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INVESTIGATING THE BIOCHEMICAL METHANE POTENTIAL OF KUMASI'S MUNICIPAL SOLID WASTES

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ABSTRACT

Purpose: This paper aims to ascertain the biochemical methane potential of organic waste generated in Kumasi for renewable energy production.

Design/Methodology/Approach: A quantitative experimental approach was employed on Batch anaerobic digestion experiments, and methane yields were analysed with kinetic models.

Findings: The modified Gompertz model had the best fit, with a $R^2 = 0.9962$, which gave a methane production rate of 19.47 ml $CH_4\ g^{-1}$ VS Day and a BMP of 219.35 ml $CH_4\ g^{-1}$ VS.

Research Limitation: It has also been pointed out that further optimisation of AD processes for methane yield and efficiency is required. Key limitations pertain to scalability and unoptimised parameters.

Practical Implication: The study confirms that organic waste-to-biogas conversion in Kumasi is viable and represents a partial solution to problems of organic waste management and renewable energy generation. That will reduce disposal costs from waste, low dependence on fossil fuel, and open opportunities in resource recovery for operational efficiencies that work toward environmental sustainability.

Social Implication: Better waste management will help reduce environmental pollution. In addition, appropriate development in terms of sustainability and enhancement of energy security will occur.

Originality/Value: This research provides information on wastes around Kumasi that can be used to produce biogas and advance sustainable waste-to-energy practices. This study introduces a novel application of kinetic models to assess Kumasi's organic waste for biogas production, offering localised data and tailored optimisation strategies. It contributes to advancing waste-to-energy practices and supports sustainable waste management in Ghana.

Keywords: *Anaerobic digestion. biochemical. kinetic models. methane. solid wastes*

INTRODUCTION

This rapid expansion of urban areas and populations in developing cities, such as Kumasi, Ghana, is accompanied by increased MSW production (Sarfo-Mensah *et al*.,2019; Kwakye *et al.*, 2024). This has become a pressing challenge due to the limited resources that characterise waste collection, disposal, and processing (Addae et al., 2021; Owusu-Nimo *et al*., 2023). In Kumasi, the similar profile of cities shows that organic matter is dominated by food waste, agricultural residues, and other organic materials that are biodegradable (Tahiru *et al.*, 2024; Darmey *et al*., 2023b; Hormenu, 2011). When poorly managed, organic waste significantly contributes to environmental pollution, greenhouse gas emissions, and public health hazards (Lukashevych et al., 2024; Abubakar *et al*., 2022; Sharma *et al*., 2019).

Traditionally, the final waste disposal in Kumasi has been with landfills; this is not sustainable for the environment, given concerns about methane emission, leachate pollution, and dwindling landfill spaces (Owusu-Sekyere, 2018). Moreover, high organic waste content in Kumasi introduces options for addressing these challenges through waste-to-energy conversion (Obuobi *et al*., 2022). Anaerobic digestion-coupled organic waste management is considered one of the most promising approaches to renewable energy generation (Shrestha *et al*., 2023; Huang *et al*., 2019).

Anaerobic digestion (AD) is a process whereby organic material is degraded in an environment devoid of oxygen into a biogas rich in CH_4 and CO_2 (Odega *et al*., 2022; Cheng, 2017). The biogas can be processed further to yield biomethane, a renewable energy vector with some uses, including electricity generation, heating, and vehicle fuel (Calise *et al.*, 2021; Iglesias *et al.*, 2021). While methane is released uncontrolled during the decomposition of landfills, AD offers a controlled production of methane, which allows for the capture and valorisation of this potent greenhouse gas (Subbarao *et al*., 2023; Stazi & Tomei, 2021). Biomethane production through the organic fraction of municipal solid wastes (OFMSW) coming from Kumasi could offer, in the future, a renewable energy supply, reducing waste management problems and diminishing greenhouse gas (GHG) emissions.

The potential biomethane from the organic fraction of Kumasi waste falls within a circle of interest in the global community on sustainable waste management and the generation of renewable energy.

Biomethane could be rated as one of the most prized products because of its high calorific value, ease of storage, and transport compatibility, especially for energy-scarce regions (Achinas & Euverink, 2019).

Diverting organic waste from the landfills to anaerobic digestion facilities offers Kumasi an opportunity to reduce the burdens on landfills, lower methane emissions, and produce a clean, renewable fuel that offsets fossil fuel use in the city. This is a critical part of a waste management approach in the circular economy, in which waste becomes a resource and a means to close the loop on resource use to create such a sustainable, self-replenishing energy cycle.

According to Kalyani and Pandey (2014), such an approach to waste management plays a significant role in the circular economy by turning the concept of waste into a resource. To such an end, there is the need for detailed investigation into elements such as the composition of waste and its biodegradability so the full biomethane potential can be realised regarding Kumasi's OFMSW.

The biomethane yield from organic wastes can vary depending on substrate composition, moisture content, temperature, and microbial populations involved in digestion. In the case of Kumasi, with a very heterogeneous organic fraction of Municipal Solid Wastes (MSW) is subject to seasonal variation (Addae et al., 2012), so quantifying biomethane potential (BMP) became an important step toward understanding the feasibility and scales at which biogas production could be developed. Through experimental BMP tests and kinetic modelling, this study will assess the biomethane potential of MSW organic fractions in Kumasi and provide data that could help optimise AD processes and enhance biomethane yields from local waste streams.

LITERATURE REVIEW

The kinetics of the anaerobic process plays a vital part in biomethane production through anaerobic digestion (Owhondah *et al*., 2016). Understanding its kinetics will help efficiently scale up the biogas generation from various organic substrates (Aworanti *et al.*, 2023). This literature review discusses mainly the relationship between biomethane potential and anaerobic kinetics, mentioning how the two influence the efficiency of biogas production.

Biomethane Potential (BMP) measures the total methane yield generated from the anaerobic digestion of a specific substrate under ideal conditions. It serves as a benchmark for assessing the efficiency of biogas production processes and provides insights into the biodegradability of substrates and microbial performance under specific conditions (Angelidaki *et al*., 2009). Due to their chemical composition, BMP values differ significantly among substrates, such as agricultural residues, municipal solid waste, and industrial effluents (Labatut *et al*., 2011; Raposo *et al*., 2011).

Every substrate, including wastewater sludge, has different BMP values regarding biochemical characteristics, from agriculture residues to food waste. A BMP test is the ultimate tool for feedstock assessment and the feasibility assessment of biogas production processes under substrate conditions (Raposo *et al*., 2011).

Developing kinetic models, such as the Gompertz equation and Monod kinetics, has significantly advanced the ability to predict methane production rates and optimise the design of anaerobic digesters. These models utilise BMP data and parameters like microbial growth rates and substrate affinity constants to simulate and enhance the performance of anaerobic digestion processes (Li et al., 2018).

Substrate composition is one of the most important factors affecting BMP and anaerobic kinetics. For example, lignocellulosic materials, which have a high lignin content, inhibit hydrolysis and thus reduce methane yields (Kumar et al., 2022). In contrast, substrates that are rich in carbohydrates and lipids exhibit higher BMP values and higher degradation rates (Motte et al., 2013). The biodegradability of such materials can be improved by mechanical grinding, chemical hydrolysis, or biological pretreatment. Co-digestion of substrates with complementary characteristics is another common approach to optimise the carbon-to-nitrogen ratio and enhance the process performance (Zhao et al., 2010).

Temperature and pH are critical factors affecting microbial activity and reaction rate. Anaerobic digestion operates under either mesophilic conditions, which fall between 35 and 40°C, or thermophilic conditions, which range from 50-60°C. While thermophilic digestion accelerates hydrolysis and improves pathogen reduction, it is also more prone to process instability (Kim et al., 2002).

Maintaining optimal pH levels is essential to sustaining microbial activity and ensuring consistent BMP values. Furthermore, inhibitory compounds, such as ammonia, sulfides, and volatile fatty acids (VFAs), pose significant challenges to anaerobic digestion.

High ammonia concentrations, for example, can inhibit methanogenic archaea, reducing methane yields. Methods often used to counteract these inhibition effects include dilution, pH adjustment, and co-digestion with low protein substrates. Chen et al. (2008) and Westerholm et al. (2012) report these methods. By ensuring these factors are appropriately handled and applying appropriate kinetic models, biomethane production can be optimised and contribute considerably to a sustainable energy future.

METHODOLOGY

This research adopted a quantitative experimental design, focusing on batch anaerobic digestion experiments to evaluate the biochemical methane potential (BMP) of organic waste from Kumasi. Methane yields were measured and analysed using kinetic models, such as the Modified Gompertz, First Order Kinetic, Chen and Hashimoto, to assess production rates, BMP, and process efficiency.

Sample Preparation

The waste samples considered in this study are organic fractions of municipal solid waste (OFMSW) collected from prominent solid waste collection and recycling plants in Greater Kumasi, Ghana. The OFMSW samples were sun-dried and milled into—200 µm.

Inoculum Preparation

The inoculum was sourced from an active lab-scale continuous stirred tank reactor (CSTR) digesting Dewatered Sewage Sludge at mesophilic temperature. It was sieved using a 1mm sieve to remove coarse materials. It was then transferred into the digestion bottles for acclimatisation to temperatures below mesophilic for 5 days before the start of digestion.

Moisture Content and Total Solids Content Determination

Moisture content was determined using the sample drying (hot-air oven) method. Three (3) clean, dried and pre-weighed crucibles were obtained. 3grams of the sample were transferred into each crucible and placed in a hot air oven for drying at $105^{\circ}C \pm 2$ for 4 hours according to AOAC 32.1.03. The samples were placed in a desiccator for cooling after 4 hours, and their masses after drying and cooling were recorded using an analytical balance. Percent Moisture is determined using equation (1).

$$\%\text{Moisture} = \frac{mb - ma}{ms} \text{ x}100 \qquad (1)$$

Where *mb*=mass of crucible + sample before drying
ma=mass of crucible + sample after drying
ms=mass of sample

Total Solids/Dry Matter was calculated using equation (2) from moisture value.

$$\%\ \text{TS/DM} = 100 - (\%\text{Moisture}) \qquad (2)$$

Volatile Fatty Acids (VFA), Total Inorganic Carbon (TIC) and their ratio Determination

The sample was centrifuged at 10,000 x g at 10°C for 10 minutes. Following centrifugation, 20 mL of supernatant was carefully pipetted into a sample beaker. A pH electrode was then immersed in the supernatant to measure pH levels. A clean magnetic stirrer was introduced into the beaker and set to operate at 150 rpm. The burette chamber of the auto-titrator was filled with 50 ml of 0.1 N sulfuric acid to prepare for titration. Next, the VFA/TIC titration protocol was selected on the auto-titrator, with the following settings: dosing speed of 2.00 ml/min, filling speed of 30 seconds, maximum titration volume of 50 mL, and a step size of 0.050 ml. The titration process was initiated by pressing the start button, and it continued until the solution reached a pH of 4.40. Upon completion of the titration, the following results were obtained: The initial pH, measured prior to titration if enabled; the Total Inorganic Carbon (TIC) expressed in mg/L or mg/kg as $CaCO_3$; the concentration of Volatile Fatty Acids (VFA) in mg/L or mg/kg as CH_3COOH; and the VFA/TIC ratio, presented as a unitless value. The auto-titrator calculates the result and provides VFA, TIC and VFA/TIC values using the equations (4) and (5).

$$\text{TIC} = A \times C_{tit} \times 50045/SA \qquad (4)$$

$$\text{VFA} = ((B \times 4 \times 1.66) - 0.15) \times 500 \qquad (5)$$

Where:
A = Volume of titrant at pH 5.0 (ml)
C_{tit} = Concentration of titrant (eq/l)
SA = Sample amount
B = Volume of titrant by difference at pH 4.4 (ml) = volume of titrant at pH 5.0 – volume of titrant at pH 4.4

Biomethane Potential Anaerobic Digestion Set-up

The batch anaerobic digestion set-up was assembled using 600ml borosilicate-made eudiometer glass tubes as the gas collection medium and 500ml borosilicate bottles (as digestion vessel), with a screw cap with a hole and a silicone septum, into which the tapered end of the eudiometers was inserted to create an airtight system. Tygon silicone tubes were connected from the base of the eudiometers to 1000ml bottles filled with barrier solution (water), serving as pressure compensation reservoir and placed at heights above the eudiometer to provide the required pressure for water flow from the bottles to the eudiometer and vice-versa, depending on gas production or accumulation. The gas displaced an equal volume of water to flow into the 1000ml bottles. Stopcocks attached to the upper end of the eudiometers were opened after each day of gas production to collect produced has into Teflon gas bags for analysis and to reset the water level back to the zero mark of the eudiometer. pH of the water was adjusted using 0.05 Molar sulphuric acid to an acidic range of below 4 to dissolve Carbon dioxide produced from the digestion. This was performed on OFMSW samples and Cellulose as a control. All runs were replicated three times.

Kinetics Studies of Anaerobic Digestion (AD) of Organic Fraction of Municipal Solid Wastes (OFMSW) from Kumasi, Ghana

Cumulative methane yields were calculated from daily biogas production. This data was fitted to three kinetics models: the first-order decay model, the Chen and Hashimoto model and the modified Gompertz model. Data fitting was done using a Microsoft Excel Data Solver Module and a nonlinear engine to minimise the residual sum of squares. The form of the first-order decay model used was as follows:

$$G_t = G_0\left[1 - e^{-k(t-\lambda)}\right] \qquad (6)$$

Where G_t is the cumulative methane yield at time t, G_0 is the methane potential of the substrate, k is the first-order disintegration rate constant, and the methane production rate is constant. The form of the Chen and Hashimoto model used was as follows:

$$G_t = G_0\left(1 - \frac{k}{t\mu_m + k - 1}\right) \qquad (7)$$

Where G_t is the cumulative methane yield at time t, G_0 is the methane potential of the substrate, k is the Chen and Hashimoto kinetic constant, μ_m is the maximum specific growth rate of microorganisms. The modified Gompertz equation used was of the following form:

$$G_t = G_0 e^{-e^{\left\{\frac{R_{max} e}{G_0}(\lambda - t) + 1\right\}}} \qquad (8)$$

Where G_t is the cumulative methane yield at time t, G_0 is the methane potential of the substrate, λ is the duration of lag phase, R_{max} is the maximal methane production rate and e is equivalent to *exp (1),* or 2.718282.

RESULTS AND DISCUSSION

Characteristics of Organic Fraction of Municipal Solid Wastes (OFMSW) and Inoculum Used

Table 1 shows the proximate analysis of an organic fraction of municipal solid wastes (OFMSW) from Kumasi. The OFMSW sample has a very low moisture content level, 21.57%, and additional water would be added for the best anaerobic digestion. Low ash content and high volatile matter indicate its promising potential for biogas production (Fajobi et al., 2022). However, high fixed carbon content could mean that certain organic materials are slowly degrading, which may take more time for retention or pre-treatment. Conclusively, the waste is ideal for anaerobic digestion; however, modification in moisture and pre-treatment of complex materials is done for better biogas yields.

Table 1: Proximate Analysis of OFMSW from Kumasi, Ghana

Moisture content, %	21.57
Ash Content, %	3.69
Volatile Matter, %	45.09
Fixed Carbon, %	29.65

Source: Darmey et al. (2023a)

Table 2 shows the characteristics of the inoculum used in this study. The OFMSW has a relatively low moisture content of 21.57% compared to the inoculum, which has a high percentage of moisture at 94.94%, thus indicating the need for possible adjustment in case anaerobic digestion must be efficiently performed. This is higher in OFMSW, with a volatile solid content of 45.09% compared to the inoculum and at a higher total solid, hence a good potential for biogas production. The inoculum had a lower volatile solids content of 3.42%, slightly below the 3.5% reported for the inoculum used by Maurus et al. (2021). Despite this, it provided adequate moisture and microbial support for digestion. The inoculum has a higher VFA concentration of 251.47 mg/l and TIC of 2874.33 mg/l, which helps buffering the system for pH stabilisation. A low VFA/TIC ratio of 0.09, which is in the range of 0.15-0.45 reported by Maurus et al. (2021) in both materials, indicates stability in the system (Platošová *et al.*, 2021). They can support effective anaerobic digestion with appropriate moisture and solids management.

Table 2: Characteristics of Inoculum Used

Moisture content, %	94.94
Total Solids, %	5.06
Volatile solids % of total solids	69.94
Volatile solids, %	3.42
VFA (mg/l)	251.47
TIC (mg/l)	2874.33
VFA/TIC	0.09

Biomethane Potential (BMP) of OFMSW from Kumasi

Figure 1 shows the daily biogas production rates using a control substrate and OFMSW. For OFMSW, anaerobic digestion began on the first day, with its peak production occurring on the sixth day, after which there was a significant decline in production until the tenth day, followed by a gradual decline to day 19. Conversely, the control substrate maintained a higher reaction efficiency after achieving peak production on the fifth day before a significant decline was observed following day sixteen. Peak production of 24.8510 mL CH_4 g^{-1} VS and 23.0701 CH_4 g^{-1} VS was observed for OFMSW and control substrate, respectively.

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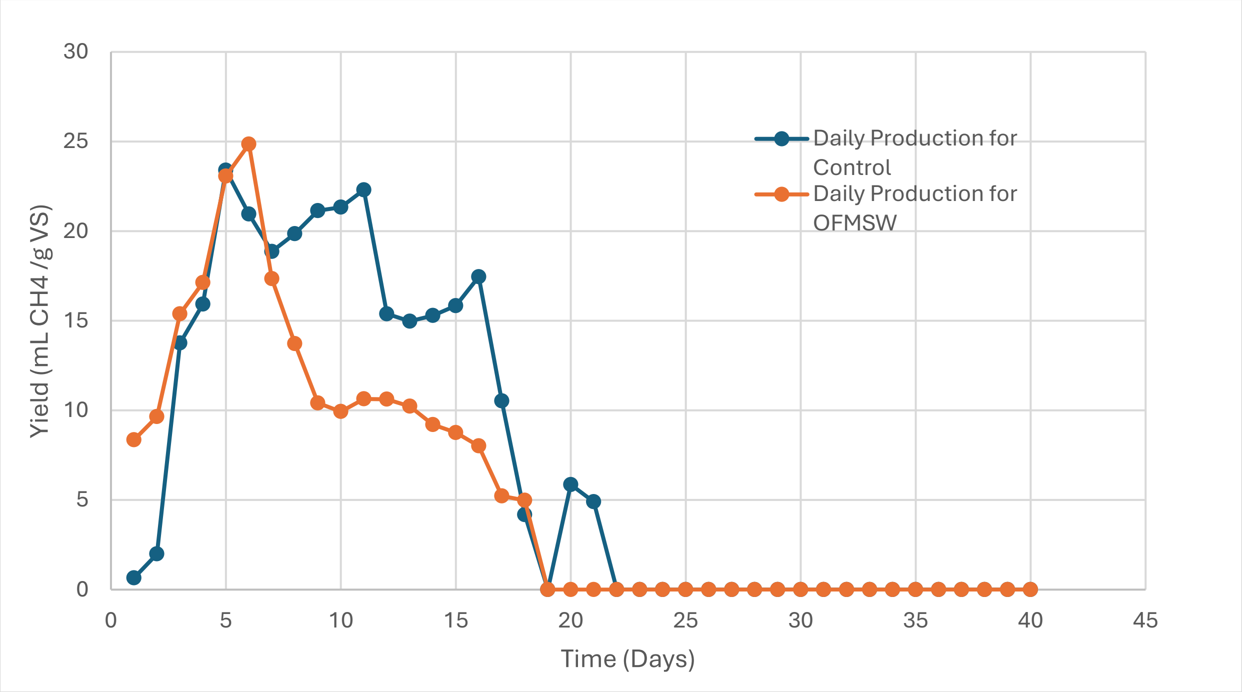

Figure 1: Daily Methane Yield

The cumulative methane yields (ml g^{-1} VS) and methane contents in the period of biogas produced from different Volatile Carbon Residues (VCRs) are presented in Figure 2 and Figure 3, respectively. At the end of batch anaerobic digestion, the average biogas yields for each substrate were calculated to be 217.5096 and 284.5594-ml g^{-1} VS for OFMSW and control substrate, respectively. The period for 80–90% of the ultimate biogas production from the substrate, known as the technical digestion time ($T_{80–90}$), is usually recommended as a suitable hydraulic residence time for continuous fermentation of identical substrate (Kafle & Chen, 2016). The $T_{80–90}$ was calculated to be 13-15 and 14–16 days for OFMSW and control substrate, respectively.

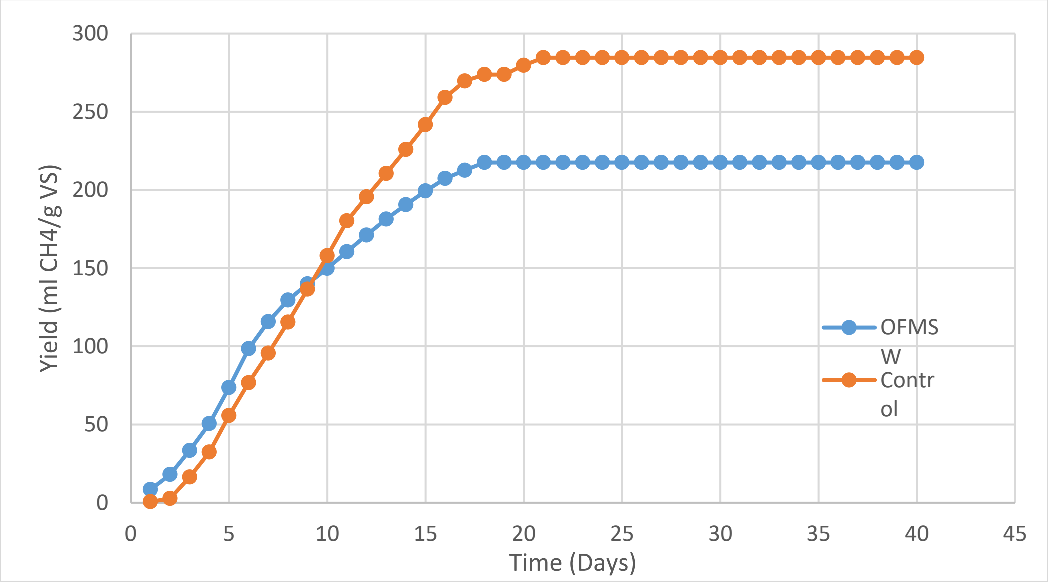

Figure 2: Cumulative Methane Yield

The methane content (%) rose rapidly during the first eight days of anaerobic digestion; thereafter, it decreased slightly and stabilised almost constantly. This is consistent with studies in anaerobic digestion, as reported by Dhull *et al*. (2024). The average methane content in the biogas produced was 47.77% for the OFMSW and 48.68% for the control substrate. These values fall within the typical range of 45% to 75% for waste-based biogas, as Tshemese et al. (2023) reported.

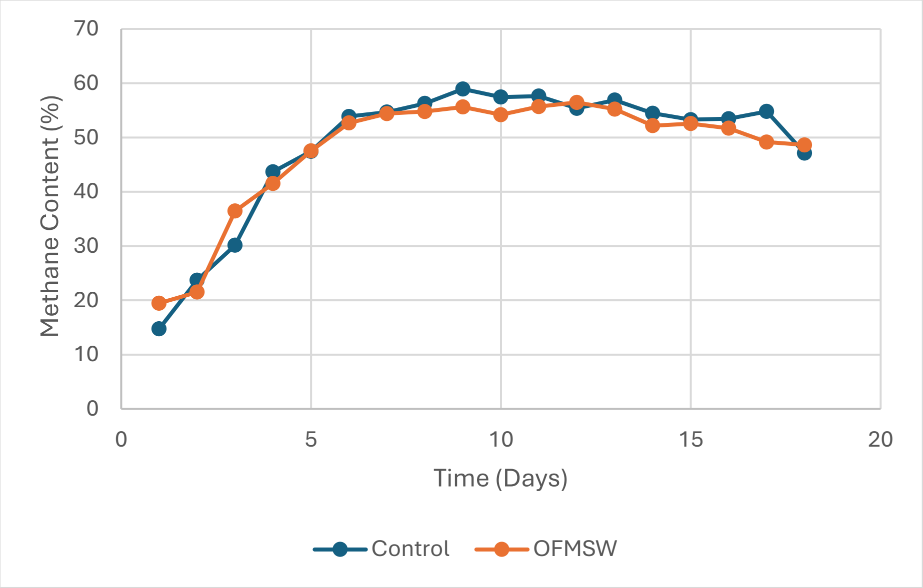

Figure 3: Biogas Methane Content

Kinetics Studies

Table 3 summarises the results of the curve fitting analysis to determine the dynamic model parameters. Three kinetic models were evaluated to find the best fit for the experimental data. Among these, the Modified Gompertz model provided the best fit with an R^2 value of 0.9962. The model estimated a lag phase of (λ) of 1.35 days, meaning about one day is required for microbial acclimatisation before methane production starts. These observations contradict a study by Nielfa et al. (2015) when the OFMSW curve fitted a first-order kinetic model, R2 = 0.99) and a shorter lag phase of 0.37 days. The differences are probably due to the different geographical origins of OFMSWs used in these two studies.

Table 3: Summary of Kinetic Model Parameters

Parameters	**Units**	**Value**
	First Order Kinetic Model	
K	Day^{-1}	0.1373
G_0	ml CH_4 g^{-1} VS	225.2053
R^2	-	0.9833
λ	Day	1.4744
RSS	-	2608.0110
	Chen and Hashimoto Model	
K_{CH}	-	4.681929
G_0	ml CH_4 g^{-1} VS	274.5307
μ_m	Day^{-1}	0.6895
R^2	-	0.9567
RSS	-	6761.4006
	Modified Gompertz Model	
G_0	ml CH_4 g^{-1} VS	219.3529
R_{max}	ml CH_4 g^{-1} VS Day^{-1}	19.4752
λ	Day	1.3533
R^2	-	0.9962
RSS	-	589.0996

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The summary of the kinetic models obtained from analysis and their coefficients of determination are in Table 3. The Gompertz model predicted a maximum methane production rate (R_{max}) of 19.4752 mL CH4_44/g VS/day and a biomethane potential (BMP) of 219.3529 mL CH4_44/g VS. The MSW used in this study demonstrated a higher BMP than the 200 mL CH4_44/g VS reported by Owens and Chynoweth (1993), highlighting its more significant potential for biogas production. High values of R_{max} and BMP point toward a good potentiality of the anaerobic digestion of OFMSW for biogas production. High values of R_{max}, indicating rapid generation of methane, in combination with high values of BMP, reflecting total methane yield, indicate good biodegradability of this material and suitable suitability for efficient methane recovery (Zhang *et al*., 2021; Hansen *et al*., 2020). This, therefore, makes it a desirable feedstock for anaerobic digestion, and under appropriate operational conditions regarding moisture and temperature, for example, this system will produce large quantities of biogas. Figures 4-6 show the goodness of fit of the three kinetic models summarised in Table 3.

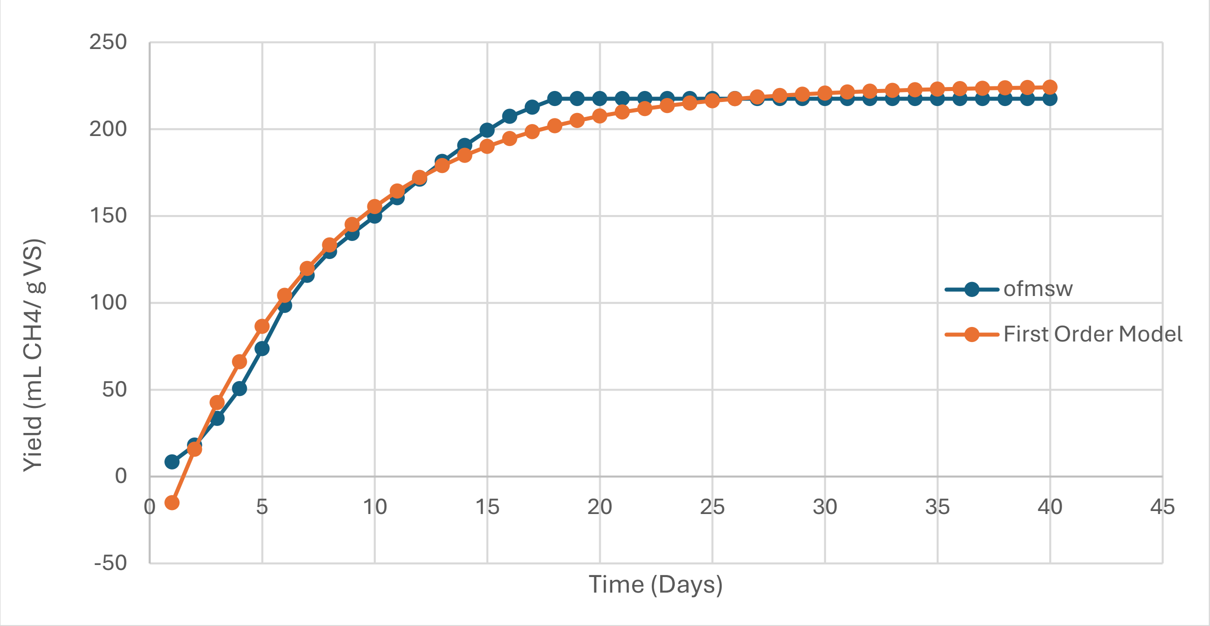

Figure 4: Goodness of Fit of First Order Kinetics model

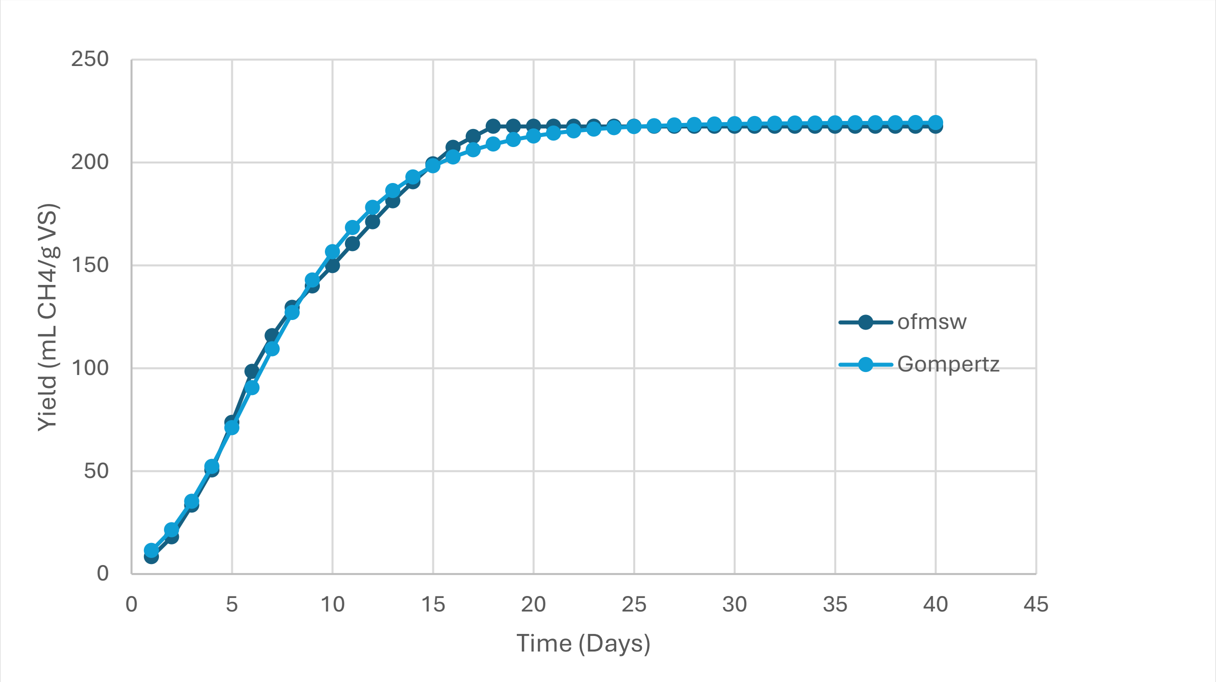

Figure 5: Goodness of Fit of Modified Gompertz Model

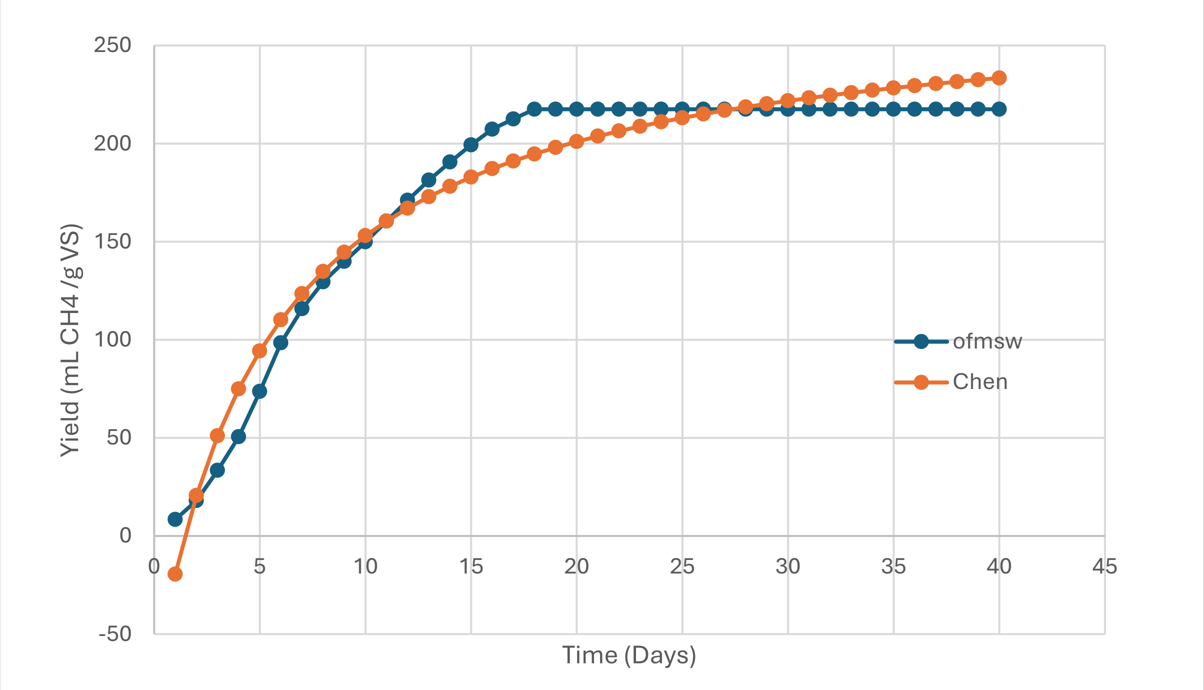

Figure 6: Goodness of Fit for Chen and Hashimoto Kinetic Model

Theoretical BMP of 271.76 mL CH_4 g^{-1} VS (Darmey *et al*., 2023a) is higher compared with the experimental BMP with Modified Gompertz Model-predicted values of 219.3529 mL CH_4 g^{-1} VS. The actual methane production from OFMSW (Organic Fraction of Municipal Solid Waste) may fall short of the theoretical BMP due to inefficiencies in the digestion process and the partial degradation of certain organic compounds. Additionally, theoretical BMP values are often overestimated, as they do not account for various inhibitions during digestion (Jingura & Kamusoko, 2017). The experimental BMP still had high potential in biogas production, but the difference indicated that the digestion process might need optimisation. The Modified Gompertz Model gave a good approximation, but practical conditions may provide less than full realisation of theoretical BMP.

CONCLUSION

The study revealed that OFMSW from Kumasi had a low moisture content with high volatile matter, and thus, it has great potential for biogas production. However, moisture adjustment is required for the anaerobic digestion process to be more efficient, and possible pretreatment may be necessary.

The high moisture content of 94.94% in the inoculum supported microbial activity for the success of the process and pH stabilisation. The peak biogas generation for OFMSW occurred on day 6 with a cumulative methane yield of 217.5096 mL CH_4 / g VS. Fitting experimental data to the Modified Gompertz Model yielded a maximal methane production rate of 19.4752 mL CH_4 /g VS/day and a biomethane potential of 219.3529 mL CH4 /g VS. indicating good biodegradability.

The observed differences between theoretical and experimental BMP values indicate the need for process optimisation to realise methane potential fully. This study affirms that organic waste-to-biogas conversion in Kumasi is a feasible and sustainable approach to managing organic waste while contributing to renewable energy generation. Improved waste management methods would reduce environmental pollution and enhance sustainability, ensuring energy security and helping to solve some of the significant challenges related to waste management.

The results have provided valuable information on waste characteristics in Kumasi, contributing to the development of sustainable waste-to-energy practices and encouraging a shift toward more resource-efficient and environmentally friendly modes of resource use.

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