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Kinetics Modeling of Biogas Production from Market Waste Inoculated with Abattoir Waste

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ABSTRACT

The anaerobic digestion process is a waste management method that is driven by microbes and therefore, it's vital to understand the basic operation kinetics. This study demonstrates the kinetic study for twenty market wastes inoculated with rumen fluid at mesophilic temperature. The substrates consisted of blended market wastes inoculated with rumen fluid for a seven days hydraulic retention time. The experimental data obtained were used for kinetic studies by fitting the data to Linear, Exponential, Gaussian, Logistics, and Modified Gompertz kinetic models. The results obtained showed that high cumulative biogas was observed in the market wastes mixed sample at 3500 mL followed by sweet potato, potato, and banana wastes at 2000 mL and 1700 mL respectively. The un-inoculated wastes fruit and vegetable wastes mixtures produced 300 mL, blank rumen 700 mL while co-digestion of waste with rumen matter produced 3500 mL of biogas. The kinetic evaluation of the biogas generation data showed that the coefficient of determination (R^2) was in the following ranges for all the twenty market wastes, linear model: 0.5478 - 0.9973, exponential model: 0.9099 - 0.9984, Gaussian model: 0.879-0.9932, Logistic Growth model: 0.9602 – 0.9963 and Modified Gompertz model: 0.9987 – 0.9999 respectively. Therefore, the Modified Gompertz model yielded high-accuracy result. Further, biogas generation from these models showed high accuracy with 25.96 mL/g cumulative biogas in contrast to the experimental yields of 23.58 mL/g with slight deviations of 2.87 %.

INTRODUCTION

Humanity generates an estimated 2.24 billion tons of municipal solid waste annually, of which only 55 percent is managed in controlled facilities. By 2050, this could rise to 3.88 billion tons per year. The waste sector is a significant contributor to greenhouse gas emissions in urban settings and biodiversity loss. Around 931 million tons of food is wasted each year, and up to 37 million tons of plastic waste is expected to enter the ocean annually by 2040 (UNEP (2022). The United Nations General Assembly on 14 December 2022 formally recognized the importance of zero-waste initiatives and proclaimed 30 March as the International Day of Zero Waste, to be observed annually beginning in 2023 (UNEP, 2022). According to a report by the United Nations Environment Programme (UNEP) in 2018, Kenya generates about 22,000 tons of waste per day, with Nairobi accounting for over 50% of the total waste generated in the country. This amount of waste is expected to increase as the population grows and urbanization continues UNEP, 2022). In Kenya's capital city of Nairobi, an estimated 2,400 tons of solid waste is generated every day, 20% of which is in plastic form. Poor waste management, coupled with rising urban pressure, have heightened the risks of environmental degradation in the city of 4.4 million people. Of the waste generated by the city, only 45% is recycled, reused or transformed into a form which can yield an economic or ecological benefit, a far cry from the 80% target set by the National Environment Management Authority (The World Bank, 2021).

As the population increases and rates of production and consumption increase, the estimated volumes of waste generated from households, industries, agricultural services, construction, healthcare facilities will triple between 2009 and 2030. Kenya generates an estimated 22,000 tons of waste per day calculated by assuming an average of per capita waste generation of 0.5 kilograms for a current population of 45 million translating to 8 million tons annually. It is estimated that 40% of the waste is generated in urban areas. Given that urbanization is increasing by 10%, by 2030, the Kenya urban population will be generating an estimated of about 5.5million tons of waste every year, which is three times more the amount of waste generated in 2009. Past inventories estimate that 60% to 70% of waste generated is organic, 20% plastic, 10% paper, 1 % medical waste and 2% metal. Inefficient production processes, low durability of goods, unsustainable consumption and production patterns lead to excessive generation of waste (ministry of environment and forestry, 2021).

Degradable wastes do contribute to the release of greenhouse gases (GHG), particularly methane, to the atmosphere (Turner *et al.*, 2015). This could have negative climate change effect through the release of greenhouse gases to the atmosphere. However, proper management of these wastes, particularly through energy recovery and recycling amongst others (Ackerman, 2000), could mitigate this effect. Global waste generation is estimated at 0.26 tons per capita, and it is projected to increase by 70% in 2050 (Sensoneo, 2020). Per capita waste production in sub-Saharan Africa has an average of 0.65 kg per person per day Bhada-Tata and Hoornweg, 2012). Organic

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wastes produced within human settlements include food waste (FW), agricultural waste, yard waste (YW), human and animal waste (Awosusi, 2010); Oladepo *et al*., 2014). Studies show that wastes, particularly organic wastes, are improperly managed in the world (Awosusi, 2010); Oladepo *et al*., 2014), inducing the necessity to find and implement suitable methods of waste management, such as the use of anaerobic digestion. Anaerobic digestion (AD) is a non-thermal technological approach to waste management. Biogas is formed by anaerobic digestion of organic materials which can be produced from kitchen wastes, cow dungs, poultry, pig faeces, etc. The bioslurry is nutrient rich organic fertilizer that can be used in farmlands and gardens (Riagbayire & Nayem, 2023). In addition, the substrate can be consumed by microbes in anaerobic conversion of substrate to electricity using microbial fuel cells (Mbugua *et al*., 2021).

The use of AD as a waste management technology has huge potential to meet both purposes of mitigation and adaptation approaches in climate change management strategies (Chand *et al*., 2012). AD produces biogas that can be used as a substitute in various sectors, including transportation, agriculture, residential/household, and industrial sectors. The gas can be particularly helpful in cottage industries in rural areas for the processing of agricultural products such as providing needed energy for frying of milled cassava to garri. For example, the use of biogas produced from AD technology has been shown to reduce the use of fuel wood and this in turn lessens forest degradation Chand *et al*., 2011) (energy need for garri processing is discussed in more detail in a later section). Also, AD of vegetal organic waste could reduce particulate matter by 5.3%, climate change by 6.4% and ozone depletion by 13.4% as opposed to using them directly as fertilizers in farms (Bacenettia *et al*., 2015). These facts highlight the need to develop integrated AD systems that not only mitigate the GHG emission from by-products of agriculture but will also serve as energy source which can then be put into agricultural processing. However, implementing the production of biogas for energy production in the world is faced by a number of challenges, insufficient amounts of substrate for biogas generation (Clemens *et al*., 2018) and unavailability of local technology in developing countries leading to increased cost of putting biogas to use (Hoo *et al*., 2018). Despite these, however, biogas production can still play a vital role in augmenting communal energy needs particularly in rural settings, hence this study.

The anaerobic digestion kinetic models are used to predict the rate of biogas production from a substrate (Rea, 2014). According to Rea, 2014, most models of anaerobic digestion rely on simple algebraic equations instead of biochemical reactions. The mathematical kinetic model used for the AD process plays a vital role in optimizing, predicting, simulating, and monitoring process performance under various conditions (Bong *et al*., 2017). The models help in the prediction of kinetic parameters as well as in clarifying the digestion process.

Therefore, this study was carried out to investigate the kinetics of biogas production from the twenty fruits and vegetable market wastes by fitting the experimental data into linear, exponential, Gaussian, logistic growth model and modified Gompertz models.

METHODOLOGY

Sampling

The inoculum used in this study was obtained from Dagoretti slaughterhouses (1°17'02.6"S 36°41'02.2"E) in Kiambu County, Kenya. The market wastes including vegetable and fruits wastes were obtained from Kangemi Market (1°15'52.9"S 36°44'55.6"E) and Wakulima Market (1°17'13.3"S 36°49'56.2"E) in Nairobi County, Kenya. A map of the sampling sites is shown in figure 1.

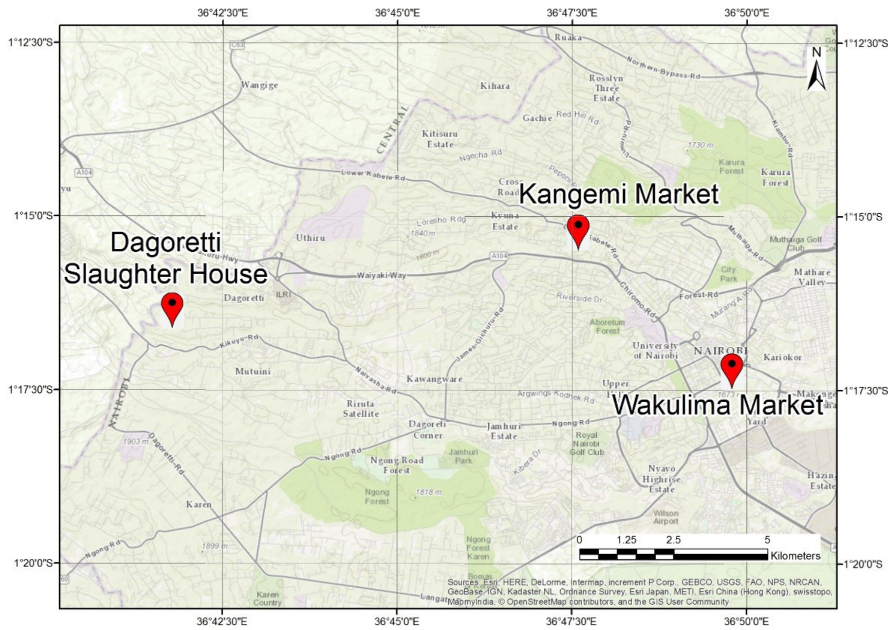

Figure 1: A map of the sampling points

Biogas Productions

The vegetable and fruit samples composing of Cabbage (*Brassica oleracea capittta*), Coriander (*Coriandrum sativum.*), Spinach (*Spinacia oleracea*), Banana (*Musa spp*), Sweet Potato (*Ipomoea batatas*), Kales (*Brassica oleracea acephala*), Cucumber (*Cucumis sativus*), Watermelon (*Citrullus lanatus*),Pumpkin Leaves (*Cucurbita maxima*), Tomato (*Lycopersicon lycopersicum*), Potato (*Solanum tuberosum*), Avocado (*Persea americana*), Carrot (*Daucas carota*), Mango (*Mangifera indica*), Papaya (*Carica papaya*), Kahurura (*Cucumis ficifolia*), Pig Weed (*Amaranthus spp.*), African Nightshade (*Solanum nigrum*), Togotia (*Erucastrum arabicum*), comfrey (*Symphytun officinale*) and Courgette (*Cucurbita pepo*) were obtained from Kangemi and Wakulima markets in Nairobi County and while rumen fluid was obtained from Dagoretti slaughterhouse. The individual wastes were chopped into smaller pieces before blending with a heavy duty commercial blender. 200ml was loaded into 500ml bottle where 200 fresh rumen fluid was added. A graduated urine bag was attached for volumetric measurement. The setup was loaded into a water bath where temperature was maintained at 55^{0}C using a thermostatic hot plate. The cumulative biogas produced was recorded daily for a HRT of seven days. The biogas production at mesophillic conditions was setup by immersing the anaerobic sealed bottle with inoculated market waste with rumen matter (1:1) in a water bath maintained at 37^{0}C as shown in figure 2 (Kamau *et al.*, 2020).

Figure 2: A set-up of biogas production at the mesophilic condition

Biogas Production Simulation

The kinetic studies were carried out by fitting the experimental data of biogas production to various kinetic equations. Biogas production rates of twenty market wastes co-digested with rumen fluid was simulated using linear, exponential, Gaussian and modified Gompertz models plots. Analysis of the experimental data was performed in MS-excel 2013-2016 using the solver feature, QtiPlot and Minitab 17.0 statistical software's by non-linear regression. The kinetic parameters of the various models were evaluated after fitting the experimental data using the non-linear curve fitting as previously described by Gunorubon *et al.* (2021).

RESULTS AND DISCUSSIONS

High biogas generation was observed for wastes inoculated with rumen waste. From figure 3, high cumulative biogas was observed in FVMW sample at 3500mL followed by

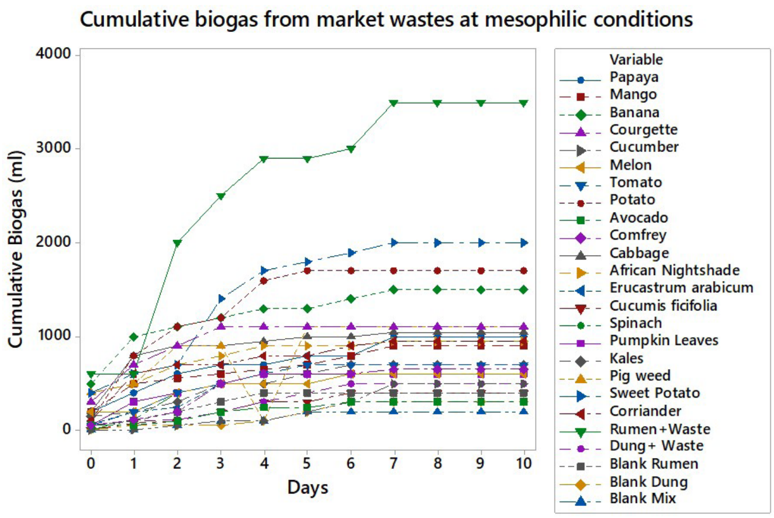

Figure 3: Mesophilic (37 ^{0}C) biogas production from inoculated market wastes

sweet potato, potato, and banana wastes at 2000 mL and 1700 mL respectively. Pages *et al.* (2011) reported that co-digestion increased biogas significantly. A ten day retention time was used to plot the cumulative biogas where the observed biogas production increased from day one on seven and plateaued thereafter as per figure 3. The results are explained by the fact that methanogens in rumen wastes degrade the volatile matter in the wastes generating biogas. In the FVMW sample, there is the availability of high levels of nutrients required for microbe activity and well as for breakdown to biogas. The balance between carbon and nitrogen in the waste mixture also explains the high production rate and levels. Further, in figure 4 control experiments were set by studying biogas production from un-inoculated waste mixtures, blank rumen waste and blank dung as well as inoculating the wastes mixtures with dung and rumen wastes. Un-inoculated wastes produced 300 mL, blank rumen 700 mL while co-digestion of waste with rumen matter produced 3500 mL of biogas. This had previously been reported by Mwaniki *et al.* (2016) on the influence of rumen microbes in biogas generation process.

Biogas Production Modeling

The five kinetic models applied in this study were fitted to the experimental data using the QtiPlot curve fitting toolbox at a coefficient confidence bound of 95% to obtain the constants in each of the kinetic models. The curve fit of the experimental data for the five models with their constants and correlation coefficient (R2) evaluated are shown thus. The cumulative biogas produced within first seven days (upward trend) was used to plot the graphs in this section.

Simulation and Modeling

Validated mathematical models built from mechanistic studies that lead to a more in depth understanding of the very complex transport phenomena, microbial biochemical kinetics and stoichiometric relationships associated with anaerobic digestion can be used to improve the design and optimization of anaerobic digestion processes for biogas development (Shete & Shinkar, 2014). Various kinetic models were used to match the obtained data in this section.

Anaerobic Digestion Kinetic Study

The performance of AD digester can be predicted by the AD Kinetic studies. The limiting parameters can also be highlighted by the kinetic studies. The performance of the AD process was investigated using first-order kinetic models (Cecchi *et al.*, 1991). The experimental data fitted differently to distinct models. For example, the fitness of the data to the linear model was observed to best explain the biogas experimental data in avocado, tomato, and mango with high regression rates of 0.98-0.99. However, in sweet potato and comfrey, the regression was 0.54-0.63, which means that the data is unfit to the linear model. In this section, some for some wastes are shown as representative plots of the twenty samples.

Linear Kinetic Model

The model suggest that biogas generated rises with HRT as per equation 1.0(Ghatak &Mahanta, 2014).

$$B_1=a_1+b_1\ t \qquad (1.0)$$

Where B_1 is the biogas production rate (L kg^{-1} d^{-1}) at time t (day), t is the time (day) over the digestion period, a1 is intercept (L kg^{-1} d^{-1}) and b1 is slope (L kg^{-1} d^{-1}). For rising limb, b_1 is positive, whereas b1 is negative for falling limb. The obtained data were fitted onto the linear kinetic model and coefficient of determination R^2 got was in the range of 0.63 to 0.98. The plots are shown in 4.

From figure 4, the slope represents feedstock's digestion rate. This is due to the high microbe counts in rumen compared to the counts in manure translating to high competition for substrate depletion.

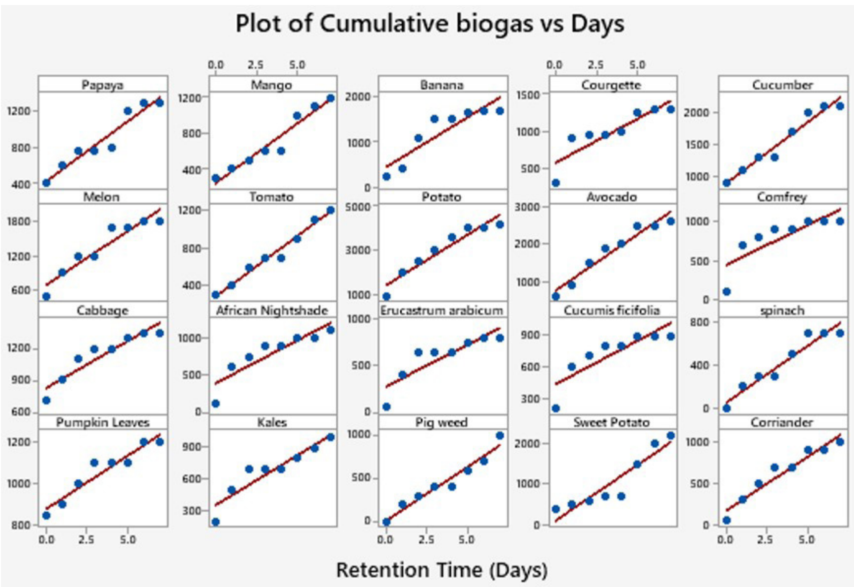

Figure 4: Plot of the linear model for market wastes biogas production

Exponential Kinetic Model

The exponential model proposes exponential increase in biogas formed with time (equation 1.1) (Kumar *et al.* 2004; Das & Mondal, 2015).

$$B_1=a_1+b_e\exp(c_e t) \quad (1.1)$$

Where B_1 is the biogas production rate (L kg^{-1} d^{-1}) at time t (day), t is the time (day) over the digestion period, a1 is intercept (L kg^{-1} d^{-1}) and b1 is the slope (L kg^{-1} d^{-2}) and c is a constant (d^{-1}). For the upward limb, b_1 is positive and b_1 is negative for downward limb.

The experimental data plot is shown in figure 5, with y representing the cumulative biogas produced in mL/day. The coefficient of determination was in the range of 0.78 to 0.99.

Figure 5 depicts the exponential curves of the cumulative biogas generated from banana market waste inoculated with rumen waste. The correlation of the operation parameters relates highly with R^2 of 0.97.

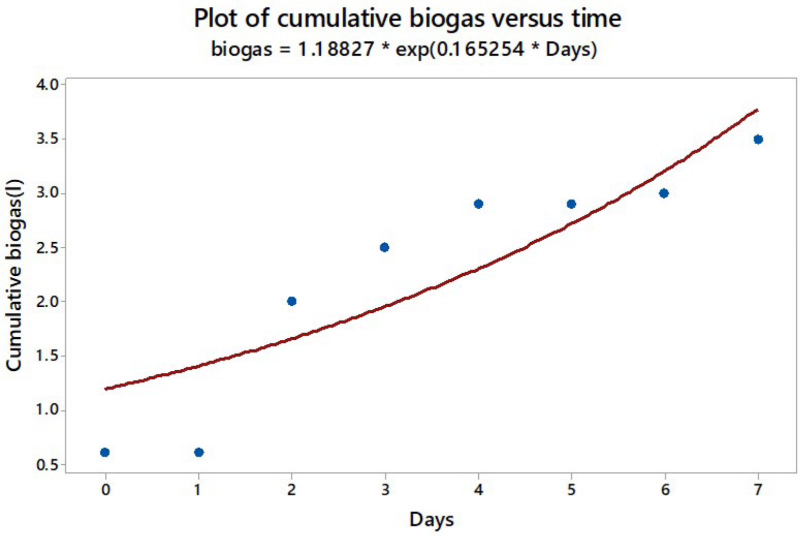

Figure 5: The exponential plot for FVMW mixture biogas production

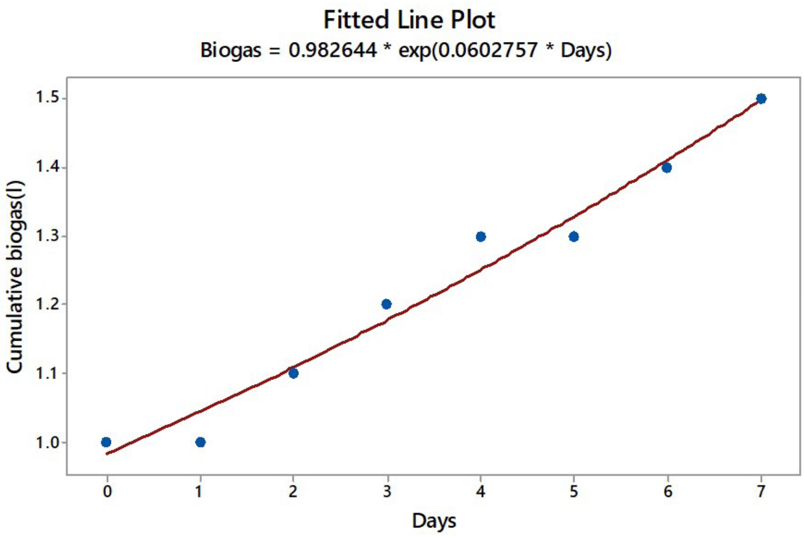

Figure 6: Exponential plot for banana wastes biogas production

Gaussian Kinetic Model

Assuming that biogas generation rates and microbial kinetic growth and its decay would follow the normal distribution throughout the breakdown period, the Gaussian equation, presented in equation 1.2 (Das and Mondal, 2015; Lo *et al.*, 2010) was employed to predict biogas recoveries rate including ascending and descending limb.

$$B_1=a_1\exp(-0.5((t-t_o)/b)^2) \quad (1.2)$$

Where t_0 is the time (day) where the peak (maximal) biogas generation rates occurred.

The obtained normal distribution curves for the growth are shown in figure 7 for the blanks and the market wastes production.

According to the Gaussian plot in figure 7, the plots rise from day one of digestion and plateaus when microbial activities stop showing depletion of substrates. The curves start to drop, indicating no further biogas production. This is the point at which loading should be done for a continuously operated digester. The coefficients of determination were 0.83, 0.96 and 0.95

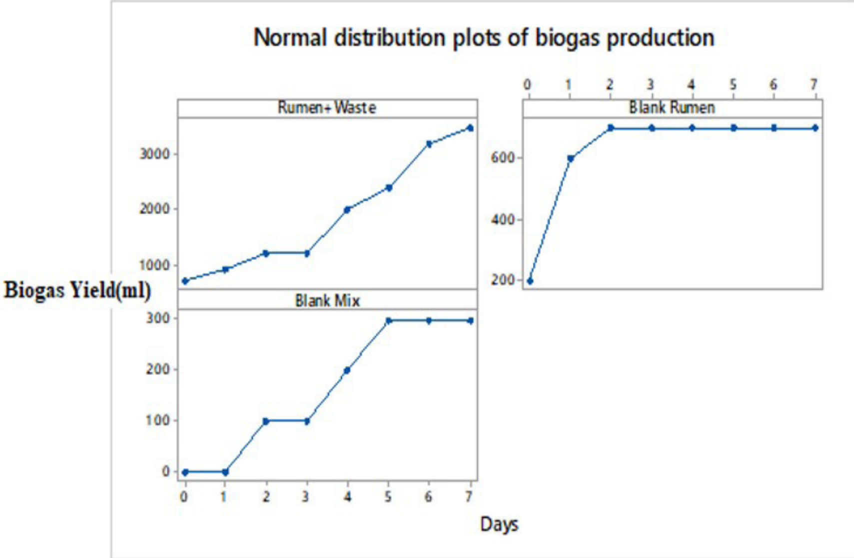

Figure 7: The normal distribution curves for biogas production

for blank waste, waste + rumen and blank rumen, respectively. The trend is very pronounced in bank rumen, where the rate of substrate breakdown is very high and stops in day two, where the curve flattens. As for the blank waste mixture, the bacteria in the wastes take time to adjust to the environment in the digester for about 3 days and then production is halted at day 5 due to pH changes (Mbugua *et al.*, 2020). The growth and development of the microbes are clearly shown in blank waste and waste inoculated with rumen waste. Initially, the microbe's concentration is low and require time to adapt at lag phase. The concentration increases rapidly and high biogas generation is witnessed (growth phase). This phase terminates when cells compete for diminishing substrate and therefore, replication equals death (stationary phase). The stationary phase ends when death is higher than reproduction and biogas generation decreases rapidly (death phase) (Velázquez-Martí *et al.*, 2018).

Modified Gompertz Equation

The experimental data from the co-digestion of market waste with rumen matter was investigated for its alignment to the modified Gompertz equation 1.3.

$$P=\gamma_m.\exp\{-\exp[(u.e)/\gamma_m(\lambda-t)+1]\} \quad (1.3)$$

The resultant curve is indicated in figure 8.

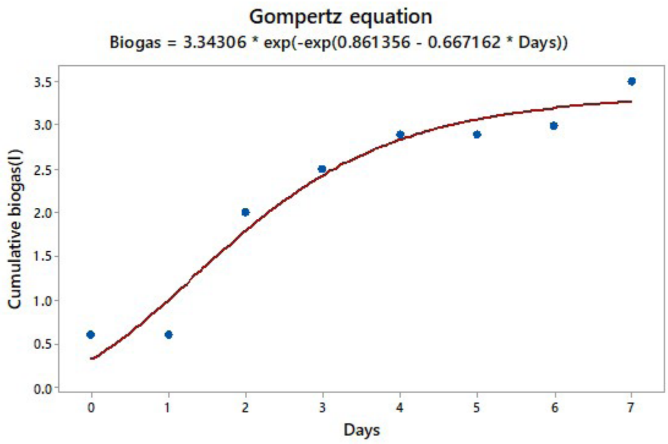

Figure 8: The Gompertz plot for FVMW plus rumen biogas production

In the simulation section, the coefficient of determination of FVMW inoculated with rumen was 0.96 and the plot is shown in figure 8. Biogas generation rate (μm) and lag phase period (λ) was found to be 3.34mL/gm/day and 0.86 days at 55°C while the biogas generation (P) was estimated at 49.09 mL/gm. This is consistent with the results reported for cow dung waste at the thermophilic temperature at 39.10mL/g biogas produced at a production rate of 1.40 mL/g/day and a lag phase 6.22 day (Ghatak and Mahanta, 2014).

The kinetic parameters of various models are shown in table 1. The parameter are ranges of constants obtained from the twenty samples used in this study.

The kinetics parameters are in corelation with other

Table 1: Kinetic Parameter of the Various Models

Model	Parameters	R^2
Linear	a=2.6983-3.6895	0.5478 - 0.9973
	b=0.9817-2.1547	
Exponential	A=-102.659 –9.0878	0.9099 - 0.9984
	b=105.5302-73.2658	
	c=0.09852 – 2.3568	
Gaussian	A1= -0.0089- -0.2587	0.879-0.9932
	T1= -6.354 – 0.4782	
	b1= 2.9851-7.7592	
Modified Gompertz	A= 23-635-30.256	0.9987 – 0.9999
	b= -0.9666 - -0.4891	
	k= 0.987-5.0524	
	A= 20.879-29.1023	
	λ= 0.987-5.6321	
	U = 1.879-7.5682	

research works in biogas experimental data simulation. For example, Mbugua *et al.* (2020) reported that modified Gompertz model was fit in modeling biogas data from organic market wastes with a correlation factor of 0.9998.

CONCLUSIONS

This study observed that the kinetic evaluation of the biogas generation data showed that the coefficient of determination (R2) were in the following ranges for all the twenty market wastes, linear model: 0.5478 - 0.9973, exponential model: 0.9099 - 0.9984, Gaussian model: 0.879-0.9932, Logistic Growth model: 0.9602 – 0.9963 and Modified Gompertz model: 0.9987 – 0.9999. Respectively. Further, the Modified Gompertz model yielded high accuracy result. Further, biogas generation from these model showed high accuracy with 25.96 mL/g cumulative biogas in contrast to the experimental yields of 23.58 mL/g with slight deviations of 2.87 %.

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