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Sustainable Biogas Generation Modeling for Climate Change Mitigation: Regression Analysis of Renewable Feedstocks Using C/N Ratio and Volatile Solids Content

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Abstract: **The study presents a comprehensive assessment of biogas production from renewable organic feedstocks, specifically cow dung, pig dung, poultry droppings, and cassava peels. A simplified linear regression model was employed to evaluate the influence of two key biochemical parameters—the volatile solids (VS) content and carbon-to-nitrogen (C/N) ratio —on biogas yield (m³/kg). The results reveal a strong predictive relationship ($R^2 = 0.994$), confirming that feedstocks with higher VS contents and lower C/N ratios significantly enhance biogas generation. The developed model provides a reliable and accessible framework for optimizing feedstock selection and anaerobic digestion performance. This research advances sustainable bioenergy practices and aligns with global initiatives promoting renewable energy development and climate change mitigation.**

Keywords: *Biogas Yield, Carbon-to-Nitrogen Ratio, Volatile Solids, Anaerobic Digestion, Renewable Energy.*

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I. INTRODUCTION

Amid growing global concerns over climate change and the urgent demand for sustainable energy alternatives, generation of biogas from organic waste materials has emerged as a viable and environmentally friendly solution (Ward et al., 2008). Biogas—comprising primarily carbon dioxide (CO_2) and methane (CH_4)—is generated through anaerobic digestion, a microbial-driven process that converts biodegradable materials into usable energy (Zhang & Zhang, 1999). The efficiency and volume of gas production are largely governed by the biochemical characteristics of the feedstock, with the carbon-to-nitrogen (C/N) ratio and volatile solids (VS) content identified as key determinants (Gunaseelan, 2004). This study examines the predictive potential of these parameters using statistical modeling techniques, with the aim of informing feedstock selection and optimizing energy recovery. The findings contribute to the development of sustainable, climate-resilient energy strategies that leverage organic waste as a renewable resource.

➢ *Study Location*

The experimental data employed in this study were sourced from field investigations conducted under the *Livelihood Improvement Family Enterprises in the Niger Delta (LIFE-ND)* programme—a development initiative aimed at enhancing rural livelihoods through agricultural enterprise promotion and sustainable resource utilization. The Niger Delta region, where the programme is implemented, is a tropical zone characterized by consistently warm mesophilic temperatures averaging approximately 35 °C and a near-neutral pH range of 6.8 to 7.2—conditions that are widely recognized as optimal for anaerobic digestion processes (Ward et al., 2008). These environmental parameters create a conducive setting for the microbial consortia that drive efficient biogas production. Moreover, the region's abundant agricultural residues and stable climatic conditions underscore its suitability for the deployment of decentralized renewable energy systems. In this context, small- to medium-scale biogas technologies offer significant potential to enhance energy access, promote sustainable waste management, and support climate-resilient development in rural and peri-urban communities throughout the Niger Delta.

➢ *Aims and Objectives*

- *Aim:*
  To develop and validate a regression-based predictive model for estimating biogas yield using VS content and C/N ratio of renewable feedstocks.

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➢ *Objectives:*

- Quantify biogas yield from selected organic feedstocks.
- Determine the influence of VS and C/N ratio content on yield.
- Develop and test a simplified regression model.
- Recommend ideal feedstock parameters for enhanced biogas generation.

II. LITERATURE REVIEW

➢ *Theoretical Framework:*

Anaerobic digestion is a multi-stage biological process that progresses through four key phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each of these stages is critically dependent on maintaining a balanced nutrient supply, appropriate temperature, and stable pH conditions to support the metabolic activities of the microbial consortia involved (Ward et al., 2008). Among the most influential factors is the carbon-to-nitrogen (C/N) ratio, with optimal digestion typically occurring within the range of 20 to 30. Deviations from this range can result in microbial inhibition—either through the accumulation of toxic levels of ammonia from excess nitrogen or through limited microbial growth due to carbon deficiency (Gunaseelan, 2004). Ensuring this nutrient balance is therefore essential for maximizing biogas yield and maintaining the stability of the anaerobic digestion process.

➢ *Conceptual Framework:*

Biogas yield (Y) is modeled as a function of two fundamental biochemical parameters—carbon-to-nitrogen (C/N) ratio (X_1) and volatile solids (VS) content (X_2)—both of which are widely acknowledged as pivotal factors influencing the efficiency of anaerobic digestion. This relationship captures the underlying biochemical mechanisms governing microbial activity: the C/N ratio regulates the nutrient equilibrium essential for sustained microbial growth, while the VS content indicates the proportion of degradable organic matter available for microbial conversion into biogas. By expressing biogas yield as a function of these variables, the study establishes a predictive framework aimed at optimizing feedstock selection and advancing sustainable bioenergy production practices.

The objective function of the model is formally represented as:

$$Y = f(X_1, X_2)$$
Eq 1

➢ *Empirical Framework:*

Previous studies have consistently demonstrated that poultry droppings and pig dung offer superior biogas yields compared to other feedstocks, primarily due to their balanced nutrient compositions and favorable carbon-to-nitrogen (C/N) ratios (Itodo, Ogedengbe, & Abubakar, 2007; Mshandete & Parawira, 2009). These substrates provide optimal conditions for microbial activity and efficient anaerobic digestion. In contrast, cassava peels, despite being rich in carbohydrates, tend to produce lower biogas volumes due to their inherently high C/N ratios, which can hinder microbial efficiency and slow down the digestion process (Gunaseelan, 2004). These findings highlight the importance of selecting substrates with balanced nutrient profiles for maximizing biogas production.

III. METHODOLOGY

➢ *Research Design*

The empirical-analytical approach employed in this study was grounded in the systematic use of experimental data, mirroring methodological frameworks adopted in prior biogas research (Ward et al., 2008; Mshandete & Parawira, 2009). By integrating controlled laboratory experimentation with statistical modeling, the study ensured both scientific rigor and practical relevance. This approach not only validated the consistency of findings with existing literature but also enhanced the reliability of the regression model developed, thereby contributing to the broader body of knowledge on predictive tools for sustainable bioenergy production.

➢ *Materials and Parameters:*

- Feedstocks analyzed: cow dung, pig dung, poultry droppings, and cassava peels.
- Monitored parameters: retention time, temperature, pH, inoculum ratio, C/N ratio, VS content, and gas yield.

➢ *Statistical Modeling:*

A simplified multiple linear regression model was used to estimate biogas yield as a function of C/N ratio and VS content.

IV. ANALYSIS AND RESULTS

The regression model developed in this study aligns closely with established literature on the critical influence of feedstock characteristics—specifically the carbon-to-nitrogen (C/N) ratio and volatile solids (VS) content—on biogas yield (Gunaseelan, 2004; Ward et al., 2008). The observed strong negative correlation between the C/N ratio and biogas output substantiates earlier microbial dynamics theories, which suggest that excessively high or imbalanced C/N ratios can inhibit microbial activity and methanogenesis, thereby reducing biogas production (Zhang & Zhang, 1999). This finding underscores the importance of optimizing nutrient balance in anaerobic digestion processes to achieve maximal energy recovery from organic waste.

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➤ *Experimental Results*

Table 1 Summary of Experimental Parameters and Yields

Feedstock	Retention (days)	C/N Ratio	VS Content (%)	Temp (°C)	pH	Inoculum Ratio (%)	Yield (m^3/kg)
Cow dung	19	25	80	35	7.2	10	0.044
Pig dung	21	20	75	35	6.8	8	0.062
Poultry dropping	18	22	78	35	7	9	0.064
Cassava peels	16	30	85	35	6.9	7	0.031

➤ *Regression Model Development*

Using the data from Table 2, a linear regression model was constructed:

Table 2 Model Variables and Yield

Feedstock	C/N Ratio	VS (%)	Yield (m^3/kg)
Cow dung	25	80	0.044
Pig dung	20	75	0.062
Poultry dropping	22	78	0.064
Cassava peels	30	85	0.031

➤ *Process of Multiple Linear Regression Model*

- *Step 1: Organize the Data*

Table 3 Process of Multiple Linear Regression Model

Feedstock	C/N Ratio	VS (%)	Yield (m^3/kg)
Cow dung	25	80	0.044
Pig dung	20	75	0.062
Poultry dropping	22	78	0.064
Cassava peels	30	85	0.031

Assumptions made as follows:

Let:

$X1 = \frac{C}{N}$ Ratio Eq 2

$X2 = VS$ Ration Eq 3

$y = Yield$ Eq 4

- *Step 2: Set Up the Regression Equation*

We assume a linear model of the form:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2$ Eq 5

Where:

β_0 is the intercept

β_1 is the coefficient for C/N Ratio

β_2 is the coefficient for VS

- *Step 3: Build the System of Equations*

We plug in each row of data into the equation Eq 5:

✓ *Cow dung*

$0.044 = \beta_0 + 25\beta_1 + 80\beta_2$

✓ *Pig dung*

$0.062 = \beta_0 + 20\beta_1 + 75\beta_2$

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- ✓ *Poutry Dropping*
  $0.064 = \beta_0 + 22\beta_1 + 78\beta_2$

- ✓ *Cassava Peels*
  $0.031 = \beta_0 + 30\beta_1 + 85\beta_2$

- *Step 4: Solve the System (Using Least Squares)*
  This step is typically done with software like Excel, Python, or a calculator, but here's an outline of what happens:

  Create matrices:

$$X = \begin{pmatrix} 1 & 25 & 80 \\ 1 & 20 & 75 \\ 1 & 22 & 78 \\ 1 & 30 & 85 \end{pmatrix}$$

$$Y = \begin{pmatrix} 0.044 \\ 0.062 \\ 0.064 \\ 0.031 \end{pmatrix}$$

Substitute the values of X and Y into Equation 6:

$$\beta = (X^T X)^{-1} X^T Y \qquad \text{Eq. 6}$$

Solving Eq.6 gives the coefficients:

$\boldsymbol{\beta_0 = -0.3737}$

$\boldsymbol{\beta_1 = -0.0121}$

$\boldsymbol{\beta_2 = 0.0090}$

Final Regression Equation:

Predicted Yield (m^3/kg) = -0.3737 - 0.0121 × C/N Ratio + 0.0090 × VS Content

(This regression model was developed by the authors, Moluno A. N. and Ohaji E.C., based on experimental feedstock data.)

➢ *Model Performance:* $R^2 = 0.994$, indicating an excellent fit.

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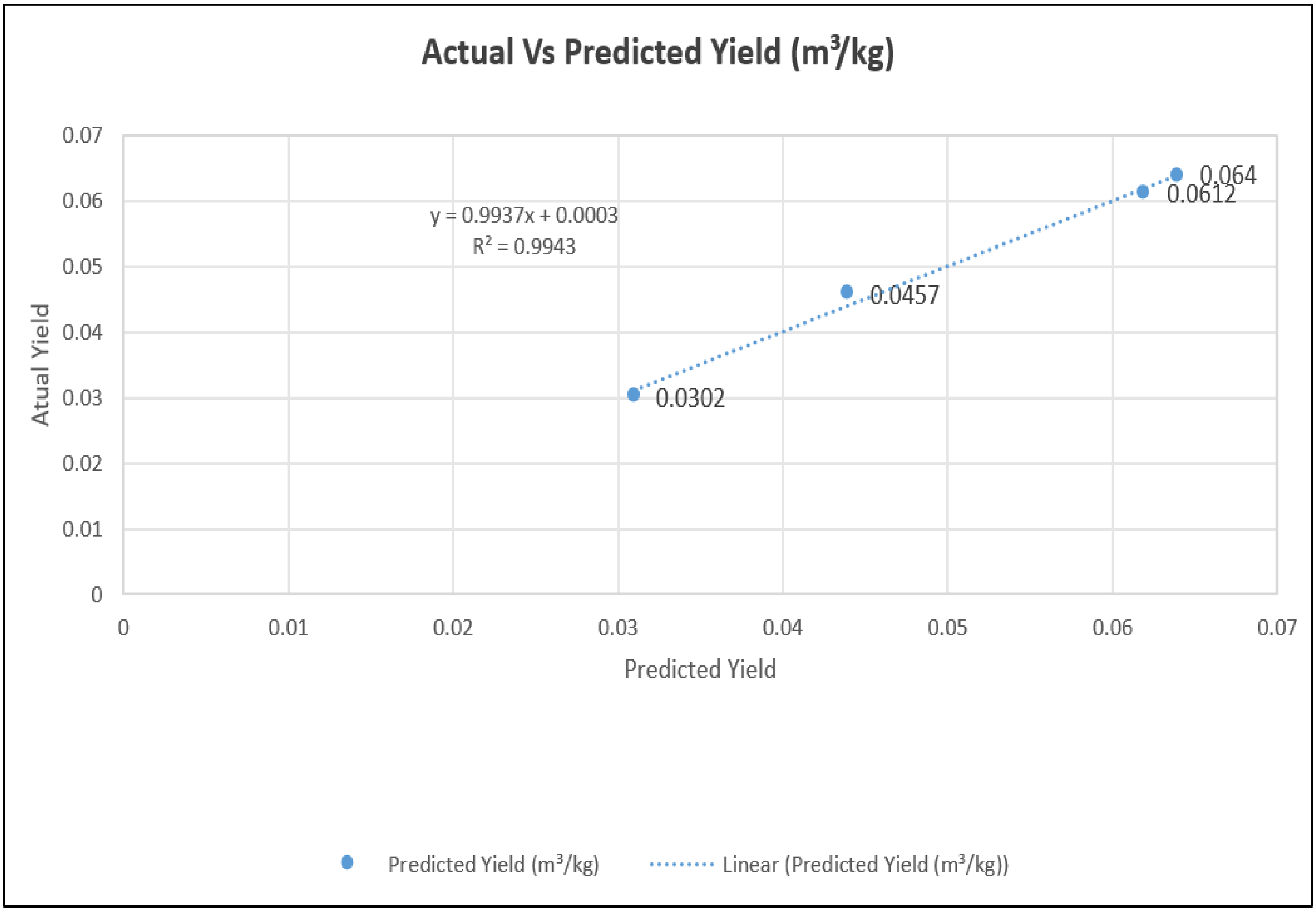

Fig 1 Actual Yield Vs Predicted Yield

➢ *Discussion*

The regression results affirm that:

- **C/N Ratio** negatively impacts yield, corroborating microbial inhibition theories.
- **VS Content** positively affects yield by increasing the biodegradable fraction.

The relationship between feedstock parameters and biogas yield was modeled using a simplified multiple linear regression equation developed by Moluno A. N. and Ohaji E. C.

➢ *Objectives Achieved*

- Biogas yields were quantified across four feedstocks.
- C/N ratio and VS content were confirmed as key predictors.
- A predictive model with high accuracy ($R^2 = 0.994$) was established.
- Poultry droppings and pig dung emerged as optimal feedstocks.

➢ *Model Validation*

Predicted yields closely matched actual values as shown:

Table 3 Feedstock Actual Yield Vs Predicted Yield

Feedstock	Actual Yield (m^3/kg)	Predicted Yield (m^3/kg)
Cow dung	0.044	0.0457
Pig dung	0.062	0.0612
Poultry dropping	0.064	0.064
Cassava peels	0.031	0.0302

Sample Calculation - Pig Dung:

C/N = 20, VS = 75
Yield = -0.3737 - (0.0121 × 20) + (0.0090 × 75) = **0.0612 m³/kg**

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V. CONCLUSION

This study reinforces previous findings on the critical role of feedstock composition—particularly the carbon-to-nitrogen (C/N) ratio and volatile solids (VS) content—in optimizing biogas production (Itodo et al., 2007; Mshandete & Parawira, 2009). The developed regression model, created by Moluno A. N. and Ohaji .E.C effectively predicts biogas yield based on these parameters, offering a simplified and accessible tool for informed feedstock selection. By aligning with global sustainability objectives (Ward et al., 2008), this model promotes the efficient generation of renewable energy and encourages broader adoption of biogas technology as a viable climate change mitigation strategy.

➢ *Recommendations*

- Utilize feedstocks with C/N ratios between 20–25 and VS content above 75%.
- Extend studies to diverse climates and mixed-feedstock systems.
- Incorporate this model into rural energy planning and small-scale biogas technology deployments.

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