



Evaluation of Biogas Production from Wastewater Treatment Plants in Owerri Municipality

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How to cite this paper: Okebaram, P.N., Uzoigwe, L.O., Onyewudiala, J.I. and Okwe, G.I. (2026) Evaluation of Biogas Production from Wastewater Treatment Plants in Owerri Municipality. *Open Access Library Journal*, **13**: e15976. <https://doi.org/10.4236/oalib.1115976>

Received: September 1, 2026

Accepted: October 6, 2026

Published: October 9, 2026

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Abstract

The unabated energy crisis, growing volume of wastewater and poor waste management system have been an issue of utmost concern. In this research, biogas production potentials from wastewater sludge of the two wastewater treatment plants (WWTPs) plants A (Aladinma) and B (Ikenegbu) of Owerri Municipality were examined, evaluated and the socio-economic benefits were evaluated by using BioWin and MATLAB softwares. The chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), total suspended solids (TSS), and volatile suspended solids (VSS) were used for the characterization of wastewater sludge samples. The measured parameters were used in BioWin for modelling anaerobic digestion for different operating conditions such as temperature, retention time, organic loading rate (OLR) and influent COD concentration. Then, MATLAB software was used for numerical calculation, graphical representation, sensitivity analysis, comparison analysis and energy-economic-environmental calculation benefits. The BioWin simulation predicted a biogas production of 700 m³/day from Aladinma and 850 m³/day from Ikenegbu, resulting in a total production of 1550 m³/day. Average concentration of methane was 60.5% and specific yield of methane was 0.16 - 0.19 m³ CH₄/kg COD removed. Among the measured parameters, MATLAB sensitivity analysis revealed that the temperature and the influent COD concentration were the most significant parameters for methane production. Total electrical-energy recovery potential of the two plants was 1.14 GWh/year, which corresponds to roughly 39.5% of the total electrical energy demand. Electricity-cost savings were calculated at an electricity tariff of ₦120/kWh, and approximated at an annual electricity cost saving of roughly ₦136.7 million, with an estimated

payback period of 3 - 5 years. The study also calculated a greenhouse-gas mitigation of about 574 tonnes CO₂-equivalent per year. The findings confirmed that wastewater sludge is a good renewable-energy resource, and the integrated BioWin-MATLAB framework can be effectively used as a basis for the optimization of biogas production and assessment of the technical, economic and environmental potential of wastewater-to-energy systems in Nigeria.

Subject Areas

Environmental Sciences

Keywords

Anaerobic Digestion, BioWin Simulation, Biogas Production, Matlab Software

1. Introduction

The need for reliable, affordable and sustainable energy has grown along with the world's rising demand to find alternative energy sources that can satisfy socio-economic development needs without causing environmental degradation. Wastewater treatment plants (WWTPs), which are mainly viewed as pollution control plants, have substantial amounts of chemical energy available in their wastewater and sewage sludge. The anaerobic digestion method is a proven technology that can be used to produce biogas, mainly composed of methane (CH₄) and carbon dioxide (CO₂) [1] [2].

Pumping, aeration, sludge processing and other treatment processes, make municipal wastewater treatment generally energy intensive. The organic matter that is removed when wastewater is treated could be a source of energy. This energy can be recovered in an Anaerobic Digester, which can decrease the electricity that needs to be imported from outside sources, and help towards the creation of more sustainable and energy efficient wastewater treatment systems [3] [4]. In developing nations, the potential for making biogas from wastewater is underutilized due to lack of infrastructure, funding, technical capability and integration between wastewater and renewable energy project planning.

The electricity supply situation remains difficult, urbanization rates are rising, the amount of waste is growing, and the demand for affordable energy is increasing, all of which presents challenges for Nigeria. Meanwhile, urban wastewater treatment plants produce organic sludge which may be in a position to be utilized for valuable energy. Wastewater to energy recovery is therefore of particular interest for the Owerri Municipality where urban activities are growing and potentially biodegradable wastewater sludges can be estimated to be available for recycling.

To better predict biogas production, wastewater composition needs to be well characterized and operational parameters like chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), total suspended solids (TSS), volatile sus-

pendent solids (VSS), temperature, hydraulic or solids retention time and organic loading rate (OLR) must be taken into account. BioWin offers a process-based tool to model wastewater treatment and anaerobic digestion processes and can be utilized to calculate biogas and methane generation if suitable input data and suitable model configuration are utilized [5]-[7].

Although numerous wastewater-treatment simulation software is available, there is a research gap that still exists on evaluating Owerri Municipality wastewater treatment plants for biogas production, which is site-specific. Limited integration of laboratory characterization of wastewater, simulation of BioWin process and MATLAB-based numerical analysis for assessing Technical, Economic and Environmental benefits of wastewater-to-energy recovery in the Nigerian context is also observed. In addition, comparative data about the potential biogas production of specific municipal wastewater treatment facilities and the effect of various operating parameters on biogas production is still limited.

These gaps have been bridged in this work through the combination of experimental characterization of wastewater and sludge and BioWin and MATLAB modeling of anaerobic digestion process. This study assessed two wastewater treatment plants namely Aladinma (Plant A) and Ikenegbu (Plant B). It has quantified the biogas generation capacity, methane yield, energy generation potential and cost savings of these treatment plants. The study also identified the key operating variables that affect methane production.

The major achievement of this study is the site-specific BioWin-MATLAB simulation framework which assesses the potential of wastewater to energy conversion. Simulation results showed an estimate of about 700 m³/day and 850 m³/day biogas generation potentials for Aladinma and Ikenegbu, respectively resulting in combined potential of 1550 m³/day. The estimated average methane content is 60.5% with specific methane generation rate of 0.16 - 0.19 m³ CH₄/kg COD removed. Electrical energy generation potential has been estimated at 3120 kWh/day or 1.14 GWh/year.

2. Methodology

2.1. Research Design

The research involved the use of a hybrid research design that included experimental work, process simulation and computerized design involving sampling and laboratory studies, modeling using BioWin, post-processing using MATLAB, energy recovery estimation, sensitivity analysis, economic analysis, and greenhouse gas emission analysis. BioWin software was adopted for process modeling while MATLAB was used for computations and post-processing.

2.2. Study Area

This research was carried out in Aladinma and Ikenegbu wastewater treatment plants found within Owerri Municipal Area, Imo State, Nigeria. These plants were chosen because they are typical municipal wastewater treatment plants ideal for

the investigation of the feasibility of renewable energy recovery from wastewater sludge.

The area is located between latitude 5°28' and 5°31'N, and longitudes 7°00' and 7°04'E and occupies an approximate land area of 551 km². The area has a tropical wet climate with average annual rainfall and temperature of about 2,250 mm and 27°C respectively. Owerri Municipal has a population of 127,213 inhabitants with about 17,000 households including shops and offices.

The people of Owerri have predominantly an urban nature with involvement in civil service, trading, business, and other ventures. The Rivers that drain the city are Otamiri and Nworie Rivers. The city has several tertiary institutions. The wastewater treatment plants selected as the sites of study include residential, institutional and commercial areas from which representative wastewater/sludge and shown in **Table 1**.

Table 1. Two selected WWTPs representative.

Plant Name	Location	Type	Treatment Capacity (m ³ /day)
Plant A	Aladinma Estate	Extended aeration + anaerobic digester	6000
Plant B	Ikenegbu Sewage Works	Conventional activated sludge + anaerobic digester	7000

Operational data of WWTPs used for biogas production assessment is contained in **Table 2**.

Table 2. Operational data of the selected WWTPs.

Operational Parameter	Unit	Plant A	Plant B
Treatment Capacity	m ³ /day	6000	7000
Treatment Process Type	-	Extended aeration + anaerobic digester	Conventional activated sludge + anaerobic digester
Operating Temperature	°C	30	32
Organic Loading Condition	mg/L COD	690	750
Sludge Treatment Method	-	Anaerobic digestion	Anaerobic digestion
Wastewater Source	-	Municipal wastewater	Municipal wastewater
Plant Location	-	Aladinma Housing Estate	Ikenegbu Sewage Works

2.3. Sample Collection and Preparation

Samples of wastewater/sludge were collected from selected sampling locations at Aladinma Wastewater Treatment Plant (Plant A) and Ikenegbu Wastewater Treatment Plant (Plant B) of Owerri Municipal, Imo State, Nigeria. Sampling was done over a period of seven (7) months from June to December 2025 to provide variations in the characteristics of wastewater/sludge under varied operating conditions.

Samples were collected from the specified locations within each of the treatment plants and duly labeled upon collection. The samples were (grab/composite)

samples, and were collected in clean sampling bottles. After sample collection, they were preserved using laboratory procedures, transferred to the laboratory, and characterized following standard methods for wastewater/sludge characterization [8] [9]. Sampling was done to provide representative samples from both plants for physicochemical analysis and further Bio-Win modeling and biogas production evaluation. The parameters used as the primary input data introduced into the Bio-Win simulation software for modeling the anaerobic digestion and wastewater treatment processes is presented in **Table 3**.

Table 3. Input data for BioWin simulation.

Parameter	Symbol	Unit	Plant A	Plant B
Average flow	Q	m ³ /day	6000	7000
COD	COD	mg/L	690	750
BOD ₅	BOD	mg/L	330	350
TSS	-	mg/L	220	250
NH ₄ -N	-	mg/L	36	39
Wastewater Temperature	T	°C	30	32
Ph	-	-	6.82	6.75

2.4. Physico Chemical Analysis

The main variables analyzed were:

- Chemical Oxygen Demand (COD);
- Biochemical Oxygen Demand in five days (BOD₅);
- Total Suspended Solids (TSS);
- Volatile Suspended Solids (VSS).

COD is used as an indicator of the amount of oxidizable organic substances, while BOD₅ stands for the biodegradable part. TSS stands for the total suspended solids, while VSS is the organic part of suspended solids. These parameters were chosen because the amount and biodegradability of organic substances affect the anaerobic digestion and methane production [10] [11].

2.5. Bio-Win Modeling

The obtained wastewater characteristics were introduced in BioWin along with some other plant operation parameters such as the amount of influent, COD concentration, temperature, retention time and OLR. Models were built separately for both plants—Aladinma and Ikenegbu treatment plants. BioWin was used as the main process simulation software in order to make a model of anaerobic digestion and biogas and methane production estimates. The model includes the main stages of anaerobic digestion including hydrolysis, acidogenesis, acetogenesis and methanogenesis. The results include the amount of produced biogas and the concentration of methane. Bio-Win has been used in the modeling of wastewater and anaerobic processes [12] [13].

The flowsheet arrangement of the Wastewater Treatment Plant at Owerri is shown in **Figure 1**. Simulations of the plant were carried out after completion of the flowsheet arrangement until convergence was attained. Different components of the WTP model were employed in the construction of the plant model as follows:

- Influent input stream for plant model parameters such as flow rate, BOD, and Total Suspended Solids (TSS).
- Primary Clarifier for separation efficiency and sludge ratio.
- Aeration tank for biological oxidation (ASM1).
- Secondary Clarifier for sludge thickening and recycling.
- Anaerobic digester for ADM1 model kinetics operated at 32°C - 33°C.
- Gas Collector for biogas and methane generation.
- Pipe component to connect components in series.

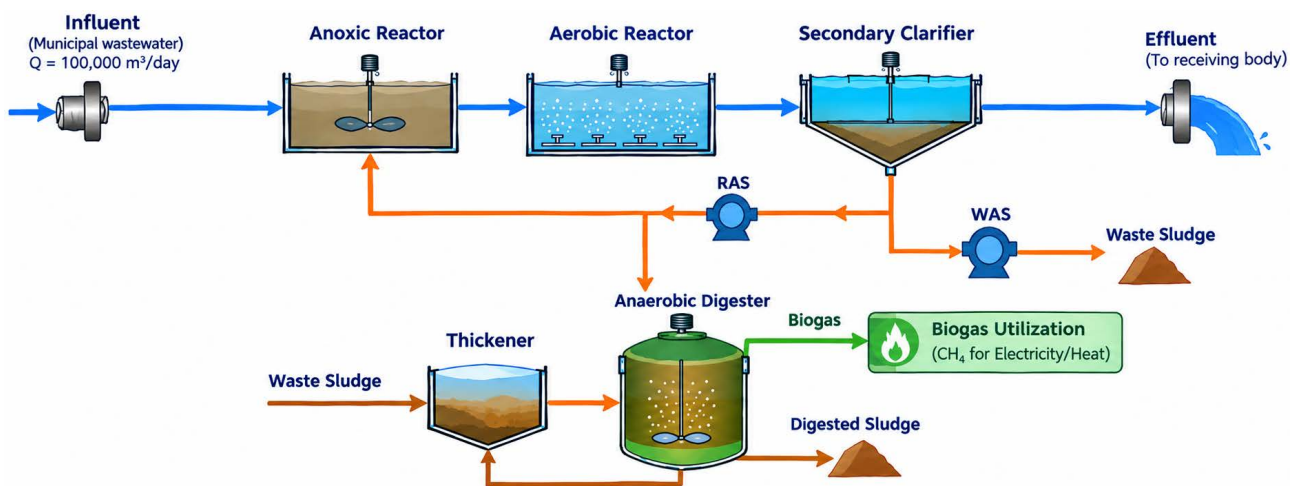


Figure 1. Bio-Win model of wastewater treatment plant.

2.6. Verification of Bio-Win Model Prediction

Data on the performance of biogas production and sludge digestion specific to plant operations was not available for the period of June to December 2025. It means that there would be no validation of Bio-Win prediction by field data. All values of biogas, methane, and energy recovery presented in the paper are considered scenario-based, rather than verified prediction. Lack of the field data is a research limitation.

2.7. MATLAB Simulation and Data Analysis

MATLAB software was applied as an auxiliary computing tool. Outputs of Bio-Win were processed in MATLAB for further numerical computation, visual presentation, and comparison and sensitivity analysis.

The MATLAB software was used to:

- Plot dynamics of biogas and methane production;
- compare the results of Aladinma and Ikenegbu;
- Analyze influence of temperature and COD;

- estimate retention time and OLR;
- compute methane production;
- assess electrical energy recovery;
- estimate possible saving in electricity cost;
- estimate payback period; and
- assess reduction of greenhouse gases.

Thus, MATLAB provided an extra flexibility in analyzing, while Bio-Win model was employed as main anaerobic digestion process-based model.

2.8. Sensitivity Analysis

The sensitivity analysis was performed by changing the values of temperature, influent COD, HRT/SRT, and OLR from their base-line Bio-Win operating conditions. The sensitivity measure was the percent change in methane generation from the base line case, as shown below.

$$\% \Delta CH_4 = \frac{CH_{4,I} - CH_{4,base}}{CH_{4,base}} \times 100 \quad (1)$$

The range of values and increment was used for the sensitivity analysis.

2.9. Energy Recovery Evaluation

Energy recovery potential was evaluated based on simulated biogas production and its methane fraction [14] [15]. Methane fraction was regarded as the main component bearing energy. Electric energy recovered per day was estimated using energy content of methane and energy conversion efficiency. Annual energy recovery was then computed as:

$$E_{annual} = E_{daily} \times 365 \quad (2)$$

2.10. Economic Assessment

Economic evaluation was conducted using an assumed electricity tariff = **120/kWh**.

Annual electricity savings were calculated using equation below:

$$S = E_{annual} \times T \quad (3)$$

where:

S = annual electricity-cost savings, E_{annual} = annual electricity recovery, T = electricity tariff, C = initial investment cost

The simple payback period was estimated from:

$$P = \frac{C}{S} \quad (4)$$

2.11. Environmental Assessment

The environmental impact assessment was related to greenhouse gas reductions due to methane capture and use. The reduction estimate is about 574 tonnes CO₂-e per year. The biogas recovery can be used environmentally in terms of reducing

the methane emissions and electricity generation using conventional energy sources [16]–[20].

3. Results and Discussion

3.1. Bio-Win Simulation Results

The BioWin simulation predicted approximately **700 m³/day** of biogas from Aladinma Treatment Plant and **850 m³/day** from Ikenegbu Treatment Plant (See **Table 4**).

Table 4. Simulated biogas production.

Treatment Plant	Biogas Production (m ³ /day)	Contribution
Aladinma—Plant A	700	45.2%
Ikenegbu—Plant B	850	54.8%
Combined	1550	100%

Ikenegbu produced about 150 m³/day more biogas than Aladinma. This corresponds to about 21.4% higher production compared to Plant A. These differences could result from differences in the amount of water treated, COD concentration, organic loading, sludge properties and other factors. The obtained results show that both wastewater treatment plants have significant opportunities for recovering energy using anaerobic digestion.

Assumptions for Electricity Recovery from Methane

The calculation of the electricity-recovery potential from the simulated methane production was carried out under normal engineering assumptions. The LHV of methane was assumed to be 9.97 kWh/m³ CH₄. The electrical efficiency of the generator gas engine was assumed to be 35%. Parasitic energy of 10% was used to consider electricity use in sludge treatment, pumping, and gas conditioning. The availability of the plant was considered 90%, while gas-cleaning loss was 5% before electricity production. The electricity-recovery net was thus calculated considering the simulated methane production and gas-cleaning loss, generator efficiency, parasitic energy use, and plant availability (See **Table 5**).

Table 5. Assumptions for electricity recovery from methane.

Assumption	Value
Methane energy content (LHV)	9.97 kWh/m ³ CH ₄
Electrical conversion efficiency	35%
Gas-cleaning loss	5%
Plant availability	90%
Parasitic energy demand	10%
Basis of calculation	Simulated CH ₄ production
Result classification	Scenario-based estimate

The net electricity that could therefore be estimated for a production of V_{CH_4} m³/day would be:

$$E_{net} = V_{CH_4} \times 9.97 \times 0.95 \times 0.35 \times 0.90 \times 0.90$$

where, the final 0.90 represents the 10% parasitic-energy allowance.

3.2. Methane Content and Specific Methane Yield

The methane content in the simulated biogas was about 60.5%. Methane is the main constituent in the biogas containing energy and thus determines the energy value of the gas. The estimated specific methane yield was about: 0.16 - 0.19 m³ CH₄/kg COD removed. It can be concluded that a considerable part of organic material removed from the wastewater can be transformed into methane.

3.3. Effect of Temperature

Temperature affects growth of microorganisms, hydrolysis, acidogenesis, acetogenesis and methanogenesis processes. Maintaining optimal temperature, thus, becomes important for effective anaerobic digestion. Temperature was found to have a high influence on methane production in the MATLAB sensitivity analysis as shown in **Table 6**.

3.4. Effect of Influent COD

COD concentration also had a high influence on methane production. Higher COD concentrations usually meant more substrate was available and thus higher methane production potential. Excessively high organic loading rate, however, could destabilize anaerobic digestion and cause accumulation of volatile fatty acids. This makes COD concentration consideration along with digester capacity and OLR important.

3.5. Effect of Retention Time

Retention time affected the level of substrate degradation and methane production. Too short retention time could cause incomplete biodegradation whereas too long retention time would increase digester volume and its cost without any energy gains. Retention time, therefore, should be optimized.

3.6. Impact of OLR on the Process

An increase in OLR will initially result in increased availability of substrates, hence increased biogas generation. Excessive OLRs can lead to instability and inhibit the methanogens. The above results show that an OLR range is required to generate maximum biogas production and a stable process.

3.7. Sensitivity Analysis

Table 6 describes the one-way sensitivity analysis which was performed in order to determine the sensitivity of methane production to various important operational parameters. Temperature was allowed to vary from 25°C to 35°C, while the

concentration of COD ranged from 300 mg/L to 700 mg/L. Retention time was changed from 10 days to 30 days, while OLR varied from 50% to 150% of the bioWin baseline. The steps sizes for the above parameters were 5°C, 100 mg/L, 5 days, and 25% of the baseline, respectively. Sensitivity of the parameter was determined by calculating the percentage change in CH₄ production.

Table 6. Results of sensitivity analysis.

Parameter	Baseline	Range investigated	Step size	Sensitivity metric
Temperature	30°C (Plant A); 32°C (Plant B)	25°C - 35°C	5°C	% change in CH ₄
COD concentration	500 mg/L	300 - 700 mg/L	100 mg/L	% change in CH ₄
Retention time	20 days	10 - 30 days	5 days	% change in CH ₄
OLR	Baseline BioWin value	50 - 150% of baseline	25% of baseline	% change in CH ₄

3.8. Comparison of BioWin and MATLAB

Complementary role was played by BioWin and MATLAB. BioWin was utilized to conduct the process-based anaerobic digestion modeling whereas MATLAB was employed for numerical analysis and sensitivity analysis (See **Table 7**).

Table 7. Comparison of BioWin and MATLAB results.

Parameter	BioWin	MATLAB Analysis	Interpretation
Primary function	Anaerobic process simulation	Numerical analysis/validation	Complementary
Plant A biogas	700 m ³ /day	700 m ³ /day*	Consistent
Plant B biogas	850 m ³ /day	850 m ³ /day*	Consistent
Combined biogas	1550 m ³ /day	1550 m ³ /day*	Consistent
Average methane	60.5%	60.5%*	Consistent
Specific methane yield	0.16 - 0.19 m ³ CH ₄ /kg COD removed	0.16 - 0.19*	Consistent
Temperature	Process simulation	Sensitivity analysis	MATLAB enhances interpretation
Influent COD	Process input	Sensitivity analysis	Complementary
Retention time	Process simulation	Trend analysis	Complementary
OLR	Process simulation	Sensitivity analysis	Complementary
Energy recovery	Biogas/methane basis	Numerical calculation	MATLAB enables assessment
Annual energy	Basis for calculation	1.14 GWh/year	Consistent
Demand offset	Simulation basis	39.5%	MATLAB enables comparison
Annual savings	Production basis	₦136.7 million	MATLAB calculation
Payback period	-	3 - 5 years	MATLAB calculation
GHG reduction	Methane basis	574 tCO ₂ -eq/year	MATLAB calculation

From the comparison, it is clear that Bio-Win provides the process model basis, whereas MATLAB offers analytical tools for supporting computation. The combined use of both approaches will help improve the understanding of the tech-

nical, economic and environmental aspects of biogas production from wastewaters.

The 3 - 5-year payback period was calculated considering the capital cost at which the biogas-powered electric generator was installed, which included costs related to the digester, gas collection and conditioning, storage, and the generator itself. The annual maintenance and operating cost was subtracted from the savings in electricity to arrive at the annual net benefit. The replacement of the generator was considered as one of the life-cycle costs.

The greenhouse gas assessment had a plant-gate boundary that included methane emissions, capturing, electrical power generation, and fugitive emissions. The methane emissions were then converted to CO₂ equivalents using the 100-year global warming potential from IPCC while the electricity generation was given credit for the avoidance of emissions from the grid.

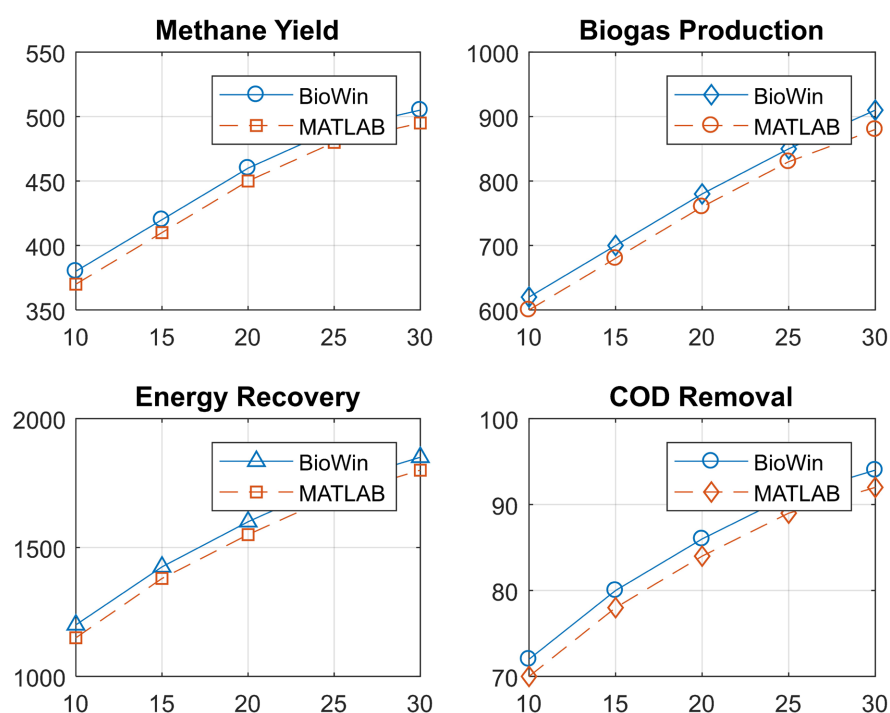


Figure 2. Overall Bio-Win vs MATLAB performance comparison (Subplots).

Figure 2 shows the comprehensive comparison of the methane yield, biogas generation, energy utilization and COD removal efficiency in both Bio-Win and MATLAB models. From the graph, it is clear that both models exhibit almost same performance tendencies in relation to all parameters under study. Bio-Win generates higher values compared to the MATLAB, which can be attributed to higher accuracy of the process simulation in Bio-Win, whereas MATLAB offers just a simple analytical approximation.

3.9. Energy-Recovery Potential

The combined energy recovery potential was estimated at approximately **3120 kWh/day**.

Annual energy recovery was calculated as:

$$3120 \times 365 = 1,138,800 \text{ kWh/year}$$

Thus:

Annual electricity recovery $\approx$ 1.14 GWh/year.

Table 8. Energy-Recovery potential.

Parameter	Value
Combined biogas production	1550 m ³ /day
Average methane content	60.5%
Daily electricity recovery	3120 kWh/day
Annual electricity recovery	$\approx$ 1.14 GWh/year
Estimated electricity-demand offset	$\approx$ 39.5%

The recovery of energy from the sludge could satisfy about 39.5% of the total power consumption needs of the two water treatment facilities. This is a clear demonstration that wastewater sludge can be used to generate renewable energy (See **Table 8**).

3.10. Economic Evaluation

At an electricity tariff of ₦120/kWh:

$$1,138,800 \times 120 = \text{₦}136,656,000/\text{year}$$

Thus, the annual cost savings in electricity = ₦136.7 million/year. The previously mentioned value of approximately ₦140 million/year could be seen as a rough estimate. The expected payback period of 3 - 5 years implies favorable economic conditions for the investment into biogas collection, treatment, and electricity generation systems. Project economics would depend on costs of construction, efficiency of the generator, maintenance of the system, cleaning of the gas, and others.

3.11. Greenhouse-Gas Reduction

The analysis shows possible mitigation of greenhouse gases around 574 tonnes CO₂-eq./year. The environmental advantage is based on the capture of the methane that would otherwise have been released into the atmosphere for the generation of electricity. This confirms the importance of wastewater treatment within a circular energy system.

3.12. Comparative Performance of the Two Plants

Comparative analysis of the two plants is displayed in **Table 9** demonstrated the higher simulated biogas production. However, greater biogas volume does not necessarily indicate better wastewater-treatment performance. Treatment efficiency should also consider COD removal, solids stabilization, specific methane yield and energy consumption.

Table 9. Comparative performance.

Indicator	Aladinma (Plant A)	Ikenegbu (Plant B)
Biogas production	700 m ³ /day	850 m ³ /day
Contribution to total	45.2%	54.8%
Average methane content	60.5%	60.5%
Specific methane yield	0.16 - 0.19 m ³ CH ₄ /kg COD removed	0.16 - 0.19 m ³ CH ₄ /kg COD removed

4. Conclusions and Recommendations

4.1. Conclusions

This study analyzed and evaluated the potential for biogas production from selected wastewater treatment plants in Owerri Municipality using the combined experimental, BioWin and MATLAB approach. The characteristics of wastewater sludge from Aladinma and Ikenegbu treatment plants were obtained through COD, BOD₅, TSS and VSS to determine its suitability for anaerobic digestion.

The Biowin model indicated an estimated biogas generation potential of 700 m³/day for Aladinma and 850 m³/day for Ikenegbu, giving a combined total of 1550 m³/day. The average methane content was 60.5%, while the specific methane yield was 0.16 - 0.19 m³ CH₄/kg COD removed.

Temperature and influent COD concentration have been identified as the most sensitive parameters affecting methane production by the MATLAB model. The retention time and OLR parameters also affected the process, though they had less influence compared to the first two.

The combined potential electrical energy recovery was estimated to be 3120 kWh/day, which equals 1.14 GWh/year. This could potentially provide 39.5% of the combined power demands of the two treatment plants.

At an electricity cost of ₦120/kWh, the calculated energy-cost savings potential would be approximately ₦136.7 million/year, and the rounded estimate of ₦140 million/year would represent approximately the same order of savings. A simple payback period of 3 - 5 years implies economic feasibility, although this may depend on accurate project costing. A potential greenhouse gas mitigation of approximately 574 tonnes CO₂-eq/year was also estimated.

Generally, the results suggest that the wastewater sludge from the selected Owerri treatment plants can be a valuable source of renewable energy. The combined Biowin-MATLAB approach used in this study has proven to be a powerful tool for process modeling, sensitivity analysis, energy evaluation and decision making.

4.2. Recommendations

From the study, the following recommendations are proposed as follows:

- The recovery system of biogas generation in Aladinma and Ikenegbu WWTPs should be examined for its feasibility.
- The temperature, COD, pH, OLR and retention time of the process should be continuously monitored and controlled to ensure that anaerobic digestion is

consistent.

- Biogas should be cleaned properly and conditioned, especially removing moisture and hydrogen sulphide, before using the biogas in generating equipment.
- The combined heat and power (CHP) system should be analyzed when both electrical and thermal energies can be efficiently utilized.
- Techno-economic feasibility analysis should be conducted with the current cost structure for the equipment and facilities in Nigeria.
- Long-term data from the experiments should be obtained to improve the calibration and validation of the BioWin model.
- The co-digestion of the wastewater sludge with municipal waste for enhancing methane generation should be studied.
- The further study of the optimization of temperature, OLR and retention time of the digesters should be conducted using MATLAB-based optimization algorithms.
- The government and municipality should promote the wastewater resource recovery by developing proper policies and incentives.
- The method used should be adopted by other wastewater treatment plants in Nigeria to build a national database for energy production using waste water.

Acknowledgements

I want to especially appreciate Engr. Prof. Luke Okwuchukwu Uzoigwe, FNSE for his understanding, support and the valuable advice he offered during this program. I must not fail to thank the Dean faculty of Engineering Engr. Prof. A.U. Iwuoha, the Head of Department of Agricultural Engineering Engr. Dr. J.I. Onyewudiala for their necessary supports, which were indispensable all through the period of this program.

I must not fail to extend my sincere appreciation to my colleagues and friends, more especially Engr. Dr. Gerald Ibe Okwe, FNSE, Engr. Mrs. Chidiebere, Elom, Princeley Onu, Engr. Ikenna David Okeke they were always behind me with huge support needed, throughout the project.

I am deeply thankful to my family especially my lovely wife Mrs. Evelyn Okebaram and children. They stood by me with understanding during the excruciating moment of the research work.

I am also grateful to the management and staff of the wastewater treatment plants in Owerri Municipal for their cooperation during data collection. Special thanks to my colleagues and friends for their moral support and contributions.

Author Contributions

Okebaram conceived and designed the experiment, Prof L.O Uzoigwe and Dr Julius Onyewudiala formulated the methodology, coordinated the characterization of the wastewater and sludge, while Engr Dr. Gerald Okwe performed Bio-Win and MATLAB simulations. He interpreted and analyzed the findings on the physical/chemical, biogas, energy, economic and environmental aspects, including

sensitivity analysis and comparison of Bio-Win and MATLAB simulation. Prof. L.O Uzoigwe, reviewed, revised the manuscript, and approved its final version.

Conflicts of Interest

The authors declare no conflicts of interest.

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