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Influence of the Construction Materials Properties of the Biodigester on the Biogas Production and Electricity Generated by the Slaughterhouse Waste

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ABSTRACT

The objective of this study was to carry out a comparative analysis of the influence of the properties of the construction materials of the biodigester based on three different materials (steel, plastic PVC, and concrete) to predict the rate of biogas production from the anaerobic digestion of slaughterhouse waste. The input parameters were substrate temperature, ambient temperature, biogas temperature, biodigester temperature, specific biogas production rate, and material properties. A thermal model was developed using MATLAB® software to predict biogas production, with readily available input data for an unheated, uninsulated, and partially buried biodigester. The results obtained showed that the temperatures and the average daily biogas productions were higher for the steel biodigester (1.5 ± 0.12 m^3/day at 36 ± 2°C) than those produced from the PVC (1.3 ± 0.1 m^3/day at 31 ± 1.5°C) and concrete (1.2 ± 0.05 m^3/day at 27 ± 2°C) biodigesters. Moreover, the production of electricity for a steel biodigester (14.64 kWh) was found to be greater than that produced from the PVC (12.81 kWh) and concrete (10.98 kWh) biodigesters. The results showed that the properties of the construction materials of the digester had a significant influence on the temperature and production of biogas, and therefore on the production of electricity. On the other hand, among the three materials studied, steel was the material, which yielded the best results. The proposed model gave rRMSE values between 7.4 and 8.3% and R^2 between 0.92 and 0.96.

1. INTRODUCTION

Rising fuel prices, greenhouse gas emissions and over-reliance on non-renewable energies have pushed researchers in recent years to find alternative methods to obtain a sustainable form of energy [1]. Urbanization has also caused rapid generation of a considerable amount of waste, resulting in to poor waste management practices in developing countries [2, 3]. All of this emphasizes the fact that environmentally friendly renewable energy sources remain a viable option for meeting rising energy demand and fossil fuel depletion [4]. Moreover, local and global energy shortages have become more prevalent [5]. Renewable energy development is currently rising, in line with the United Nations Sustainable Development Goal 2030 [6]. Hamed et al. [7- 9] demonstrated the synthesis of a renewable energy source extraction from biogas by anaerobic digestion (AD) as an alternative. AD is the conversion of organic waste into biogas, specifically a combination of CH_4 (from 50 to 70%), CO_2 (from 30 to 50%), and digestate [10-13]. Hydrolysis, acidogenesis, acetogenesis, and methanogens are the four important phases of the AD [14-17].

Slaughterhouse wastes are animal by-products that contain a wide spectrum of bacterial, viral, and parasite pathogens, and are mostly made up of rumen and blood. The daily quantity of slaughterhouse waste (e.g., blood and rumen) varies according to the type of animal (e.g., large ruminants, small ruminants and poultry). Rumen and blood were analyzed for big ruminants (cattle and camels), small ruminants (sheep and goats), and poultry based on slaughtered animals and the kind of livestock [18, 19].

Several types of the materials have been used for the construction of anaerobic digesters. For instance, Kumar and Sharma [20] reported that concrete had a low initial cost and a long life. In addition, Rajendran et al. [21] investigated the use of plastic digester and concluded that it could be a good insulator, non-corrosive, and less costly. Furthermore, Olojede et al. [22] reported that steel used for the construction of air proof metallic digester for biogas production exhibited high strength and great ability to resist corrosion [22]. AD is significantly influenced by process-related parameters such as temperature and organic loading rate (OLR) [23]. In a study on bio-methane production from anaerobic digestion of farming waste, it was shown that the thermophilic state yielded the maximum amount of biogas [24, 25]. In addition, the production of biogas has a strong influence on the OLR as it was found that the biogas yield increased with a reduction in the OLR [26]. In addition, it was shown that methane production stopped due to reduced growth of methanogens at lower pH (acidic condition) [27]. In another study, it was emphasized that the small particles could give a good yield of biogas since the producing bacteria were intimately linked to the degradable organic matter of the substrate [28]. It is noted that methanogenic bacteria multiply rapidly and double in size in two to four days [29]. Moreover, other researchers show that the cumulative volume of biogas and the methane content are significantly affected by the mass ratio, the addition of water, the chemical treatment of pH, all of these effects being under mesophilic temperature conditions [30]. For normal operation of anaerobic digester, the C/N ratio should be between 20 and 30 [31]. For a stable anaerobic reactor, the suggested concentration of VFAs is between 50 and 250 mg/L [32, 33]. Indeed, the conversion of complex substrates into AGV makes it possible to supply the AD with a waste with a high content of bioavailable compound, which makes it possible to reduce the lengthening of the hydrolysis and acidification phases and to increase the production of methane [34]. Several researchers have studied the influence of parameters on biogas production without reporting the effect of the construction material of the digester [35]. As a result, there is insufficient information on the influence of the properties of the construction material of the biodigester on the production of biogas and electricity. Considering the apparent literature gap on this subject, the novelty of this research is to report that the properties of biodigester building materials have an influence on biogas production and on electricity.

The primary objective of this study was to develop a new model for estimating biogas production and electricity production taking into account the influence of the properties of construction materials for a partially buried biodigester. In this paper, for the first time, the material and method covering the experimental set-up, heat transfer, biogas production and electricity production were introduced. Finally, the results and discussions were presented by clarifying the points mentioned in the methodology.

2. MATERIALS AND METHODS

2.1 Materials

The volume of biogas production was measured with a Puxin gas flow meter (JBD-2.5SA, Shenzhen Puxin Technology, Guangdong, China). Biogas compositions were determined by using a biogas analyzer (Optima 7 Instruments, Inc. Humble, Texas, USA). The temperatures were measured by thermometers with thermo couple probes (PCE-T390, PCE Instruments, and Strasbourg, France). The pH of samples was determined by using a pH meter combined with a pH electrode PE 03 (PCE-228, PCE Instruments, and Strasbourg, France).

2.2 Methods

2.2.1 Assumption

The three digesters (concrete, steel and plastic) have the following same assumptions:

- Sized at 4 m^3
- Metrological data
- Input parameters except the property values of each material
- Output parameters
- Feeding mode

2.2.2 Prototype biodigester

A domestic biodigester was constructed at the Faculty of Sciences and Techniques (FST) of the University of Nouakchott Al Aasriya (UNA), Mauritania (Figure 1). This prototype biodigester of 4 m^3 of concrete construction was built with anti-salt and full bricks (25 cm × 12 cm × 6.5 cm). During the construction of the reactor, two layers of 5 cm thick cement were used inside and outside, and a 2.5 cm thick paint layer was used outside. 2.5 m^3 of this biodigester was buried in the ground and the remaining 1.5 m^3 was above the ground. It included a concrete inlet and outlet (50 cm × 50 cm × 13 cm) connected to the biodigester by PVC pipes (45 mm in diameter and 2 m long), and the biogas was stored in a cubic PVC gasometer of 2 m^3 capacity connected to the biodigester by a pipe (1 mm in diameter and 1 m long). The biodigester was fed every second day with 30 kg of slaughterhouse waste (supplied from El Mina (a suburb of Nouakchott and urban commune in western Mauritania) located 10 km to the south) diluted with 60 L of water. Moreover, the slaughterhouse waste used in this study is mainly composed of rumen and blood (Table 1).

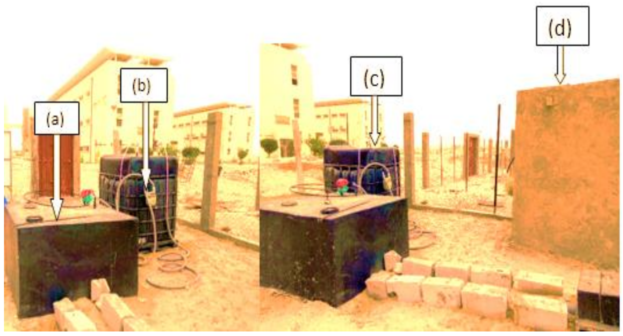

Figure 1. Biodigester constructed at the Faculty of Science and Technology (FST): (a): digester, (b): flowmeter, (c): gasometer and (d): shelter for testing

Table 1. the components of slaughterhouse waste

Slaughterhouse Waste	TS (%)	M (%)	A (%)	VS (%)
Blood and Rumen	5.3	94.7	12.3	87.6

2.2.3 Data collection

Biodigester, biogas, and substrate temperatures were recorded every day at two-hour intervals. The pH and biogas flow were measured every day at three-hour intervals. The biogas production was analyzed every week by determining its composition (CH_4, CO_2, O_2, and H_2S), pressure, and calorific value. The real-time climatic data were measured every day on hourly-basis. In addition, the hydraulic retention time (HRT) was kept at 35 days during the digestion process.

2.2.4 Heat transfer

A heat transfer model that takes into account the properties of building materials is presented in Table 2. It consists of three equations related to biogas, construction material (cover), and substrate (slaughterhouse waste) respectively. The biogas production prediction model, which takes into account the properties of the construction materials of the biodigester, was developed using a MATLAB® tool. The input data of the model were ambient temperature, substrate temperature, biogas temperature, hydraulic retention time, digestion temperature, specific biogas production rate, the geometrical characteristics of the biodigester, and feed material (amount of waste mixed with water after treatment).

Thermal balance at the level of the constituents of the digester is given Table 3.

Table 2. Thermal properties of biodigester construction materials

	Units	Concrete	Plastic	Steel	Air	Substrate	Biogas	Reference
Density (ρ)	kg/m^3	2150	680	220	1.205	1000	1.156	
Thermal conductivity (λ)	W/m/K	1.65	43	0.035	0.026	0.605	0.026	[36-39]
Specific heat (Cp)	J/kg/K	1008	1046	795	1010	0.149	498.1	
Thermal diffusivity (αs)	10^{-6} m²/s	78	20	0.2	211.2	4.179	1682.2	
Absorptivity	-	0.92	_	0.75	1.82	97.72	1.16	
Emissivity (ε)	-	0.92	0.84	0.75	15.11	0.98	11.93	

Table 3. Thermal balance at the level of the constituents of the biodigester

Constituents	Equations	Reference
Cover	$0 = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$ (1)	[37, 39]
Biogas	$m_G C_{P,G} \frac{dT_{Gas}}{dt} = Q_4 + Q_6 + Q_7$ (2)	
Substrate	$m_S C_{P,S} \frac{dT_{Subsrate}}{dt} = Q_5 + Q_6 + Q_8 + Q_9 + Q_{10}$ (3)	

Q_1 is the heat gain at the level of the biodigester cover made up of solar radiation during the day; Q_2 and Q_3 are the heat exchanges by radiation and convection, respectively, between the cover and the ambient air; Q_4 is the heat transfer between the cover and the biogas by conduction and convection; Q_5 is the heat which is transferred from the slurry to the cover by radiation; $m_G C_{P,G} \frac{dT_{Gas}}{dt}$ represents the energy accumulated in the biogas, where m_G, is the mass of the gas; $C_{P,G}$ is the heat capacity of the gas, and $\frac{dT_{Gas}}{dt}$ is the temperature variation over time; Q_6 is the heat transfer by convection between the biogas and the substrate; Q_7 is the heat loss of the biogas through the walls of the biodigester to the ground; $m_S C_{P,S} \frac{dT_{Substrate}}{dt}$ is the energy accumulated by the substrate; Q_8 and Q_9 are the heat losses of the substrate through the walls and the floor of the biodigester, respectively; and Q_{10} is the heat loss from the storage tank due to daily substrate loading.

2.3 Biogas production

In this study, Chen–Hashimoto model as a function of substrate temperature was used to predict the production of biogas taking into account the influence of the construction materials of the biodigester. The biogas produced by anaerobic digestion of slaughterhouse waste generally contains methane (CH_4) with a typical proportion of 60% [40, 41]. The volume production P_V can be expressed by the following equation [42]:

$$P_V = ([(1–R) *A *S_i]/ (HRT *\alpha_m)) (1–[K_{CH}/ (HRT *\mu_m + K_{CH} –1)]) \quad (4)$$

$$\mu_m = 0.013\ T_{substrate} – 0.129 \quad (5)$$

where, P_V is the volume production or production of biogas per m^3 of fermenter per day, μ_m is the kinetic coefficient (the maximum specific microbial growth rate of microorganisms) (1/day), R is the dimensionless refractory coefficient (experimental non biodegradability based on substrate), S_i is the concentration of substrate in the inflow (kg/m^3), A is the CH_4 production potential (m^3/kg), HRT is the average hydraulic retention time of the effluent in the reactor (day), αm is the mean methane percentage in the produced biogas (%), T substrate is the temperature of the substrate (°C), K_{CH} is the dimensionless inhibition constant which is specific for a given substrate and for a bacterial consortium.

Finally, the daily volume production is calculated as G = P_V * V [43], where G denotes the quantity of biogas produced per day (m^3/day), and V is the useful volume of the fermenter in (m^3).

2.4 Electricity production

The potential for producing electricity from biogas from slaughterhouse waste is given by the following formula [44-46]:

$$E_{biogas}=(C)*(\alpha_m)*(m_{biogas})*(\eta) \quad (6)$$

where, Ebiogas represents quantity of electricity produced (kWh/year), C designates the calorific value of methane (6 kWh/m^3), α_m is the methane content (%) (here in 60% for the slaughterhouse waste), m_{biogas} is the amount of biogas produced per year (m^3/year), η is the conversion efficiency (herein it was assumed to be equal to 30% and 80% for the electrical and thermal energies, respectively) [46].

3. RESULTS AND DISCUSSION

All the results obtained were found by the predictive model developed constituting the heat balance coupled with the hashimoto model. In addition, the evaluation of the reliability of the model is based on the comparison with other research using the same model for the prediction, comparing the results obtained from the model with the experimental data and then using the statistical parameters.

The influences of the properties of the construction materials of the biodigester on the temperature, the production of biogas and the amount of energy produced were explored during the process of anaerobic digestion of the studied substrates (slaughterhouse waste from El Mina).

3.1 Temperature prediction

Figure 2 shows the changes in predicted temperatures for three building materials, on an average day of each month (during four months of study). It can be broadly divided into three zones: (i) zone 1: between 0–9 a.m., (ii) zone 2: between 9 a.m. and 5 p.m., and (ii) zone 3: 5–11 p.m. It could be noted that the monthly average temperatures of the three materials decreased in the first zone (between 0–9 a.m., and then 5-11 p.m.). This decrease might be due to the total absence or low intensity of solar radiation [47, 48]. On the other hand, in the zone 2, the temperatures increased gradually, and this increment was ascribed to the rising of the intensity of the global solar illumination [49]. The maximum temperatures were measured as 47°C, 96 ± 2.5°C, 40.52 ± 2°C, and 34.76 ± 1.5°C, and the minimum temperatures were recorded as 20.07 ± 1.5°C, 20.02 ± 1.2°C, and 21.56 ± 1°C. On the other hand, the average temperatures were monitored as 30°C, 13 ± 1°C, 28.28 ± 0.75°C, and 27.3 ± 0.5°C for biodigesters made of steel, PVC, and concrete, respectively. These results show that the temperatures obtained according to the three construction materials of the digester are totally different despite the hypothesis, which is explained by the effect of the properties of the construction material of the digester on the temperature [50].

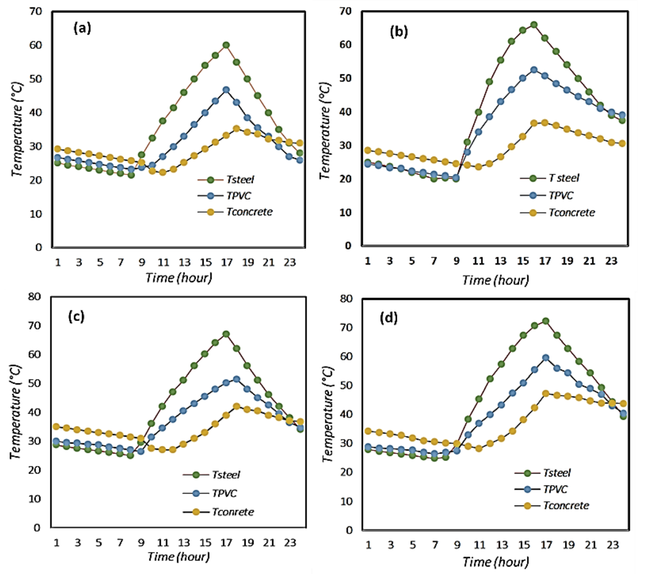

Figure 2. Predicted temperature trends for three types of building materials on an average monthly day during the study period: (a): predicted temperature for an average day in March, (b): predicted temperature for an average day in April, (c): predicted temperature for an average day in May and (d): predicted temperature for an average day in June

3.2 Prediction of biogas production

Figure 3 presents the evolution of biogas predictions according to the construction material such as concrete, PVC plastic and steel, during four months of study.

Overall, it appears that the evolution of this figure presents a similar trend to that of the temperature (Figure 2), which is identical with other research revealing that the increase in temperature leads to an increase in the production of biogas [51, 52] and also the decrease in temperature causes the decrease in the production of biomethane [25]. Specific observations are as follows:

Between 9am to 4pm, the production from the steel digester starts to grow rapidly from 9am and the others from 10am. This observation is justified by the higher thermal conductivity value of the steel fiber, followed by the PVC and finally the concrete one [50]. As a result, the smallest production corresponds to the biogas production of the biodigester built in concrete, because the latter material is the least conductive compared to the other two materials.

Between 16 and 23 o'clock, we can see that the biogas production from the steel digester decreases faster than from the plastic digester (PVC), while the production from the concrete digester decreases slowly. This description is explained by the influence of the characteristic properties of each material.

Despite the use of the assumption, the values of biogas production according to the construction materials of the digesters are not the same, which indicates that the properties of the construction materials have direct or indirect influence on the biogas production. This result is similar to the result obtained by Zhu and his colleagues who show that the properties of materials have effect on the temperature inside (substrate temperature) and according to Hashimoto; this temperature has influence on the biogas production [35, 42, 52, 53].

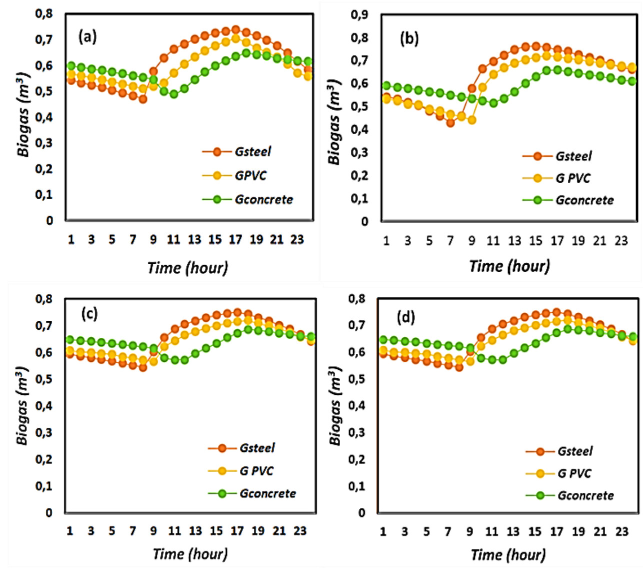

Figure 3. Evolution of the biogas productions predicted according to the construction material for an average monthly day during the study period: (a) production of biogas for an average day in March, (b) production of biogas for an average day in April, (c) production of biogas for an average day in May, and (d) production of biogas for an average day in June

3.3 Electricity production

Figure 4 shows the variations in the amounts of electricity produced monthly from biogas as a function of the three different building materials of the biodigester (steel, PV plastic, and concrete).

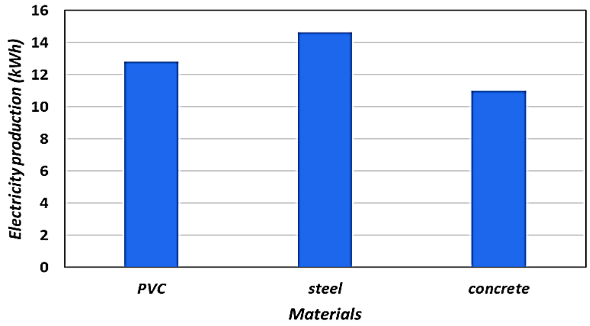

Figure 4. Electricity production from the prototype biodigester with a size of 4 m^3 based on three types of construction materials

3.4 Assessment of the accuracy of the prediction

For the prediction to be accurate, the model to be implemented must be thoroughly validated. The objective is to prove that the model generates good estimates of the values of the variable studied. For this purpose, the use of the coefficients of determination (R^2) and the relative root mean squared error (rRMSE) was designed by Triolo and his colleagues [53]. The evolution of the predicted and measured temperature has coefficient of determination of 0.96 and relative square error of 7.4% is presented in Figure 5, moreover, the value of coefficient of determination is bigger and the value of square error is smaller comparing with terrada and his colleagues [39].

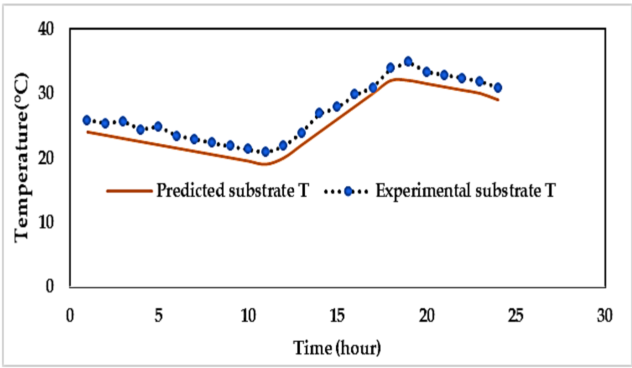

Figure 5. Evolution of predicted and experimental temperatures for a concrete digester on an average day in March

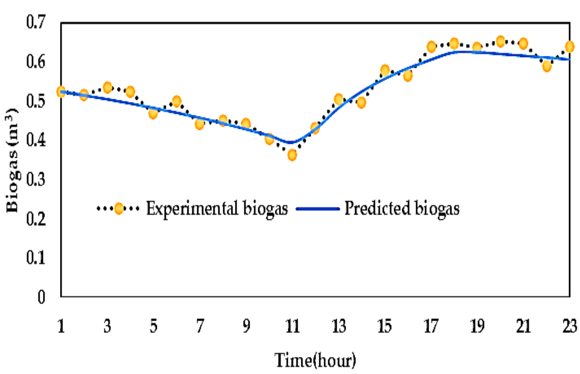

Figure 6. Evolution of predicted and experimental biogas production for a concrete digester on an average day in March

Figure 6 shows the predicted biogas production versus the measured production showed that the prediction is quite accurate, i.e., the R^2 value for the prediction of biogas production is 0.92 and the relative square error is 8.3% this result is similar with Triolo and colleagues and Madsen and colleagues [54-56]. In addition, this precision is identical for the four months of the study.

4. CONCLUSIONS

Accurately estimating greenhouse gas emissions from anaerobic digestion by sampling is a difficult task due to the large area in conjunction with the complex and dynamic behavior included in the process. In this perspective, a systematic use of appropriate predictive models is a major element for better monitoring of biogas installations and the dissemination of this technology. On the basis of the experimental data collected from a prototype of a 4 m^3 concrete biodigester built at the FST of the UNA (Mauritania), a thermal model based on heat transfer and the properties of the construction materials of was developed to predict the rate of biogas production from the anaerobic digestion of slaughterhouse waste. Based on the results obtained within the scope of the present study, the following conclusions can be drawn:

(1) According to the comparative computational analysis carried out based on three building materials (steel, PVC plastic, and concrete), the results revealed that the steel construction yielded better performance on prediction of both the cumulative methane production and methane production rate.

(2) The PVC plastic construction provided a higher biogas production rate than concrete construction. The average temperatures were found as 35.21 ± 1.5℃, 33 ± 1℃, and 30.1 ± 0.5℃, respectively, for steel construction, PVC plastic, and concrete.

(3) The differences in the obtained values of the results were explained by the influence of the properties (conductivity, emissivity, density, capacity, and so forth) of each construction material.

(4) The proposed steel construction material produced a higher average amount of electricity (14.64 kWh) than those obtained for PVC plastic (12.81 kWh) and concrete (10.98 kWh) materials. Therefore, the steel was considered as the best construction material for the present study.

(5) The proposed model gave rRMSE values between 7.4 and 8.3% and R^2 between 0.92 and 0.96.

(6) Engineers and decision makers may utilize the quantitative results obtained in the current research to determine the most suited biodigester setup depending on their demands. Given the positive findings achieved, the suggested biodigester technology may find further particular applications for biogas, electricity, bioslurry, and fertilizer production from different organic matter-rich substrates, allowing African countries to better evaluate and prioritize their renewable energy and biowaste potentials.

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NOMENCLATURE

A	methane production potential (m^3/kg)
C	calorific value of methane (6 kWh/m^3)
c_P	specific heat (J/(kg·K))
dt	time interval (s)
k	kinetic constant
L	characteristic length (m)
m	optical air-mass number
m_{gas}	massflow rate of the biogas (kg)
m_{load}	slurry feeding massflow (kg)
m_s	massflow rate of the slurry (kg)
T_{air}	air temperature (K)
T_{cover}	temperature of the cover (K)
T_{dig}	temperature of the digester's floor (K)
T_{gas}	temperature of the gas (K)
T_{slurry}	temperature of the slurry inside the digester (K)
V_{gas}	gas volume (m^3)
M	moisture
TS	total solids
VS	volatile solids

Greek symbols

α	absorbance for cover, thermal diffusivity for the cover (m^2/s)
β	expansion coefficient (1/K)
ε	coefficient of emissivity
λ	thermal conductivity (W/(m·K))
μ	dynamic viscosity (Pa·s)
μ_m	maximum specific growth rate (1/day)
ρ	density (kg/m^3)
υ	kinematic viscosity (m^2/s)

Abbreviations

AD	Anaerobic digestion
C/N	Carbon to nitrogen ratio
CH_4	Methane
CO_2	Carbon dioxide
FST	Faculty of Sciences and Techniques
H_2	Hydrogen gas
kWh	Kilowatt-hour
MATLAB	MATrix LABoratory
O_2	Oxygen gas
OLR	Organic loading rate
PVC	Polyvinyl chloride
UNA	University of Nouakchott Al Aasriya
VFAs	Volatile fatty acids