing 5 kg of seeders (anaerobic bacteria) to speed the rate of fermentation. The plant was closed and then the slurry was stirred with the manual stirrer incorporated in the digester plant on a daily basis to speed up the gas production. The experiment was allowed to run for 33 days in batch fermentation during and after which the following were carried out:

- (i) Volume of gas produced was recorded daily.
- (ii) The temperature of the digester content was taken once daily.
- (iii) The pH of the digester content was taken once daily.
- (iv) Measurement of the retention time (time between the commencement of gas production and termination of the experiment).
- (v) Measurement of the amount of gas produced daily during the experiment.
- (vi) Analysis of the gas to separate it to its different components.

#### **Analysis of gas to evaluate its contents**

A gas delivery pipe fixed with rubber hose was connected from the digester to two 1000 ml gas absorbers flask containing 25 g each of potassium hydroxide and potassium permanganate ( $\text{KMnO}_4$ ) dissolved in 250 ml distilled water to obtain a 10% solution for  $\text{CO}_2$  absorption and  $\text{H}_2\text{S}$  respectively along the pipe. The gas collection bag was connected to the moisture trap container containing water for gas collection over water which was finally connected to gas cylinder to collect methane gas under high

pressure. The digester was maintained at room temperature and pH was monitored with a pH meter connected to a sampling point. Weights of both flasks and gas cylinder were then measured, using an electronic scale on daily basis.

As the biogas flowed, potassium hydroxide solution absorbed  $\text{CO}_2$ , while potassium permanganate ( $\text{KMnO}_4$ ) absorbed  $\text{H}_2\text{S}$ . The remaining unabsorbed gas was collected as methane. After a period of 33 days the pressure continues to remain unchanged, the set up was disconnected and weights of flask with their solutions were again taken. The difference in weights of (flask + solution) from the initial readings gave the mass of  $\text{H}_2\text{S}$  and  $\text{CO}_2$  absorbed; while the increase in mass of the collecting bag indicated the mass of methane in the gas. The procedure was repeated twice, in each case; fresh solutions of potassium permanganate ( $\text{KMnO}_4$ ) and potassium hydroxide were prepared. The sketch for the setup is shown in Figure 1 whereas the results of gas analysis are presented in Table 2.

#### **RESULTS AND DISCUSSION**

The analysis of the compositions of biogas generated comprised of 58%  $\text{CH}_4$ , 25%  $\text{CO}_2$ , 15%  $\text{H}_2\text{S}$  and 2% other impurities as presented in Table 1. The compositions of the biogas is in collaboration with work of Dahunsi and Oranusi (2013) who reported biogas compositions of  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and other impurities to be 58, 24 and 18% respectively. Figure 2 depicts the results of biogas

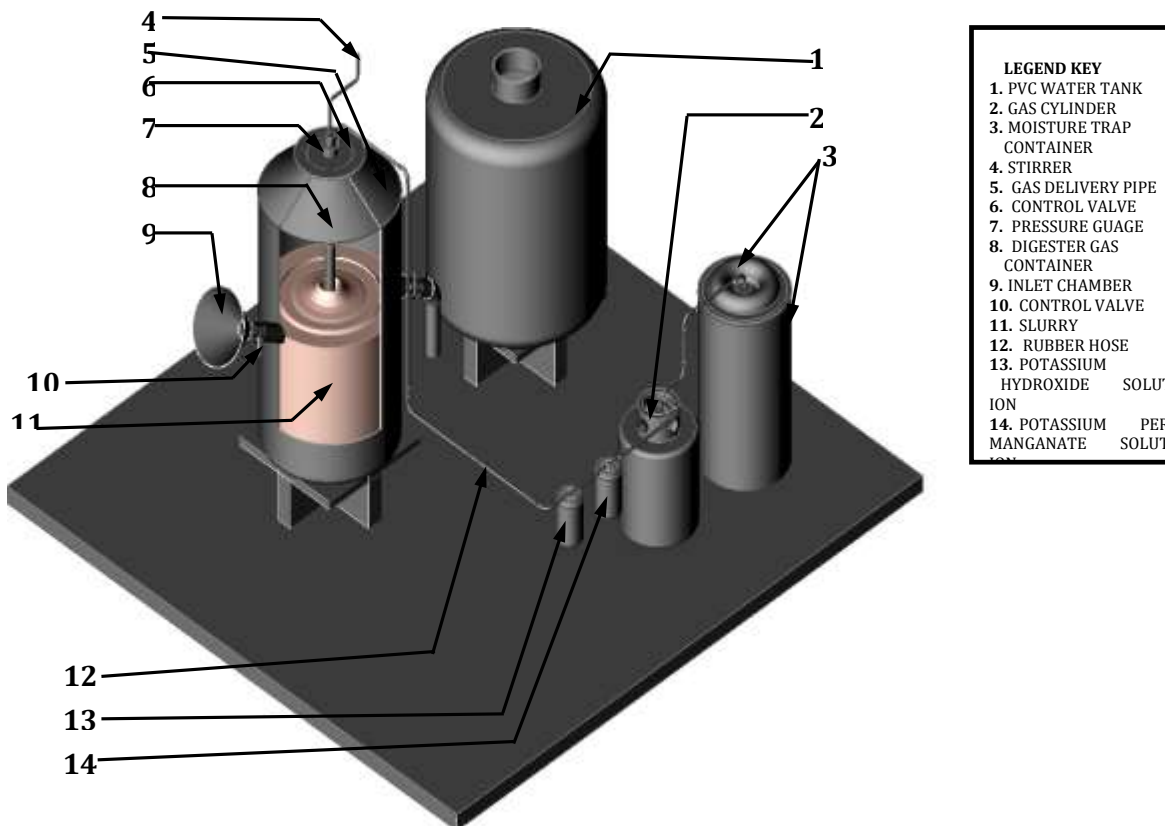


Figure 1. Sketch of gas analysis.

Table 2. Compositions of gas analysis.

Source of gas	Gas	Composition of gas mixture (%)
Cow dung	CH <sub>4</sub>	58
	CO <sub>2</sub>	25
	H <sub>2</sub> S	15
	Other gases	2

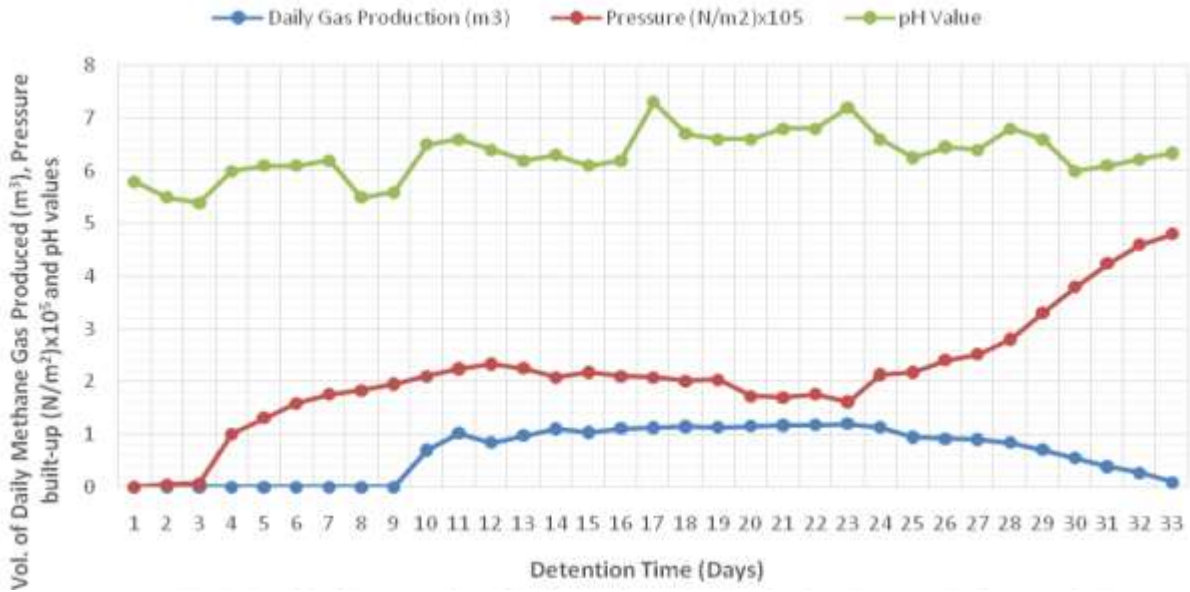
generated during the fermentation, pressure built-up and pH values whereas Figure 3 shows the relationship between volume of daily methane gas production and temperatures (ambient and slurry) during and after the organic fermentation.

#### Volume of biogas produced during and after the fermentation

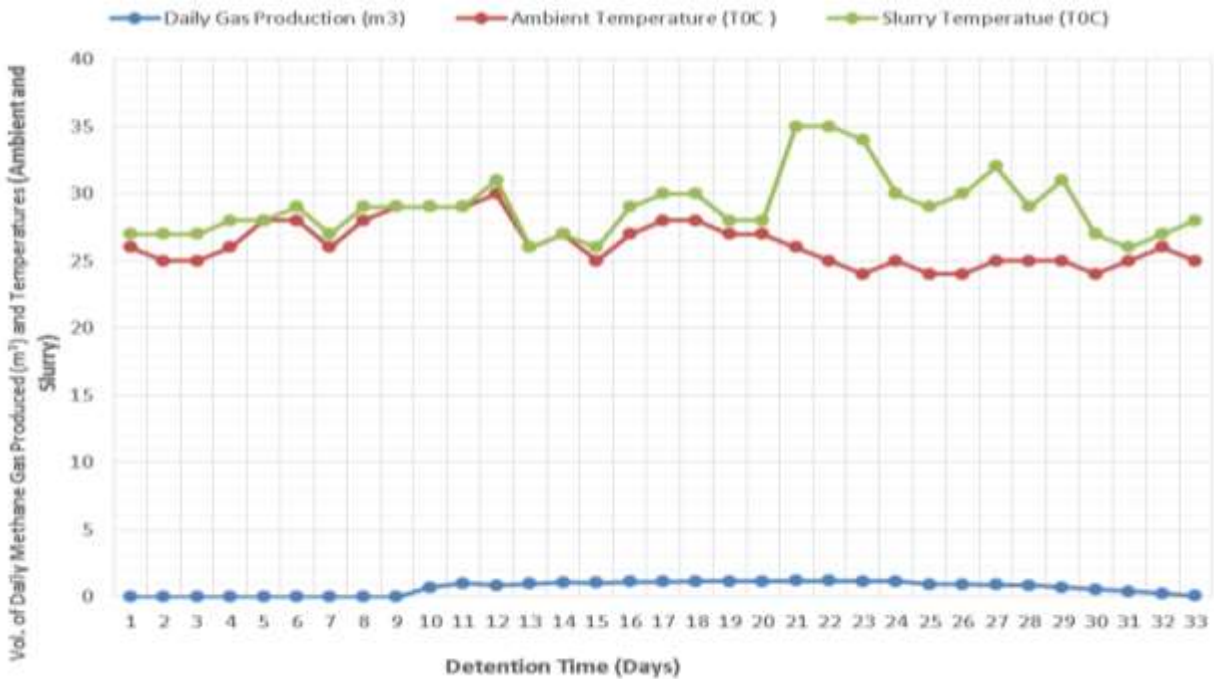
Methane gas production started on 10th day of detention producing 0.7 m<sup>3</sup> of methane biogas as shown in Figure 2. The methane gas production followed an increasing trend on the 11th day of organic digestion with the value of 1.02 m<sup>3</sup> and reduced to 0.84 m<sup>3</sup> on the 12<sup>th</sup> day after which the methane gas production continued to increase

reaching the peak range values of 1.17, 1.18 and 1.2 m<sup>3</sup> on the 21<sup>st</sup>, 22<sup>nd</sup> and 23<sup>rd</sup> day respectively. Thereafter the volume continued to drop gradually for the rest of the study period until it finally fell back to 0.08 m<sup>3</sup>. The delay in the production of gas till the 10<sup>th</sup> day asserts that cow dung contains fibrous materials that takes time to degrade which is in line with the report of Babatola (2008).

From the analyses, the increase in methane gas production per unit time from the 21<sup>st</sup> day onwards to 23<sup>rd</sup> can be attributed to the effects of a more settled bacteria culture due to increase in ambient and operating temperatures. The breaks or nonlinearity of gas production in some days during the fermentation period showed that there may be possibility of unfavorable ambient condition and temperature fluctuation among



**Figure 2.** Graphical presentation of daily methane gas production, pressure built-up and pH values against detention time.



**Figure 3.** Graphical presentation of Daily Volume of Methane Gas production and Temperatures during and after digestion of the organic matter

others that influenced methane producing bacteria which is a major factor in biogas yield (CSANR, 2012; Ubwa et al., 2013). The lower biogas yield at the beginning and at the end of digestions is attributed to the fact that biogas

production rate in batch condition directly corresponds to time and specific growth rate of methanogenic bacteria in the bio-digester (Gupta et al., 2009; Rabah et al., 2010). More so, about 70% of the methane is produced from



acetate-consuming organisms that are slow-growing and highly sensitive to changes in the environment.

### **Relationship between volume of daily gas production and pH value against detention time**

The initial pH was 5.8 with a decrease in value of 5.5 to 5.4 on the second and third day of fermentation as shown in Figure 2. A progressive increase in pH value was observed from Day 4 after which a sharp drop in value was noticed on the second week of organic fermentation. The highest pH value was recorded on the 17<sup>th</sup> day of the experiment as 7.3 when gas production has started yielding. A final pH value of 6.34 was recorded at the end of the experiment. The effect of increase in pH value of organic matter in the digester was that it reduced the growth of microbes which resulted to lower gas production. When the digester pH value is 7.2 or lower,  $\text{NH}_4^+$  is favoured. When the digester pH value is greater than 7.2,  $\text{NH}_3$  is favoured. Ammonia-nitrogen concentration beyond 1500-3000 mg/L is not only inhibitory; but creates an additional problem of foam and scum generation. On the other hand, presence of ammonia facilitates the regulation of pH and may by that means prevent volatile fatty acids (VFA) inhibition which can lead to system failure (Vidal et al., 2000).

The initial drop in pH values for second and third day of detention may have influenced the activities of aerobes and facultative aerobes to produce relevant acidic metabolites, which are acted on by methanogenic bacteria to produce methane. The highest biogas yields were observed at digester pH value of 7.2 which is in the close range of the findings of Report No. ETSU B 1118, (1986); Mahanta et al. (2004) and Wise (1987), who stated that an optimum biogas production is achieved when the pH value of input mixture in the digester is the range of 6.25 and 7.50.

According to de Mes et al. (2003), production rate of methane is lower for pH values outside the range of 6.5 to 7.5. If pH is maintained within the optimum range of 6.8-7.2, the percentage of methane in the produced biogas will be at its maximum (Ghaly, 1996). The pH value in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH value inside the digester can decrease below 5. This hinders or even stops the fermentation process. Methanogenic bacteria are very sensitive to pH value and do not thrive below a value of 6.5.

### **Relationship between volumes of daily gas produced and Pressure built-up against detention time**

The pressure built up of the digester (Figure 2) ranged

from 0 to 480,000  $\text{N/m}^2$  whereas the average pressure of the digester was 214,000  $\text{N/m}^2$ . The maximum methane gas was produced on the 23<sup>rd</sup> day of organic fermentation which is 132,000  $\text{N/m}^2$ . The maximum daily methane biogas production at pressure of 172,000, 170,000, 176,000 and 162,000  $\text{N/m}^2$  were observed to be 1.16, 1.17, 1.18 and 1.20  $\text{m}^3$  respectively. It was discovered that methane forming bacteria works best in the pressure of about 110,000 to 120,000  $\text{N/m}^2$ . The volume of methane gas obtained per day decreased with increasing pressure. The gas composition was also affected by increasing the digester pressure.

As also seen from Figure 2, the methane content increased daily reaching a maximum at the digester pressure of 162,000  $\text{N/m}^2$ , after which the methane content tended to have a constant value. This can be attributed to the increase in carbon dioxide dissolution in the liquid slurry with increasing pressure. Thus, the noted decrease in the amount of gas obtained was partially compensated for by the increase in the methane content. It should also be noted that high concentrations of pressure inside the digester, increases the dead slurry volume present in the outlet chamber. Since the gas generated from this portion of slurry was generally not collected, it would thus represent a loss and contribute to the prevailing decrease in gas production rate.

### **Relationship between volume of daily methane gas production and temperatures (ambient and slurry) during and after digestion of the organic matter**

Figure 3 shows the ambient and slurry temperature variations for the detention period of 33 days. The minimum and maximum ambient temperatures of 24 and 30°C were observed while the slurry temperatures varied from 27 to 35°C which shows that both temperatures were within the mesophilic range (30 to 40°C). The result of the analysis shows that slurry temperatures were higher than ambient temperatures in most of the days.

Thus, the highest amount of daily methane biogas generated was 1.2  $\text{m}^3$  on the 21<sup>st</sup> day of digestion at 35°C. The higher temperatures produced increased the rate of digestion of the slurry, thereby leading to increased gas generation. The gas yield depends on the ambient temperature and frequency of agitation of the substrate in the biogas plant. The higher the temperature, the shorter digestion time needed to attain a specific rate of biogas production. When the digester temperature is maintained at 25°C, it takes approximately 50 days for digestion of cattle waste. But, if the temperature ranges between 32 and 38°C is maintained, digestion is completed within 28 days (Babatola, 2008). Digestion at high temperature range (30 to 40°C) supports higher rates of biological degradation and biogas production (Itodo et al., 2002). But, raising the temperature above 40°C will lead to inhibition of methane production

(Rajeshwari et al., 2000). A shock change in temperature may also lead to pH drop in the reactor. This drop is due to temperature inhibition of methanogenesis, leading to accumulation of fermentation products (Leitão et al., 2005).

## CONCLUSION AND RECOMMENDATIONS

It is evident from the study that the total volume of gas generated from the digestion was 21.68 m<sup>3</sup> and comprised of 58% CH<sub>4</sub>, 25% CO<sub>2</sub>, 15% H<sub>2</sub>S and 2% other impurities. The optimal efficiency of anaerobic digestion and gas production depend on the intensity of bacterial activity, which is influenced by several factors such as ambient temperature, temperature of digester material, loading rate, hydraulic retention time and pH value of digester content. The results showed that upper limit of the mesophilic range gives a higher biogas yield. The optimum temperature observed from the experiment was 40°C. Therefore, to achieve optimal biogas production, it is expected that a high temperature range within mesophilic condition of 25 to 40°C be maintained.

Thirdly, it was observed that a pH of 7 gave favourable condition for bacterial growth and better biogas yield in the digester when compared to other pH values. Evaluation of the effect of dead slurry volume present in the outlet chamber is important since the gas generated from this portion of slurry is generally not collected. Above all, for efficient performance of the biogas plant, it is necessary to regulate all the above factors suitably. The analysis of the effluent slurry indicates that it is rich in nutrients and can be used as an organic fertilizer.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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## REFERENCES

- Arthur M (2004). Biogas Production from Stillage (Scientific, Technical and Economic Aspects): University of Luneburg, Germany. Available at [www.hachlange.com](http://www.hachlange.com).
- Babatola JO (2008). Comparative Study of Biogas Yield Pattern in Some Animal and Household Wastes, African Research Review. An International Multi-Disciplinary Journal 2(4):54-68.
- Center for Sustaining Agriculture and Natural Resources (CSANR) (2012). Climate Friendly Farming. Center for Sustaining Agriculture and Natural Resources, Research Report 2012. <http://csanr.wsu.edu/program-areas/climate-friendly-farming/climate-friendly-farming-final-report/>
- Dahunsi SO, Oranusi US (2013). Co-digestion of Food Waste and Human Excreta for Biogas Production. British Biotechnology Journal 3(4):485-499.
- de Mes TZD, Stams JH, Reith JH, Zeeman G (2003). Methane production by anaerobic digestion of wastewater and solid wastes. Bio-methane & Bio-hydrogen 58-102.
- Dobre P, Nicolae F, Matei F (2014). Main factors affecting biogas production - an overview: Romanian Biotechnological Letters 19(3):9283-9296.
- Ghaly AE (1996). A comparative Study of Anaerobic Digestion of Acid Cheese Whey and Dairy Manure in a Two-stage Reactor. Biosource Technology 58:61-72.
- Gupta A, Chandra R, Subbarao PMV, Vijay VK (2009). Kinetics of Batch Biomethanation Process of Jatropha and Pongamia Oil Cakes and their Co-digested Substrates. Journal of Scientific and Industrial Research 68:624-629.
- Itodo IN, Philips TK (2002). Covering Materials for Anaerobic Digesters Producing Biogas. Nigerian Journal of Renewable Energy 10(1&2):24-52.
- Leitão RC, van Haandel C, Zeeman G, Lettinga G (2005). The effects of operational and environmental variations on anaerobic wastewater treatment systems: A review Bioresource Technology pp. 76-77.
- Mahanta P, Dewan A, Saha UK, Kalita P (2004). Influence of Temperature and Total Solid Concentration on the Gas Production Rate of Biogas Digester. Journal of Energy in Southern Africa 15(4):112-117.
- Mateescu C (2016). Influence of the Hydrostatic Pressure on Biogas Production in Anaerobic Digesters, Romanian Biotechnological Letters 21(5):11941-11948.
- Mir MA, Hussain A, Verma C (2016). Design considerations and operational performance of anaerobic digester: A review: Cogent Engineering 3(1):1181696 Available at <http://dx.doi.org/10.1080/23311916.2016.1181696> (accessed on 8<sup>th</sup> February, 2019).
- Mitel KM (1996). Biogas Systems-Principle and Application: New Age International Publishers Ltd., New York; 6:9-12.
- Mshandete AM, Parawira W (2009). Biogas Technology Research in selected Sub-Saharan African Countries - A review. African Journal of Biotechnology 8:116-125.
- Ocwieja SM (2010). Life Cycle Thinking Assessment Applied to Three Biogas Projects in Central Uganda. An M.SC project thesis submitted to the Department of Environmental Engineering Michigan Technology University. Available at <http://www.cce.mtu.edu/peacecorps/studentfiles/Ocwieja-Uganda.pdf> 2010; (17/5/2011).
- Olaoye JO, Oyeleke IF, Adeniran KA (2014). Design, Fabrication and Testing of a Modified Floating Drum Bio-digester. Proceedings of the International Soil Tillage Research Organisation (ISTRO) Nigeria Symposium, Akure 2014. November 3 - 6, Akure, Nigeria.149-161.
- Rabah AB, Baki AS, Hassan LG, Musa M, Ibrahim AD (2010). Production of Biogas Waste at Different Retention Time. Scientific World Journal 5(4).
- Rajeshwari KV, Balakrishnan M, Kansal A, LataKishore VVN (2000). State-of-the-artof Anaerobic Digestion Technology for Industrial Wastewater Treatment. Renewable and Sustainable Energy Reviews 4:135-156.
- Report No. ETSU B 1118 (1986). Research into the Development of Prototype Units for the Production of Biogas Methane from Farm Wastes and Energy Crops, Department of Microbiology, University College, Cardiff.
- Republic of Rwanda (2012). Technical Guidelines for Construction of Domestic Fixed Dome Biogas Plants pp. 1-39. available at <http://www.build-a-biogas-plants.com> (accessed on 23rd December, 2018).
- Sibiya NT, Muzenda E, Tesfagiorgis HB (2014).Effect of Temperature and pH on The Anaerobic Digestion of Grass Silage. 6th Int'l Conf. on Green Technology, Renewable Energy and Environmental Engg. (ICGTREEE'2014) Nov. 27-28, 2014 Cape Town (SA) 198-201.
- Thakur IS (2006). Environmental Technology: Basic Concept and

- Applications, New Delhi; IK international Pvt Ltd.
- Ubwa ST, Asemave K, Oshido B, Idoko A (2013). Preparation of Biogas from Plants and Animal Waste, *International Journal of Science and Technology* 2(6):6-7.
- Ukpai PA, Agbo PE, Nnabuchi MN (2015). The Effect of Temperature on the Rate of Digestion and Biogas Production using Cow Dung, Cow Pea, Cassava Peeling. *International Journal of Scientific and Engineering Research* 6(1):1255-1261. available at <http://www.ijser.org>(accessed on 9<sup>th</sup> February, 2019).
- Vidal G, Carvalho A, Mendeza R, Lema JM (2000). Influence of the Content in Fats and Proteins on the Anaerobic Biodegradability of Dairy Wastewaters. *Bioresource Technology* 74(3):231-239.
- Wise DL (1987). *Global Bioconversions*. CRC Press, Florida 4:178-189.

*Full Length Research Paper*

# **Efficiency of empirical methods for reference evapotranspiration estimation in the district of Vilankulo, Mozambique**

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**Precise quantification of reference evapotranspiration (ET<sub>o</sub>) is crucial for calculating crop water demand. Eight empirical methods based on temperature and six on solar radiation were evaluated against Penman-Monteith FAO 56 method based on: Mean Bias Error (MBE), Root Mean Square Error (RMSE), Willmott coefficient (“d”), determination coefficient (R<sup>2</sup>) and the Student’s t-test. The meteorological data of Vilankulo district (maximum, minimum and medium temperature, relative humidity, wind speed and sunshine hours) were used and collected in the National Institute of Meteorology of Mozambique from 1979 to 2006. The results showed that Mak solar radiation method had the best efficiency (MBE = -0.03 mm day<sup>-1</sup>; RMSE = 0.28 mm day<sup>-1</sup>; “d” = 0.97 and R<sup>2</sup> = 0.98). When sunshine hours or global solar radiation are not measured in order to use Mak method, Schendel method can be an alternative which requires air temperature and relative humidity (MBE = -0.09 mm day<sup>-1</sup>; RMSE = 0.81 mm day<sup>-1</sup>; “d” = 0.84 and R<sup>2</sup> = 0.74). Both methods were not statistically different with PMF 56 method. The merit of this study stems from the fact that no similar study was conducted in Vilankulo district.**

**Key words:** Reference evapotranspiration, empirical methods, Penman Monteith.

## **INTRODUCTION**

Agricultural activities demand large volumes of water, making their scarcity more and more worrying. Therefore, efforts have been employed so far in the development of research that allows its economy (Cunha et al., 2012). Water economics in agriculture can be obtained accurately by estimating crop evapotranspiration (ET<sub>c</sub>). According to Allen et al. (2011), precise measurement of

ET<sub>c</sub> is obtained using lysimeters or through imaging techniques. However, Valipour (2015) mentioned that both techniques carry high costs.

Due to the high costs to obtain ET<sub>c</sub>, it is necessary to calculate them from reference evapotranspiration (ET<sub>o</sub>) and crop coefficient. ET<sub>o</sub> represents the water loss of an hypothetical crop with a height of 0.12 m, in active and

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uniform growth, albedo of 23%, surface resistance of  $70 \text{ m s}^{-1}$ , without water stress and covering the surface of total soil (Allen et al., 1998). Usually, ETo is estimated from methods based on climatic data. Among them, Allen et al. (1998) recommended Penman Monteith FAO 56 (PMF 56) as standard method. Many authors have reported that this method presented good efficiency in different climatic conditions (Mohawesh, 2011; Cao et al., 2015). However, according to Valipour (2015), PMF 56 method is rarely used because requires a series of meteorological variables that are not available at several stations. In addition, quite complex calculations are involved in this method.

The limitations of PMF 56 method have led researchers to develop other alternatives, for example: empirical methods. These methods are very simple to use and require few variables in relation to the PMF 56 method. According to Valipour (2015), empirical methods include mass transfer methods, tank evaporation methods, methods based on solar radiation and air temperature (method most used). Some methods based on temperature are: Hargreaves and Samani-HS, Hamon-Ham, Mc Cloud-McC, Blaney and Criddle-BC and on solar radiation are: Makkink-Mak, Turc, Priestley and Taylor-PT and Ravazzani-Rav. Shiri et al. (2014), using meteorological data of nine years verified that the HS method exceeded the efficiency of Mak, Turc and PT methods. On other hand, Sabziparvar and Tabari (2010) observed that HS method overcame the efficiency of Mak and PT methods in arid and semi-arid conditions of Iran. Many other authors reported better efficiency of temperature methods than solar radiation methods (Djaman et al., 2015; Ahooghalandari et al., 2016). However, opposite result reported by Liu et al. (2017) in their study, revealed that Mak method was better in estimation ETo than temperature-based methods of Ham, BC and McC. In addition, Mak method was found better than HS method in arid, semi-arid and Mediterranean conditions of Iran by Valipour et al. (2017).

The results presented show that there is a variability of the efficiency of empirical methods. Thus, it is essential to evaluate their efficiency for each site, under the risk of select methods that underestimate or overestimate the real ETo value, consequently, reducing agricultural productivity and product quality.

The main goal of the present research was to evaluate the efficiency of eight empirical methods based on temperature and six on solar radiation against PMF 56 method in Vilankulo district.

## MATERIALS AND METHODS

### Study area and data collection

Vilankulo district was located in Inhambane province of Mozambique (LAT  $22^{\circ}36'S$ ; LONG  $35^{\circ}19'E$ ; and 20 m OSL). Based on Köppen climatic classification, Vilankulo district shows an Aw climate (humid tropical climate with dry winter and summer rains)

with a monthly average temperature of  $24.4^{\circ}C$ , annual total precipitation of 761.5 mm and an annual total ETo of 1804.9 mm. The data used correspond to 1980 to 2009 (30 years) period.

Then, data of maximum temperature (Tx), minimum temperature (Tn) and average temperature (T), relative humidity (RH), wind speed ( $U_2$ ) and sunshine hours (n) were collected in the National Institute of Meteorology of Mozambique (period from 1979 to 2006). The data of the other years were discarded since they presented numerous failures. In case study period, some failures were observed and filled using mathematical methods. For Tx, Tn, T and RH data, missing values were considered equal to the average of the existing values in a given period. For  $U_2$ , the missing data was considered equal to  $2 \text{ m s}^{-1}$  based on the recommendation by Allen et al. (1998). In Table 1, are presented the collected monthly average meteorological data from 1979 to 2006.

After the described procedure, the ETo was estimated using eight empirical methods based on air temperature and six based on solar radiation. All empirical methods were evaluated in relation to PMF 56 method. Based on the fact that it is necessary to use global solar radiation (Rs) in PMF 56 method, it was estimated from Equation 1 and the results were put in Table 1. According to Allen et al. (1998), in Rs data absence and local calibration of parameters a and b of Equation 1, the following values are adopted:  $a = 0.25$  and  $b = 0.50$ . The equations used in the PMF 56 method and in empirical methods are presented in Table 2.

$$Rs = \left( a + b \frac{n}{N} \right) Ra \quad (1)$$

Where: Rs- global solar radiation ( $\text{MJ m}^{-2} \text{ day}^{-1}$ ); Ra- extraterrestrial radiation ( $\text{MJ m}^{-2} \text{ day}^{-1}$ ); n- sunshine hours (n); N- photoperiod; a & b- constant of the Angstrom equation.

### Evaluation of empirical methods

The efficiency of empirical methods was evaluated in relation to PMF 56 method based on statistical parameters like: Mean Bias Error (MBE), Root Mean Square Error (RMSE), "d" (Willmott coefficient) and based on  $R^2$  (coefficient of determination). The significance of each method in relation to PMF 56 method was analyzed based on t-test at significance level of 5%.  $MBE > 0$  indicates overestimate and the opposite underestimate. RMSE indicates method accuracy and "d" indicates the agreement. The best methods should present the following results:  $MBE \cong 0$ ;  $RMSE \cong 0$ ; "d"  $\cong 1$  and  $R^2 \cong 1$ . Equations 2; 3; 4 and 5 were used to calculate the MBE, RMSE, "d" and  $R^2$  parameters, respectively.

$$MBE = \frac{1}{N} \sum_{i=1}^N (ETo_{Est} - ETo_{PMF56}) \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (ETo_{Est} - ETo_{PMF56})^2}{N}} \quad (3)$$

$$"d" = 1 - \frac{\sum_{i=1}^N (ETo_{Est} - ETo_{PMF56})^2}{\sum_{i=1}^N (|ETo_{Est} - ETo_{PMF56}| + |ETo_{Est} - \overline{ETo_{PMF56}}|)^2} \quad 0 \leq "d" \leq 1 \quad (4)$$

$$R^2 = \frac{\sum_{i=1}^N (ETo_{PMF56} - \overline{ETo_{PMF56}})(ETo_{Est} - \overline{ETo_{Est}})}{\sqrt{\sum_{i=1}^N (ETo_{PMF56} - \overline{ETo_{PMF56}})^2 (ETo_{Est} - \overline{ETo_{Est}})^2}} \quad 0 \leq R^2 \leq 1 \quad (5)$$

Where:  $ETo_{Est}$ - values estimated by the methods ( $\text{mm day}^{-1}$ );  $ETo_{PMF56}$ - values estimated by the standard method ( $\text{mm day}^{-1}$ ); N- number of estimates per period and  $\overline{ETo_{PMF56}}$ - mean ETo estimated by the standard method ( $\text{mm day}^{-1}$ );  $\overline{ETo_{Est}}$ - mean ETo estimated by the appraised methods ( $\text{mm day}^{-1}$ ).

**Table 1.** Average meteorological data from 1979 to 2006 in Vilankulo district.

Months	Meteorological data						
	Tx	Tn	T	RH	U <sub>2</sub>	n	Rs
Jan	31.19	23.80	27.49	77.43	2.43	8.96	24.81
Feb	31.23	23.65	27.44	78.36	2.61	8.85	23.87
Mar	30.76	22.87	26.82	79.36	2.43	8.76	21.92
Apr	29.51	20.48	24.99	80.21	2.23	8.75	19.04
May	27.67	17.69	22.68	81.29	2.22	8.64	16.35
Jun	26.06	15.33	20.69	83.93	2.12	8.15	14.45
Jul	25.46	14.88	20.17	84.75	2.22	8.35	15.34
Aug	26.07	16.33	21.20	82.46	2.23	8.85	18.16
Sep	27.31	18.86	23.08	79.57	2.36	8.64	20.73
Oct	28.33	20.76	24.54	76.25	2.32	8.78	23.10
Nov	29.62	22.68	26.15	76.46	2.42	8.73	24.21
Dec	31.23	23.51	27.49	76.50	2.61	8.96	24.93
<b>Average</b>	28.65	20.70	24.40	79.71	2.35	8.70	20.58

## RESULTS AND DISCUSSION

### Estimation of ETo from temperature-based methods

Table 3 shows the statistical efficiency of empirical methods based on temperature in Vilankulo district from 1979 to 2006. All methods correlated significantly ( $p < 0.05$ ) with PMF 56 method,  $R^2$  values ranging from 0.55 (Rom method) to 0.94 (HSm method). The  $R^2$  values of each method are shown in Figure 1(a-h).

Observing Table 3, all methods underestimated ETo estimated by the PMF 56 method ( $MBE < 0$ ), with the exception of the McC, McG and Kha methods which overestimated. In terms of absolute value of MBE, the Sch method presented the closest value of zero ( $MBE = -0.09 \text{ mm day}^{-1} = 1.8\%$ ), showing the tendency to be the best method for estimating ETo in the district of Vilankulo. The worst MBE result was observed in the McC method ( $MBE = 1.97 \text{ mm day}^{-1} = 39.4\%$ ). Jakimavičius et al. (2013) found that the Sch method underestimated ETo by 0.6%, but overestimate results were reported in Namanye ( $MBE = 39\%$ ) and Fanaye ( $MBE = 10\%$ ) by Djaman et al. (2015).

In relation to the RMSE values, the best accuracy was observed in Sch method ( $RMSE = 0.81 \text{ mm day}^{-1}$ ) and the worst in McC method ( $RMSE = 2.11 \text{ mm day}^{-1}$ ), reinforcing the observed results from MBE parameter. The result observed in Sch method was already predictable since it presented the mean value of ETo ( $ETo = 4.92 \pm 0.74 \text{ mm day}^{-1}$ ) closest to mean value obtained by PMF 56 method ( $ETo = 5.01 \pm 1.34 \text{ mm day}^{-1}$ ), Table 3. In addition, this method presented the parameter "d" = 0.84 which can be considered close to 1, indicating a good agreement with the PMF 56 method. In Ndiaye and Fanaye, the Sch method presented an accuracy of 2.65 and 4.33  $\text{mm day}^{-1}$ , respectively, according to Djaman et al. (2015). Tabari et al. (2013)

observed the following efficiency:  $MBE = -0.86 \text{ mm day}^{-1}$ ;  $RMSE = 1.03 \text{ mm day}^{-1}$  and  $R^2 = 0.87$ . In 31 provinces of Iran, Valipour (2015) reported that Sch method presented values of  $R^2$  ranging from 0.85 to 0.96. Some of these results are inferior to those presented in the present research, evidencing that efficiency of the empirical methods can vary from place to place.

Similarly, in line with this study, Liu et al. (2017) evaluated different ETo estimation methods and did not recommend the use of McC method. However, in Chapadão do Sul, Brazil, McC method was recommended to estimate ETo at different time scales by Cunha et al. (2012), showing the need to choose methods carefully.

From Table 3, it was also observed that the t-test results showed that only Sch method is not statistically different with PMF 56 method in ETo estimation at 5%. Thus, Sch method can be safely used instead of PMF 56 method. The use of Sch method instead of PMF 56 method is extremely advantageous as this method requires the use of meteorological data (T and RH) which are available at several meteorological stations than those required in PMF 56.

### Estimation of ETo from methods based on solar radiation

Table 4 shows the efficiency of empirical methods based on solar radiation, from 1979 to 2006, similarly to temperature-based methods, a significant correlation was observed with PMF 56 method ( $p < 0.05$ ), with  $R^2 = 0.98$  in all methods, as indicated in Figure 1(i-n).

With the exception of JHa and Mam methods, all methods underestimated PMF 56 method. The best result is observed in Mak method ( $MBE = 0.03 \text{ mm day}^{-1}$ ) and worse in JHa method ( $MBE = 0.88 \text{ mm day}^{-1}$ ). The

**Table 2.** Methods for estimating Eto.

Methods	References	Equation	Parameter
Penman Monteith FAO 56 (PMF56)	Allen et al. (1998)	$E_{To} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900U_2(es - ea)}{T + 273}}{\Delta + \gamma(1 + 0.34U_2)}$	T, RH, U <sub>2</sub> & n
<b>Temperature-based methods</b>			
Hargreaves-Samani (HS)	Hargreaves and Samani (1985)	$E_{To} = 0.023Ra(T_x - T_n)^{0.5}(T + 17.8)0.408$	T, T <sub>x</sub> , T <sub>n</sub> & Ra
Ravazzani (Rav)	Ravazzani et al. (2012)	$E_{To} = 0.408(0.817 + 0.0022Z)0.0023Ra(T_x - T_n)^{0.5}(T + 17.8)$	T, T <sub>x</sub> , T <sub>n</sub> & Ra
Romanenko's (Rom)	Romanenko's (Oudin et al.,2005)	$E_{To} = 4.5 \left[ \left( 1 + \frac{T}{25} \right) \right]^2 \left( 1 - \frac{es}{es'} \right)$	T & RH
Trajkovic (HSm)	Trajkovic (2007)	$E_{To} = 0.023Ra(T_x - T_n)^{0.424}(T + 17.8)0.408$	T, T <sub>x</sub> , T <sub>n</sub> & Ra
Mc Cloud (McC)	Mc Cloud (1995)	$E_{To} = 0.245 * 1.07^{1.8T}$	T
Schendel (Sch)	Schendel (1967)	$E_{To} = 16 \frac{T}{RH}$	T & RH
Mc Guinness-Bordne (McG)	Mc Guinness and Bordne (1972)	$E_{To} = 0.408Ra \frac{T + 5}{68}$	T & Ra
Kharrufa (Kha)	Kharrufa (1985)	$E_{To} = 0.34pT^{1.3}$	N & T
<b>Solar radiation-based methods</b>			
(Abt)	Abtew (1966)	$E_{To} = \frac{0.53}{\lambda} R_s$	T & R <sub>s</sub>
Makkin (Mak)	Makkin (1957)	$E_{To} = 0.408R_s \frac{0.61R_s\Delta}{(\Delta + \gamma)} - 0.12$	T & R <sub>s</sub>
Irmak (Irm)	Irmak et al. (2003)	$E_{To} = 0.149R_s + 0.079T - 0.611$	T & R <sub>s</sub>
Jensen-Haise (JHa)	Jensen and Haise (1963)	$E_{To} = 0.408R_s(0.0252T + 0.078)$	T & R <sub>s</sub>
Jones-Ritchie (JRi)	Jones and Ritchie (1990)	$E_{To} = \alpha_1 0.00387R_s(0.6T_x + 0.4T_n + 29)$ Se T <sub>x</sub> < 0.5; α <sub>1</sub> = 0.01EXP(0.18(T <sub>x</sub> + 20)) Se ≤ T <sub>x</sub> < 35; α <sub>1</sub> = 1.1 Se T <sub>x</sub> ≥ 35; α <sub>1</sub> = 1.1 + 0.05(T <sub>x</sub> - 35)	T, T <sub>x</sub> , T <sub>n</sub> & R <sub>s</sub>
Makkin (Makm)	Makkin (1967) modified by Hansen (1984)	$E_{To} = 0.7 \frac{\Delta}{(\Delta + \gamma)} 0.408R_s$	T & R <sub>s</sub>

E<sub>To</sub>-reference evapotranspiration (mm day<sup>-1</sup>); R<sub>n</sub>-net radiation balance (MJ m<sup>-2</sup> day<sup>-1</sup>); G-soil heat flux (MJ m<sup>-2</sup> day<sup>-1</sup>); γ-psychrometric constant (kPa °C<sup>-1</sup>); n- sunshine hours (h); T-average air temperature (°C);T<sub>x</sub>, T<sub>n</sub>-maximum and minimum air temperature; U<sub>2</sub>-wind speed at 2 meters high (m s<sup>-1</sup>); es- saturation pressure in dry-bulb temperature (kPa); ea-actual pressure (kPa); Δ- slope of the saturated vapor pressure curve (kPa °C<sup>-1</sup>); RH-relative air humidity (%); N-photoperiod (h); λ - latent heat evaporation (MJ m<sup>-2</sup> day<sup>-1</sup>); p-percentage of annual daylight hours for any day of the year; z- altitude (m).

best result of Mak method is confirmed by RMSE parameter which presented a value closer to zero (RMSE = 0.28 mm day<sup>-1</sup>), meaning high precision.

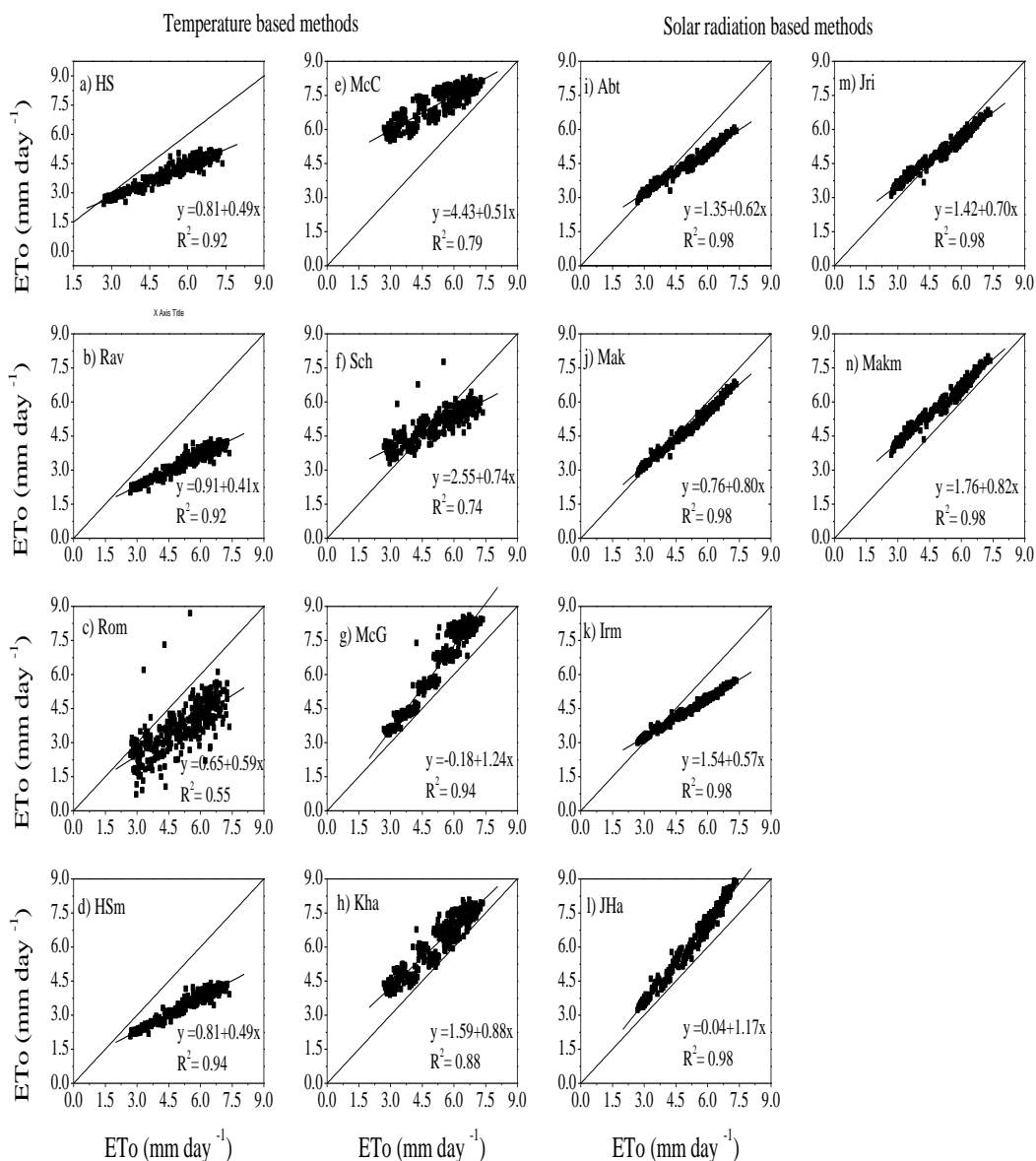
The worst result observed through MBE parameter is also confirmed by RMSE parameter (0.94 mm day<sup>-1</sup>) which was the highest, indicating

lower precision (Table 4). In relation to the mean E<sub>To</sub> values, is also observed that JHa method (E<sub>To</sub> = 5.90 ± 1.59 mm day<sup>-1</sup>) was worse than

**Table 3.** Performance of empirical temperature methods.

Methods	ETo Values (mm day <sup>-1</sup> )				Statistical parameter			
	Max	Min	Ave.	Sd	MBE (mm day <sup>-1</sup> )	RMSE (mm day <sup>-1</sup> )	"d"	t-test
PM56	7.37	2.69	5.01	1.34	---	---	---	---
HS	5.21	2.43	3.86	0.77	-1.15	1.32	0.74	-13.64*
Rav	4.33	2.02	3.21	0.64	-1.8	1.95	0.61	-22.23*
Rom	8.70	0.72	3.62	1.08	-1.4	1.67	0.68	-14.88*
HSm	4.42	2.07	3.29	0.68	-1.72	1.86	0.63	-20.96*
McC	8.31	5.50	6.99	0.77	1.97	2.11	0.59	23.35*
Sch	7.76	3.30	4.92	0.74	-0.09	0.81	0.84	-1.07 <sup>NS</sup>
McG	8.59	3.38	6.05	1.72	1.03	1.15	0.87	8.68*
Kha	8.05	3.90	5.99	1.25	0.97	1.07	0.85	9.73*

\*- Significance at 5% and NS- non significance.

**Figure 1.** ETo estimated by empirical methods in relation to the PMF method 56.

**Table 4.** Efficiency of empirical methods based on solar radiation.

Methods	ETo values (mm day <sup>-1</sup> )				Statistical parameters			
	Max	Min	Ave.	Sd	MBE (mm day <sup>-1</sup> )	RMSE (mm day <sup>-1</sup> )	"d"	t-test
PMF56	7.37	2.69	5.01	1.34	---	---	---	---
Abt	6.07	2.80	4.45	0.84	-0.56	0.77	0.88	-6.53 <sup>*</sup>
Mak	6.87	3.09	4.98	0.97	-0.03	0.28	0.97	-0.35 <sup>NS</sup>
Irm	5.77	2.99	4.38	0.77	-0.63	0.87	0.85	-7.52 <sup>*</sup>
JHa	8.91	3.23	5.90	1.59	0.88	0.94	0.91	7.79 <sup>*</sup>
JRi	6.88	2.81	4.78	1.08	-0.23	0.37	0.98	-2.44 <sup>*</sup>
Makm	8.00	3.68	5.85	1.11	0.84	0.89	0.88	8.86 <sup>*</sup>

\*- Significance at 5% and NS- non significance.

**Table 5.** Selection of the best ETo estimation methods.

Position	Method	RMSE (mm day <sup>-1</sup> )
1	Mak <sup>*</sup>	0.28
2	JRi <sup>*</sup>	0.37
3	Abt <sup>*</sup>	0.77
4	Sch	0.81
5	Irm <sup>*</sup>	0.87
6	Makm <sup>*</sup>	0.89
7	JHa <sup>*</sup>	0.94
8	Kha	1.07
9	McG	1.15
10	HS	1.32
11	Rom	1.67
12	HSm	1.86
13	Rav	1.95
14	McC	2.11

Mak method (ETo = 4.98 ± 0.97 mm day<sup>-1</sup>), since the last method estimated a closer value to the method of PMF 56 (ETo = 5.01 ± 1.34 mm day<sup>-1</sup>).

Mohawesh (2011), when evaluating eight methods of ETo estimation in the arid and semi-arid conditions of Jordan obtained the following performance with Mak method: MBE = 2.63 mm day<sup>-1</sup>; RMSE = 3.72 mm day<sup>-1</sup> and R<sup>2</sup> = 0.45; MBE = 1.82 mm day<sup>-1</sup>; RMSE = 2.52 mm day<sup>-1</sup> and R<sup>2</sup> = 0.57, respectively. The efficiency obtained by this author is lower than that reported in this research. Other lower results were reported by Liu et al. (2017). These researches were carried out under dry climate conditions and Mak method is indicated as the proper for these conditions. However, in the current paper research (humid tropical climate), Mak method presented better efficiency. With this, the climate of Vilankulo district probably has a tendency to be dry, being necessary to use other climatic classifications (out of our scope) to better understand Vilankulo's climate. According to Vianello and Alves (2012), Köppen climatic classification has the limitation of not having a rational basis in

temperature and rainfall selection values.

Also in Table 4, it was observed that Mak method, similar to some methods, showed high agreement rate with the PMF 56 method ("d" = 0.97). On the other hand, unlike the other methods evaluated, Mak method did not show statistically significant differences in ETo estimation in relation to PMF 56 method by the t-test, reinforcing that this method is the best for estimation of ETo among evaluated methods.

### Comparison of all empirical methods

Methods were analyzed and judged based on RMSE parameter (Table 5) such as criterion used by Liu et al. (2017). To facilitate understanding of Table 5, the asterisked methods are based on solar radiation and those without asterisks are based on temperature.

In comparison of all methods, it was verified that Mak radiation method occupied the first position (RMSE = 0.28 mm day<sup>-1</sup>) and McC temperature method occupied

the last position (RMSE = 2.11 mm day<sup>-1</sup>) (Table 5). All temperature-based methods presented a lower accuracy than those based on solar radiation, although the Sch method occupied the 4<sup>th</sup> position (RMSE = 0.81 mm day<sup>-1</sup>). The tendency of the solar radiation methods to produce better results in relation to temperature methods was reported in several studies (Tabari et al., 2013; Valipour et al., 2017), corroborating to present research.

If it is impossible to measure Rs or to be estimated (which is one of parameter necessary for Mak method use), Sch method can be used as an alternative, which requires less parameter such as T and RH. In addition, T and RH are measured in almost all meteorological gauges in worldwide. Although, Mak method presented the best result of present research, Sabziparvar and Tabari (2010) and Liu et al. (2017) found that efficiency of this method was less to some methods evaluated in this study case. Therefore, if it requires the use of Mak method in different conditions detailed in this research, its efficiency should be assessed first in order to check the risk on application of improper irrigation. Figure 1(i-n) confirms the tendency of solar radiation methods to estimate ETo better; hence, presenting high mathematical adjustments ( $R^2 \cong 1$ ), they presented regression lines closer to the line  $y = x$ .

## Conclusion

Among temperature-based methods, Schendel (Sch) method showed better efficiency (MBE = -0.09 mm day<sup>-1</sup>; RMSE = 0.81 mm day<sup>-1</sup>; "d" = 0.84 and  $R^2 = 0.74$ ), whereas among solar radiation-based methods, the original Makkink (Mak) method presented the best efficiency (MBE = -0.03 mm day<sup>-1</sup>; RMSE = 0.28 mm day<sup>-1</sup>, "d" = 0.97 and  $R^2 = 0.98$ ). Both methods were not statistically different with Penman Monteith FAO 56 standard method by t-test.

Comparing all methods through RMSE parameter, it was concluded that Mak method occupied the 1<sup>st</sup> position. If it is not possible to measure or to estimate global solar radiation (Rs), instead of Mak method, the Sch method can be used as an alternative. This method requires only data of air temperature and relative humidity, which are usually measured in several stations.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

## REFERENCES

- Abtew W (1966). Evapotranspiration measurements and modeling for three wetland systems in South Florida. *Journal of the American Water Resource Association* 127(3):140-147.
- Ahooghalandari M, Khiadani M, Jahromi ME (2016). Developing equations for estimating reference evapotranspiration in Australia. *Water Resource Management*, 30:3815-3828.
- Allen RG, Pereira LS, Howell TA, Jensenme J (2011). Evapotranspiration information reporting: I. Factors governing measurement preciseness. *Agricultural Water Management* 98(3):899-920.
- Allen RG, Pereira L, Raes D, Smith M (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. In: *Irrigation and Drainage, Paper No. 56*, Food and Agriculture Organization of the United Nations, Rome.
- Blaney HF, Criddle WD (1950). Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. USDA. SCS-TP-96, 48p.
- Cao JF, Li YZ, Zhong XL, Zhao YM (2015). Comparison of four combination methods for reference crop evapotranspiration. *Chinese Journal of Agrometeorology* 36(4):428-436.
- Cunha FF, Magalhães FF, Castro MA, Cruz GHM, Souza EJ (2012). Estimativa da evapotranspiração de referência em diferentes métodos e intervalos de tempo para Chapadão do Sul-MS. In: XXII CONIRD. Cascavel Paraná.
- Djaman K, Balde AB, Sow A, Muller B, Irmak S, N'diaye MK, Manneh, B, oukoubi YD, Futakuchi K, Saito K (2015). Evaluation of sixteen reference evapotranspiration methods under Sahelian conditions in The Senegal River Valley. *Journal of Hydrology* 3:139-159.
- Hargreaves GH, Samani ZA (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* 1(2):96-99.
- Irmak S, Irmak A, Allen RG, Jones JW (2003). Solar and net radiation based equations to estimate reference evapotranspiration in humid climates. *Journal of Irrigation and Drainage Engineering* 129(5):336-347.
- Jakimavičius D, Jūrat E, Kriauciūnien E, Brunonas G, Dianašaruskien E (2013). Assessment of uncertainty in estimating the evaporation from the Curonian Lagoon. *Baltica* 26(2):177-186.
- Jensen ME, Haise HR (1963). Estimating evapotranspiration from solar radiation. *Proceeding Journal of Irrigation and Drainage*, 89:15-41.
- Jones JW, Ritchie JT (1990). Crop growth models. Management of farm irrigation systems. In: Hoffman GJ, Howel TA, Solomon KH (Eds.), *ASAE Monograph* 9:63-89.
- Kharrufa NS (1985). Simplified equation for evapotranspiration in arid regions. *Beitrage zur Hydrologie* 5(1):39-47.
- Liu X, Xu, C, Zhong X, Li Y, Yuan X, Cao J (2017). Comparison of 16 models for reference crop evapotranspiration against weighing lysimeter measurement. *Agricultural Water Management* 184:145-155.
- Makkink GF (1957). Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineers* 11(3):277-288.
- Mc Guinness JL, Bordne EF (1972). A comparison of lysimeter-derived potential evapotranspiration with computed values. US Dept. of Agriculture, Washington, DC.
- Mohawesh OE (2011). Evaluation of evapotranspiration models for estimating Daily reference evapotranspiration in arid and semiarid environment. *Plant Soil and Environment* 57(4):147-152.
- Sabziparvar AA, Tabari H (2010). Regional Estimation of reference evapotranspiration in arid and semiarid regions. *Journal of Irrigation and Drainage Engineering* 136(10):724-731.
- Schendel U (1967). *Vegetations Wasserverbrauch und Wasserbedarf*. Habilitation, Kiel. 137p.
- Shiri J, Nazemi AH, Sadraddini AA, Landeras G, Kisi O, Fard AF, Marti P (2014). Comparison of heuristic and empirical approaches for estimating reference evapotranspiration from limited inputs in Iran. *Computers and Electronics in Agriculture* 108:230-241.
- Tabari H, Grismer MA, Trajkovic S (2013). Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrigation Science* 31(2):107-117.
- Valipour M (2015). Temperature analysis of reference evapotranspiration models. *Meteorological Applications*, 22:385-394.
- Valipour M, Sefidkouhi MAG, Raeni- Sarjaz M (2017). Selecting the best model to estimate potential evapotranspiration with respect to climate change and magnitudes of extreme events. *Agricultural Water Management* 180:50-60.
- Vianello RL, Alves AR (2012). *Meteorologia básica e aplicações*. 2. Ed. Viçosa, MG: Ed. UFV. 460p.

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