World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

Check for updates

MODELLING BIOGAS RECOVERY FROM ANAEROBIC DIGESTION OF SEWAGE SLUDGE: TEMPERATURE CALIBRATION AND VALIDATION OF A COD MASS-BALANCE MODEL

Greg. U. Nwigwe *, Herbert. U. Nwoke and Robert. O. Onosakponome

Department of Civil Engineering, Federal University of Technology, Owerri, Imo State, Nigeria.
* Corresponding Author

ORCID Details
Herbert. U. Nwoke: https://orcid.org/0000-0003-2856-4660
Robert O. Onosakponome: https://orcid.org/0000-0002-2112-9925
Greg U. Nwigwe*(Corresponding Author): https://orcid.org/0009-0004-2918-1711

World Journal of Advanced Research and Reviews, 2026, 32(02), 265–269

Publication history: Received on 22 September 2026; revised on 01 November 2026; accepted on 03 November 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.32.2.2810

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

Anaerobic digestion recovers energy from sewage sludge as biogas, but predicting yield without lengthy digester trials remains difficult. This study calibrated a chemical oxygen demand (COD) mass-balance model for methane recovery and tested it against independently published digester data. The standard Metcalf and Eddy COD-balance equation was calibrated for temperature by replacing its 0°C methane conversion factor (0.35L CH_4 per g COD) with the 35°C value (0.40L CH_4 per g COD), derived from the ideal gas law. Daily gas yields (mL/g VS) were taken from two semi-continuous laboratory reactors fed sewage sludge from the Wupa wastewater treatment plant, Abuja, Nigeria, and operated at 35°C for 16 days. Model output was compared with the observed yields using Pearson correlation (r), mean absolute percentage error (MAPE) and root mean square error (RMSE). Model and observed yields agreed closely: r = 0.983, MAPE = 1.34% and RMSE = 5.40 mL/g VS for Reactor 1, and r = 0.972, MAPE = 1.62% and RMSE = 5.68 mL/g VS for Reactor 2. The model under-predicted the mean yield by 3.3 and 3.7 mL/g VS (about 1%), which errs on the safe side for design. The temperature-calibrated model reproduced the rise, peak and decline of daily yield over the 16-day trial and can support preliminary sizing and energy-recovery estimates for mesophilic sludge digesters. Validation rests on a single short trial, so further testing on independent datasets and at larger scale can be considered.

Keywords: Anaerobic Digestion; Biogas; Sewage Sludge; Mathematical Modelling; Model Calibration; Energy Recovery

1 INTRODUCTION

Wastewater treatment generates large quantities of sludge that must be stabilized before disposal, and sludge handling can account for a large share of plant operating cost [1,2]. Treatment plants are also among the largest electricity consumers in a municipality [3]. Anaerobic digestion (AD) addresses both problems: it stabilizes sludge, reduces solids and pathogens, and converts organic matter into biogas, a mixture of methane and carbon dioxide that can fuel

combined heat and power units [2,4]. In many developing countries, including Nigeria, wastewater treatment infrastructure rarely captures this energy, and reliable design tools for estimating recoverable biogas are scarce.

Biogas production depends on feedstock biodegradability, operating temperature, retention time, pH and loading [5,6]. Detailed kinetic models such as ADM1 describe these processes mechanistically but need many parameters that are rarely measured at small plants [7]. Simpler design models based on a steady-state COD balance are widely used in practice because they need only influent and effluent biodegradable COD (bCOD), flow rate and biomass yield [8]. A central constant in this approach is the volume of methane produced per unit of COD converted, which is quoted at 0°C and 1 atm (0.35L CH_4/g COD). Digesters, however, run at mesophilic temperatures near 35°C, where a mole of gas occupies a larger volume, so the unadjusted constant understates the volume actually produced.

The objectives of this study were: (i) to calibrate the COD mass-balance methane model for an operating temperature of 35°C; (ii) to apply it to published daily data from sewage-sludge digesters at the Wupa treatment plant, Abuja; and (iii) to validate its predictions statistically against the observed gas yields.

2 MATERIALS AND METHODS

2.1 Source of experimental data

The experimental data were taken from a published laboratory study of ultrasound-assisted digestion of municipal sewage sludge from the Wupa sewage treatment plant, Abuja, Federal Capital Territory, Nigeria [9]. This study did not repeat the experiment; it modelled and re-analyzed the published values. In the original work, fresh waste activated sludge and partly digested sludge were collected from the plant and divided into four portions feeding four Erlenmeyer flask reactors, two receiving ultrasound-treated sludge (420 W probe) and two receiving untreated sludge. The reactors were covered with black plastic, kept in a 35°C water bath and operated in semi-continuous mode, with feeding once per feeding day over a 16-day period. Biogas was collected over acidified water to prevent CO_2 dissolution, and gas volume was measured by water displacement. Total solids (TS), volatile solids (VS), filtered COD and pH were determined by standard methods [9]. The daily gas yields of the two test reactors, referred to here as Reactor 1 and Reactor 2, were used for validation.

2.2 COD mass-balance model

Following the design approach for completely mixed suspended-growth anaerobic processes [8], influent COD is partitioned among effluent COD, COD incorporated into cell tissue and COD converted to methane:

$$COD_{in} = COD_{eff} + COD_{VSS} + COD_{CH4} \quad (1)$$

Net biomass production P_x (kg/d) was estimated from:

$$P_x = [\, Y\, Q\, (S_0 - S) \cdot 10^{-3} \,] \,/\, [\, 1 + k_d \cdot \mathrm{SRT} \,] \quad (2)$$

where Y is the synthesis yield coefficient (g VSS/g bCOD), Q the flow rate (m^3/d), S_0 and S the influent and effluent bCOD (mg/L), k_d the endogenous decay coefficient (d^{-1}, typically 0.02–0.04) and SRT the solids retention time, which equals the hydraulic retention time in a complete-mix digester without recycle. The volume of methane produced per day is then

$$V_{CH4} = f_T\, [\, (S_0 - S)\, Q \cdot 10^{-3} - 1.42\, P_x \,] \quad (3)$$

where 1.42g COD/g VSS is the oxygen equivalent of cell tissue and f_T is the methane conversion factor (m^3 CH_4 per kg COD converted). The original formulation uses f_0 = 0.35 at 0 °C and 1 atm [8].

2.3 Temperature calibration

Complete oxidation of methane requires 2mol O_2 per mole CH_4 ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$), so each mole of methane corresponds to 64g COD. The molar volume of an ideal gas follows from V = nRT/P, with R = 0.082057 L·atm/(mol·K).

At 0°C (273.15 K) and 1 atm, V = 22.414 L/mol, giving 22.414/64 = 0.35L CH_4/g COD.

At 35 °C (308.15 K), V = 25.29 L/mol, giving 25.29/64 = 0.395, rounded to 0.40L CH_4/g COD.

The calibrated model therefore uses f_T = 0.40 in Equation 3.

The 35°C value matches the operating temperature of the reference experiment.

2.4 Model inputs and unit conversion

For each day, the influent and effluent bCOD, flow rate and net cell-tissue production recorded for Reactors 1 and 2 in the source experiment were entered into Equation 3 to generate Model Reactor 1 and Model Reactor 2. Model output (m^3/d) was converted to mL/g VS by multiplying by 10^6 and dividing by the mass of VS fed (g), so that it matched the units of the experimental yields.

2.5 Statistical validation

Agreement between experimental (E_t) and modelled (M_t) daily yields over n = 16 days was assessed with three measures. The Pearson correlation coefficient (r) measures linear association; the mean absolute percentage error (MAPE) measures average relative error; and the root mean square error (RMSE) measures average error in the units of yield:

$$r = [\, n\Sigma E_t M_t - \Sigma E_t \, \Sigma M_t \,] \,/\, \sqrt{\{\, [\, n\Sigma E_t^2 - (\Sigma E_t)^2 \,]\, [\, n\Sigma M_t^2 - (\Sigma M_t)^2 \,]\,\}} \qquad (4)$$

$$\text{MAPE} = (100/n)\, \Sigma\, |E_t - M_t| \,/\, E_t \qquad (5)$$

$$\text{RMSE} = \sqrt{[\, (1/n)\, \Sigma\, (E_t - M_t)^2 \,]} \qquad (6)$$

Values of r above 0.90 and MAPE below 10% were taken as indicating strong agreement. All statistics were computed directly from the paired daily values in Table 2.

3 RESULTS AND DISCUSSION

3.1 Quality of the experimental data

The sludge feeding the reactors had TS of 1.1–3.3% (mean 2.2%), VS of 62–63% of TS (mean 62.5%) and pH 7.4–7.5 (Table 1). The methane content of the biogas was stable at 58.5% in both reactors, within the usual range for sewage-sludge digestion of about 55–70% [4]. Reactor pH stayed at 7.3–7.7 (Reactor 1) and 7.4–7.6 (Reactor 2), and organic acid concentrations were below 100 mg/L, indicating that neither reactor was overloaded. Effluent TS was nearly constant at about 2.5%. The reported VS reduction was 31% in Reactor 1 and 33% in Reactor 2, below the 50–65% typical of well-operated digesters, which is expected for a short, high-loading trial designed mainly to study gas production [9]. The mean yield of 293 mL/g VS on days 7–12 fell in the lower part of the range reported in the literature, so the gas measurements were considered plausible.

Table 1: Characteristics of the digested sludge making up the inoculum [9]

Digestion chamber	TS (%)	VS (% of TS)	pH
1	3.3	62	7.4
2	1.1	63	7.5

3.2 Model performance

Table 2 lists the daily experimental and modelled yields, and Figure 1 plots them. Both reactors followed the same pattern in experiment and model: yield rose over the first week, peaked (Reactor 1 at 325 mL/g VS on days 7 and 13 experimentally, and 327 mL/g VS on day 13 in the model), dipped in the second half of the first fortnight and recovered. The model therefore captured the rise, peak and decline phases of gas production, not only the overall level.

Table 2: Daily gas yield (mL/g VS): experimental (Exp.) and model results for Reactors 1 (R1) and 2 (R2)

Day	Exp. R1	Model R1	Exp. R2	Model R2
1	256	248	270	266
2	256	252	279	277
3	281	280	289	281
4	281	281	289	284

5	290	283	298	299
6	295	296	298	299
7	325	312	300	300
8	314	314	282	280
9	285	275	285	287
10	304	300	257	248
11	295	296	257	249
12	322	323	285	288
13	325	327	295	290
14	322	318	314	309
15	311	309	309	304
16	311	306	285	272

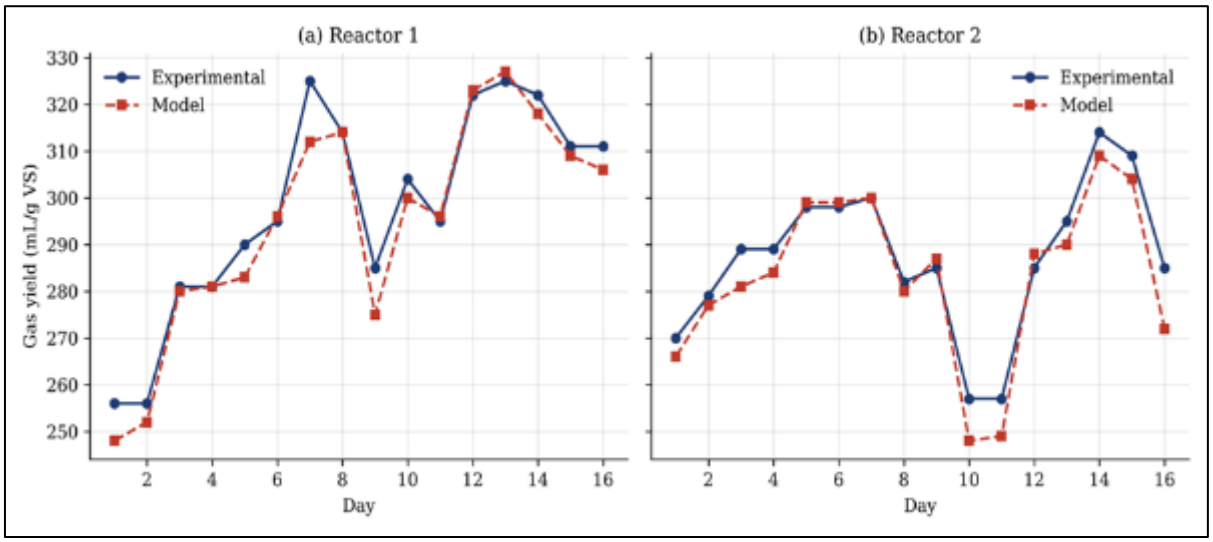

Figure 1: Daily gas yield from experimental and model reactors over 16 days: (a) Reactor 1; (b) Reactor 2.

Statistical results are in Table 3. Correlation exceeded 0.97 in both reactors, MAPE was below 2%, and RMSE was about 5–6 mL/g VS, under 2% of the mean yield. These values are well inside the benchmarks adopted in Section 2.5.

Table 3: Validation statistics for the temperature-calibrated model (n = 16 days)

Reactor	r	MAPE (%)	RMSE (mL/g VS)	Mean bias, E − M (mL/g VS)
1	0.983	1.34	5.40	+3.3
2	0.972	1.62	5.68	+3.7

The mean experimental yield exceeded the mean modelled yield by 3.3 mL/g VS (1.1%) in Reactor 1 and 3.7 mL/g VS (1.3%) in Reactor 2, and the model under-predicted on 12 of the 16 days in each reactor. Because over-estimation of gas yield would overstate recoverable energy and could lead to under-sized storage or over-sized generators, a small systematic under-prediction is the safer error for design. The bias is small, however, and should not be treated as a built-in safety factor; independent data would be needed to confirm its direction.

3.3 Effect of temperature calibration

Moving from 0.35 to 0.40L CH_4/g COD raises predicted volumes by about 14%, the ratio of the molar gas volumes at 308.15K and 273.15K. Without this correction the model would under-predict gas at a digester temperature of 35°C by that margin. The calibration needs no new empirical parameter; it follows from gas-law physics, so it can be applied to any other digester temperature by recalculating the molar volume.

Limitations

Three limitations should be noted. First, the validation uses one 16-day laboratory trial from a single plant, with model inputs (bCOD, flow, P_x) taken from the same experiment, so the test shows consistency rather than predictive power on new feedstocks. Second, Equation 3 estimates methane volume, whereas the reference study reports gas yield per gram VS; the comparison implicitly assumes that the reported yields are comparable with the model output on the same basis, and the 58.5% methane content should be considered if biogas volume is the quantity of interest. Third, the reactors were small, fed dilute sludge (TS 1.1–3.3%) and run for a short time, so the model has not been tested on thickened sludge, at other temperatures or at full scale. Repeating the validation on independent datasets, including thickened sludge (for example TS of 5–7%) and full-scale plant records, is recommended.

4 CONCLUSION

A COD mass-balance model for methane recovery from sewage-sludge digestion was calibrated for 35°C by correcting the methane conversion factor from 0.35 to 0.40L CH_4/g COD. Against published daily yields from two laboratory reactors at the Wupa plant, Abuja, the model gave r of 0.983 and 0.972, MAPE of 1.34% and 1.62%, and RMSE of 5.40 and 5.68 mL/g VS, reproducing both the level and the day-to-day pattern of gas production. The model slightly under-predicted mean yield (by about 1%). It offers a simple, low-data tool for preliminary estimation of biogas energy recovery at mesophilic sludge digesters. Its use for design should await validation on independent and larger-scale datasets.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors are thankful to the anonymous reviewers of this work.

Disclosure of conflict of interest

The authors declare no conflict of interest.

REFERENCES

[1] Lee DH, Behera SK, Kim JW, Park HS. Methane production potential of leachate generated from Korean food waste recycling facilities: a lab-scale study. Waste Manag. 2009;29(2):876-882.

[2] Appels L, Baeyens J, Degrève J, Dewil R. Principles and potential of the anaerobic digestion of waste-activated sludge. Prog Energy Combust Sci. 2008;34(6):755-781.

[3] Hoornweg D, Bhada-Tata P. What a waste: a global review of solid waste management. Washington (DC): World Bank; 2012.

[4] Nikolausz M, Kretzschmar J. Anaerobic digestion in the 21st century. Bioengineering. 2020;7(4):157.

[5] Chae KJ, Jang A, Yim SK, Kim IS. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour Technol. 2008;99(1):1-6.

[6] Holm-Nielsen JB, Al Seadi T, Oleskowicz-Popiel P. The future of anaerobic digestion and biogas utilization. Bioresour Technol. 2009;100(22):5478-5484.

[7] Batstone DJ, Keller J, Angelidaki I, Kalyuzhnyi SV, Pavlostathis SG, Rozzi A, et al. The IWA Anaerobic Digestion Model No 1 (ADM1). Water Sci Technol. 2002;45(10):65-73.

[8] Metcalf & Eddy Inc. Wastewater engineering: treatment and reuse. 4th ed. New York: McGraw-Hill; 2003.

[9] Onyenobi CS, Chukwuneke LJ, Achebe HC, Okolie CP. Biogas production from municipal sewage sludge using ultrasound speeding digestion process. Int J Sci Eng Investig. 2013;2(15):109-118.