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Kinetic Model for Production of Carbon(iv)oxide (CO_2) from Brewers Spent Grain Using Anaerobic Digester

Chukwuemeka Peter Ukpaka[1,*], Vincent Godfrey Ikoro[2], Patience N. Ikenyiri[3]

Abstract

In this research paper, investigation studies were carried out to determine which model best predicts the amount of using the linear, power, growth rate decay, and non-elementary rate models, the kinetics of the biogas produced under the impact of biodegradation were explored. Carbon(iv)oxide was produced as a fraction of the biogas acquired from the experimental conditions. Either of the linear, power, growth rate decay, and non-elementary rate models can be used to investigate biogas production, as all the models with a regression value R^2 of approximately 1 is proven to be suitable. Increase in the production of CO_2 was observed with an increase in the degradation of the spent grain in anaerobic digested as well as decrease in the concentration of spent grain. The kinetic of the linear model is $r_{biog} = 0.0367C_S$, and that of the power model is $C_s = 4.944 \times 10^{-4} C_S{}^{-4.5}$ as well as the established model can be found useful in monitoring, predicting and simulating the rate of spent grain degradation as well as the CO_2 production under the action of microbial activities in anaerobic digester. This study has proved the significance of anaerobic digester in the production of CO_2 as the MATLAB simulation demonstrates the trend of product yield as well as functional parameters and coefficients determination.

Keywords: Anaerobic digester, biokinetic model, brewers spent grain, carbon(iv)oxide production, CO_2

INTRODUCTION

Brewery wastewater, surplus yeast, and brewery spent grain (BSG) are all examples of by-products and waste generated by the brewing industry. It is generally recognized that surplus yeast and BSG can be used as animal feed or other secondary resources [1–3]. However, with the rising energy costs, the brewing industry which uses roughly a large amount of Carbon(iv)oxide (CO_2) gas per L of brew, is attempting to shift most of its waste to the production of alternative energy sources especially CO_2. In this light, anaerobic digestion has become an important aspect of the brewing industry for producing sustainable energy in the form of biogas, which is created from the waste substrates indicated above [4]. Similarly, Carbon(iv)oxide (CO_2) is an integral, and important constituent in beverage production in the brewing industry, hence large amount of money is spent annually to purchase carbon(iv)dioxide CO_2. This has made the brewing industry focus on using its production waste like brewery spent grain to produce biogas and hence CO_2 through the process of anaerobic digestion [5]. In recent years, the treatment of brewing wastewater has been extensively researched and developed. This field has primarily used granular sludge blanket technologies, such as the UASB (up-flow anaerobic sludge blanket) reactor. Excess yeast has also been effectively used as a source of bioenergy. Due to its vast quantity, the BSG is the most promising

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substrate for biogas production [6]. However, because of its low biodegradability, a practical and long-term industrial technique is yet to be established. BSG has a significant quantity of lignin, hemicellulose, and cellulose [7].

The kernel husk, pericarp, and seed coat, which are high in cellulose, non-cellulosic polysaccharides, lignin, and proteins, make up the bulk of the BSG. In general, the BSG is a lignocellulosic material that is high in fibers and proteins, accounting for a large percentage of its makeup. Biodegradation of this lignocellulosic substrate is difficult due to the structural complexity of lignin, its large molecular mass, chemical stability, and insolubility. Lignin is a complex molecular structure cross-linked polymer of phenolic chemical compounds. It is found in plant principal cell walls, where it gives structural support, non-permeability, and microbial resistance [8]. Lignin is biodegradable in aerobic settings and can also degrade slowly in anaerobic settings. Pre-treatment of lignocellulosic biomass to make it more sensitive to biodegradation is one of the possible strategies for improving anaerobic digestion of the biomass. Physical, chemical, biological, and hybrid pre-treatments have all been employed to improve the digestibility of lignocellulosic biomass. Higher temperatures and acidic conditions are known to promote cellulose and hemicellulose hydrolysis, which leads to the synthesis and release of a variety of low molecular mass molecules. Alkali and some enzymes were shown to have a similar impact [9].

Only by separating the hydrolytic and methanogenic processes can anaerobic fermentation produce biogas from BSG efficiently. The presence of lignin in the BSG inhibits the hydrolysis of the fibre material while also acting as a potential limiting step for the complete breakdown of the substrate. Weak acids, furan derivatives, and phenolic compounds produced by microbial hydrolysis of lignocellulose may hinder the subsequent microbial degradation stages of acidogenesis, acetogenesis, and methanogenesis [10]. The final stage is particularly delicate, making biogas production from lignocellulosic substrates extremely difficult. As a result, research on BSG anaerobic digestion is limited. Older publications showed that traditional digestion was not a cost-effective option [11]. To digest the BSG successfully, the anaerobic digestion process hydrolysis stage must be segregated from subsequent stages because it is the limiting phase. It has also been demonstrated that the separated hydrolysis stage can give up to eighty-five percent overall degradation efficiency [5, 6]. These procedures, however, have never been used, owing to the high parasitic energy demands of hydrolysis and/or economic impossibility (low energy prices at the time).

Solid-state anaerobic digestion (SS-AD), or anaerobic digestion with a total solids content greater than fifteen percent, is a promising technology for converting lignocellulosic biomass to renewable energy in the form of biogas. Because of the reduced floating and stratification problems associated with fibrous materials, the SS-AD is thought to be better suited for the treatment of lignocellulosic biomass than conventional AD [11]. In addition, as compared to traditional anaerobic digestion, the SS-AD has various advantages, including a smaller reactor volume, fewer energy requirements for heating, less material handling requirements, and a reduced total energy demand for process operation. The biogas produced by SS-AD is comparable to that produced by traditional AD [9], but it is more effective at greater organic loading rates and has a greater volumetric biogas productivity. The biodegradability of raw and processed BSG was investigated in this study. The BSG's biogas potential was first determined.

MATERIAL AND METHODS

Materials

The following materials were used in this study; bio-digester (batch reactor), GC-MS chromatography, gas recovery cylinder, brewers' spent grain BSG, digital pressure gauge, digital pH meter, digital thermometer, weighing balance, distilled water, hand glove, mask, flexible hose and clips etc.

Model of Kinetics

The acquired experimental data were fitted into four empirical rate models to improve appropriate assessment and comprehension of the biogas generation rate from the brewers spent grain (biomass). Among the rate equations examined are the linear, power, growth rate decay (GRD), and non-elementary rate (NER) models.

Linear Model

The rate of biogas generation was calculated using a linear model that is stated as follows in terms of biomass content in Equation (1).

$$-r_s = r_b = kC_S \tag{1}$$

where, r_s = Biomass depletion rate (g/ml.day), r_b = Biogas production rate (g/ml.day), C_s = Biomass concentration (g/ml) and k = Specific rate constant (day^{-1}).

Plotting the rate of biogas generation against the instantaneous concentration of biogas yielded the value of the rate constant. The rate constant is represented by the slope of this graph.

Power Model

The power model for the rate of biogas generation studied in this research work is given in Equation (2), and we have

$$-r_s = r_b = kC"_S \tag{2}$$

Model of Growth Rate Decay

The following is the growth rate decay model for the rate of biogas production that was studied in this study.

$$-r_s = r_b = \frac{kC_s}{M+C_s} \tag{3}$$

where, r_b = Biogas production rate (g/ml.day), Cs = Biogas concentration (g/ml), k = Maximum rate specific rate constant (g/ml.day) and M = Constant (g/ml)

Model of Non-Elementary Rates

The following is the non-elementary rate model for biogas generation that was examined in this study.

$$-r_s = r_b = \frac{k_1C_s+k_2}{c_s} \tag{4}$$

where, r_b = Biogas production rate (g/ml.day), C_s = Biogas concentration (g/ml), k_1 = Specific rate constant (g/ml.day) and k_2 = Constant ((g/ml) 2.day).

The Use of Rate Equations in Batch Reactors (Application)

The effectiveness of the rate equations was assessed by applying the various rate equations in a batch reactor (Figure 1).

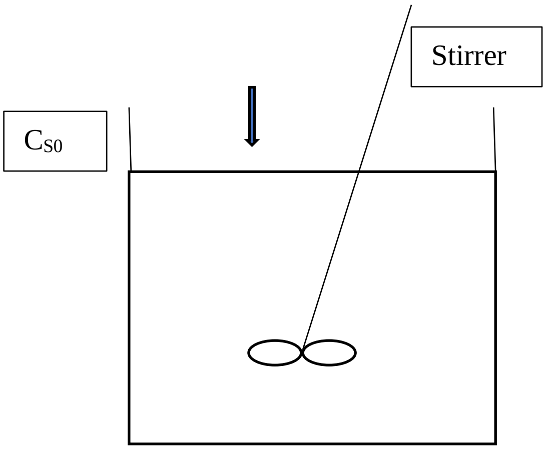

Figure 1. Batch reactor.

The resultant equation was used to forecast the quantity of biogas generated over time, or yield. The following is the model equation for a batch reactor derived from the mass continuity equation.

where, C_{so} = Initial concentration of biomass (g/ml), C_s = Instantaneous concentration of biomass (g/ml) and C_b = Biogas concentration (g/ml)

$$\begin{bmatrix} Rate\ of\ mass \\ flow\ into\ the \\ reactor \end{bmatrix} = \begin{bmatrix} Rate\ of\ mass \\ flow\ out\ of\ the \\ reactor \end{bmatrix} + \begin{bmatrix} Rate\ of\ biomass \\ deplection \end{bmatrix} + \begin{bmatrix} Rate\ of\ mass \\ accumulation \\ within\ the \\ reactor \end{bmatrix} \quad (5)$$

Rate of mass flow into the reactor = $F_0 C_{0S}$ (6)

Rate of mass flow out of the reactor = FC_S (7)

Rate of biomass depletion = $-\,r_s V$ (8)

Rate of mass accumulation = $\frac{dM_B}{dt}$ (9)

Equations (6) through (9) are substituted into (5) to produce

$$F_0 C_{0S} = FC_s + \ -r_s V + \frac{dM_B}{dt} \quad (10)$$

The inflow and outflow terms of a batch reactor are lowered to zero since there is no mass flow. As a result, Equation (10) becomes:

$$-\frac{dM_B}{dt} = \ -r_s V \quad (11)$$

such that,

$$-d\left(\frac{M_B}{V}\right) = \ -r_s dt \quad (12)$$

Integrating the above Equation (11) with respect to time gives:

$$-r_s = \frac{-d\left(\frac{M_B}{V}\right)}{t} = \frac{-dC_s}{t} \quad (13)$$

The model equation for a batch reactor is stated as Equation (13), where, Fo = Outlet volumetric flow rate (ml/day), F = Inlet volumetric flow rate (ml/day), V = Volume of reactor (ml), ms = Mass of biomass (g), t = Time of biogas production (day). We derived the model equations by substituting the rate terms of the various models into Equation (13).

The Linear Model in Application

When the linear model is substituted into the batch equation, the following results are obtained:

$$\frac{-dC_s}{t} = kC_s \tag{14}$$

Using the separation of variables approach to solve problem (14), we get

$$-\int_{C_0}^{C_{s0}} \frac{dC_s}{C_s} = k\int_0^t t \tag{15}$$

$$-In\left(\frac{C_s}{C_{s0}}\right) = kt \tag{16}$$

$$-In\, C_s = In\, C_{s0} - kt \tag{17}$$

A plot of ln C_s vs t yields the rate constant as the slope of the curve. However, the exponentiation of Equation (17) is used to forecast the concentration of biomass reduced over time in the batch reactor.

$$C_s = C_{s0}\exp(-kt) \tag{18}$$

Power Model

The power model was replaced into the batch model Equation (12) in the same way as the linear model.

$$-\frac{dC_s}{t} = kC_s^n \tag{19}$$

When both sides of Equation (19) are logarithmized, the result is

$$-In\left(\frac{dC_S}{T}\right) = Ink + nInC_s \tag{20}$$

The slope of the graph of n is determined by plotting $-In\left(\frac{dC_S}{T}\right)$ vs InC_s, whereas the intercept represents the logarithm of the rate constant. Again, Equation (19) is solved by integrating using the separation of variables technique to estimate the concentration of biomass in the batch reactor over time.

$$-\int_{c_{s0}}^{c_s} \frac{dC_s}{C_s^n} = k\int_0^t dt \tag{21}$$

Following the simplification, we have:

$$\frac{C_{s0}^{1-n} - C_s^{1-n}}{1-n} = kt \tag{22}$$

Or

$$C_s^{1-n} = C_{s0}^{1-n} - (1-n)\,kt \tag{23}$$

By multiplying both sides' powers by $\frac{1}{1-n}$, we get

$$C_s = [C_{s0}^{1-n} - (1-n)\,kt]^{\frac{1}{1-n}} \tag{24}$$

The prediction equation for the concentration of biomass left in the batch reactor with time is Equation (24)

Application of the Growth Rate Decay Model

When the growth rate decay model of Equation (3) is substituted into Equation (12), the result is as follows.

$$-r_s = -\frac{dC}{dt} = \frac{kC_s}{M + C_s} \tag{25}$$

However, inverting both sides of Equation (25) as follows is one of the easiest ways to derive the constants in Equation (25):

$$\frac{1}{-r_s} = \frac{M}{k}\left(\frac{1}{C_s}\right) + \frac{1}{K} \tag{26}$$

The slope of the graph of $\frac{M}{k}$ is determined by $\frac{1}{-r_s}$ plotting vs $\frac{1}{C_S}$, whereas the intercept represents $\frac{1}{K}$. to forecast the biomass concentration in the batch reactor over time, Equation (25) was solved numerically using the Runge-Kutta technique, as shown below:

$$C_s(j+1) = C_s(j) + [k_1 + 2(k_2 + k_3) + k_4]/6 \tag{27}$$

where

$$k_1 = hf(t(j), C_s(j) \tag{28}$$

$$k_2 = hf\left(t(j) + \frac{1}{2}h, C_s(j) + \frac{1}{2}k_1\right) \tag{29}$$

$$k_3 = hf\left(t(j) + \frac{1}{2}h, C_s(j) + \frac{1}{2}k_2\right) \qquad (29)$$

$$k_4 = hf(t(j) + h, C_s(j) + k_4) \tag{30}$$

H = Step size

The Runge-Kutta method was computed with the help of the MATLAB software.

Application of the Non-Elementary Rate Model

To apply the non-elementary rate model to the batch and utilize it to estimate the biomass concentration over time in the batch reactor, the rate equation supplied by the power model was substituted into the batch Equation (12).

$$-r_S = -\frac{dC}{t} = \frac{k_1 C_S - k_2}{C_S} \tag{31}$$

The following is a simplified version of Equation (31), we have

$$\frac{1}{-r_s} = k_1 - \frac{k_2}{C_s} \tag{32}$$

The slope of the graph of k_2 is determined by plotting $\frac{1}{-r_s}$ vs $\frac{1}{C_s}$, whereas the intercept is determined by k_1. However, using the Runge-Kutta technique, Equation (31) was solved numerically to estimate the biomass content in the batch reactor over time. The solution technique is the same as the algorithm given in Equations (26), (27) and (30).

Determination of Biogas Production Rate

The rate of biogas generation was calculated using the numerical technique.

$$\left(\frac{dC_s}{dt}\right)_{t_0} = \frac{-3C_{s0} + 4C_{s(1)} - C_{s(2)}}{2\Delta t} \tag{33}$$

$$\left(\frac{dC_s}{dt}\right)_{t_i} = \frac{C_{s(i+1)} - C_{s(i-1)}}{2\Delta t} \tag{34}$$

$$\left(\frac{dC_s}{dt}\right)_{t_n} = \frac{C_{s(n-2)} + 4C_{s(n-1)} - 3C_{s(n)}}{2\Delta t} \tag{35}$$

Equation (33), Equation (38), and Equation (35) were used to get the rate at time zero, all intermediate rates at any given time, and the final rate.

Determination of Biogas Concentration and Yield

The following mathematical relationship was used to calculate the concentration of biogas generated at any given time:

$$C_{biog} = C_{s0} - C_s \tag{36}$$

$$C_{biog} = \text{Biogas concentration(g/m)} \tag{37}$$

The biogas yield may be calculated in the same way

$$\mathrm{Y} = \frac{C_{biog}}{C_{s0}} = \frac{C_{s0} - C_s}{C_{s0}} \tag{38}$$

Determination of the Deviation Between Measured and Predicted Parameters

Using the expression in Equation (38), the difference between experimental and predicted biomass and biogas concentrations, as well as the biogas production, was calculated.

$$\mathrm{D} = \frac{\sum_{i=1}^{n} X_{\exp t.} - \sum_{i=1}^{n} X_{pred.}}{\sum_{i=1}^{n} X_{\exp t.}} \tag{39}$$

where, $\sum_{i=1}^{n} X_{\exp t.}$= The sum of all the values acquired from the experiment at any point in time, and $\sum_{i=1}^{n} X_{pred.}$ = The total of all values acquired from the model at any given time.

RESULTS AND DISCUSSION

Determination of Biogas Production Kinetics

The constants had to be calculated before the rate equations could be used successfully. Importantly, the constants may vary depending on a variety of circumstances, including the environment, process conditions, and operation mechanism. On the other hand, a Microsoft Excel spreadsheet was used to find the constant coefficients in the corresponding rate equations after the experimental data were fitted to the model equation.

Linear Model Coefficient

The determination of the biogas production kinetic parameters and coefficients are presented in figures below:

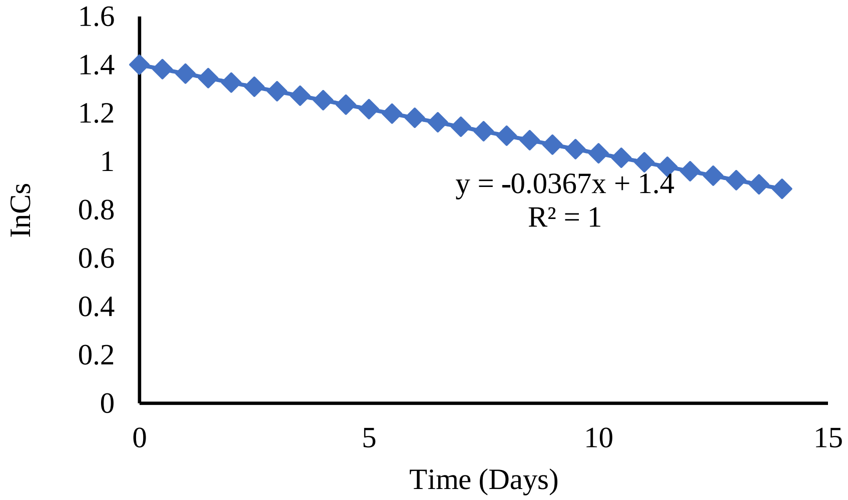

Figure 2. Determination of the coefficient of Linear Model (MATLAB Plot).

The equation in Figure 2 was used to calculate the specific rate constant in Equation (4), and the detail calculation was completed. The rate constant was calculated as 0.0367 day^{-1}. Thus, the rate of biogas production may be expressed as a function of the substrate (biomass) concentrate using the linear model.

This implies that a decrease in the concentration of the biomass simply indicates an increase in the biogas concentration, hence biogas (methane and carbon iv oxide) production.

$$r_{biog} = 0.0367C_S$$

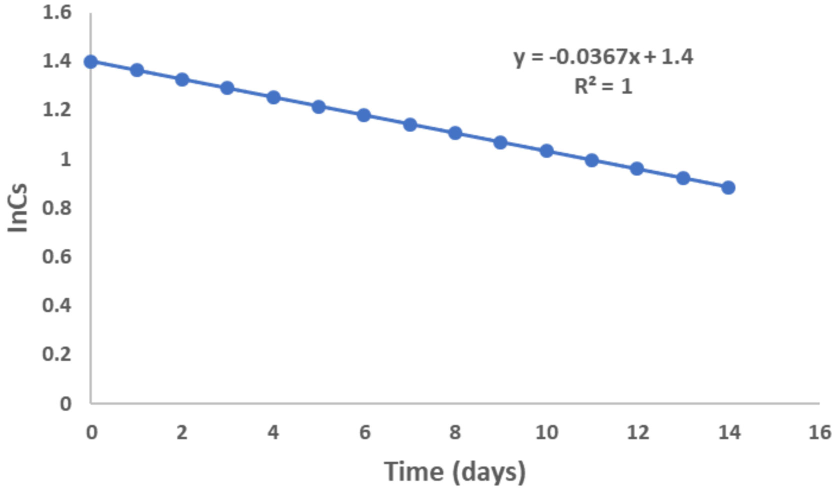

Figure 3. Determination of the coefficient of Linear Model (Excel Plot).

Figure 3 is an excel plot of the linear which further validates Figure 3. It shows that the linear model can be used accurately to predict the production of biogas from spent grain with a steady decrease in the concentration of the biomass as time increases. Also, from Figure 3, it is clearly observed that on the last day (14th day) of the experiment, only about 45% of the biomass have been consumed which indicates that the duration of the experiment can be increased to 30 days to allow complete biomass consumption and

Power Model Coefficients

Same as the linear model, Equation (23) was used to determine the precise rate constant and order of reaction in the power model. According to the calculations on the rate constant, k, is 0.000419 (ml/g) for 3.5.day, and the order of the bio-reaction, n, is almost equal to 4.5.day. Therefore, the rate of biogas production may be expressed as a function of the substrate concentration using the power model.

$$C_s = 4.944\ x\ 10^{-4}{C_S}^{-4.5}$$

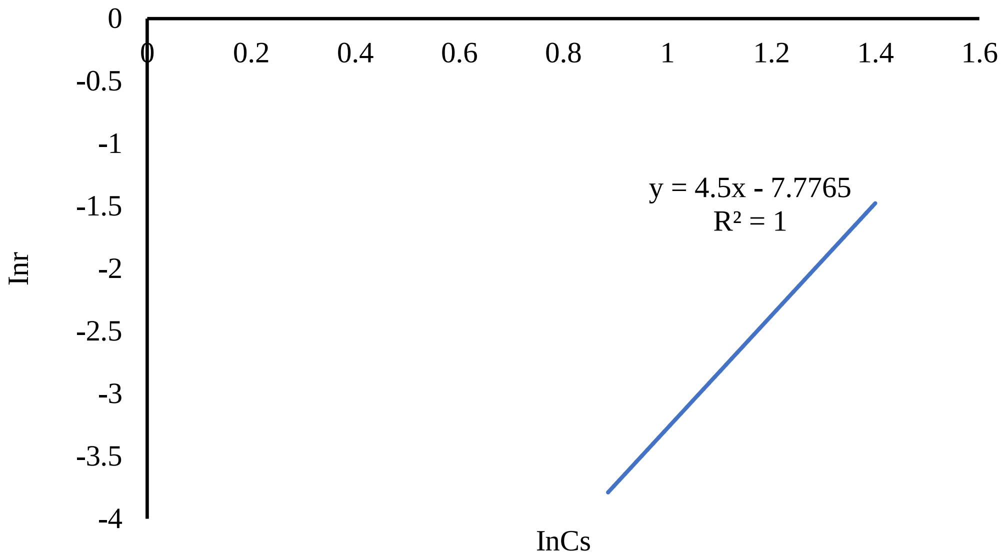

Figure 4. Determination of the coefficient in Power Model Inr against $\mathrm{InC_s}$ (MATLAB Plot).

The link between the substrate concentration and reaction rate is plotted in MATLAB in Figure 4. In this plot, it is clearly observed that at the beginning of the bio-reaction process with a high concentration of the biomass (spent grain), microbial activity was high and hence the reaction rate of the bio-reaction. Also, it can be observed that relationship between the rate of reaction and the concentration of the substrate is in a linear plot, so with a slope of 4.5x and a regression of 1, it can be stated that the rate of reaction is directly proportional to the concentration of the substrate which implies an increase in the concentration of the substrate will lead to a simultaneous increase in the rate of the bio-reaction.

Figure 5 is an excel plot of the power model coefficient which further validates Figure 4. But it can be clearly observed that the MATLAB plot is more accurate in determining the coefficients of a bio-reaction processes with a slope of 4.5x and a regression of 1, when compared to the Excel plot with a slope of 6.812x and a regression of 0.9964. Both Figures 4 and 5 show that the power model can be used accurately to predict the production of biogas from spent grain as a steady decrease in the concentration of the biomass with time flow simultaneously with a steady decrease in the reaction rate with time.

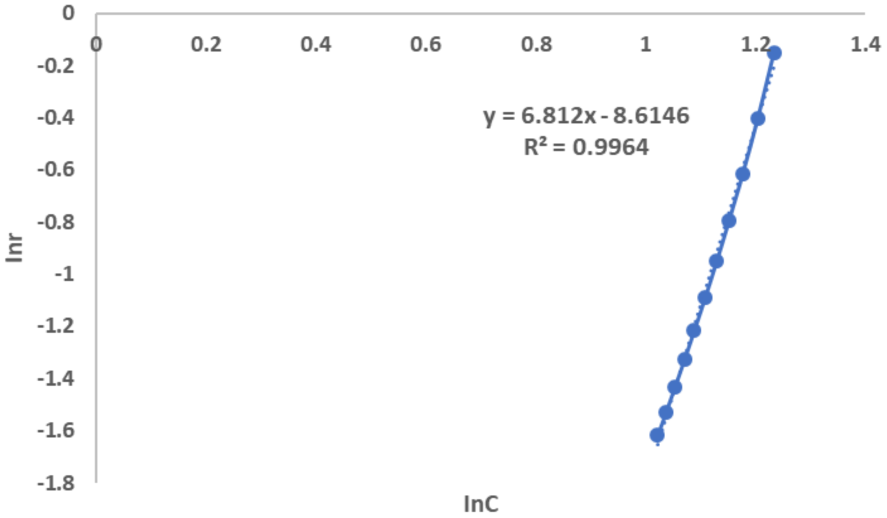

Figure 5. Determination of the Coefficient in Power Model Inr against $\mathrm{InC_s}$ (Excel Plot).

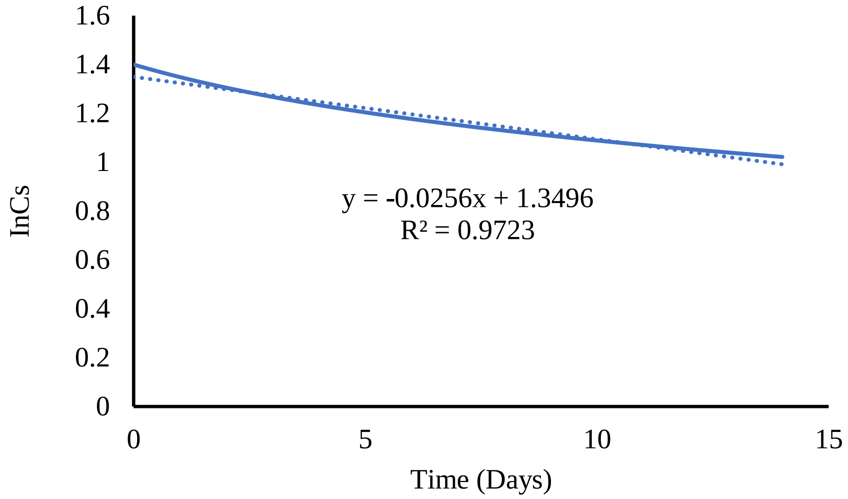

Figure 6. Determination of the coefficient in Power Model InC_s against Time (MATLAB Plot).

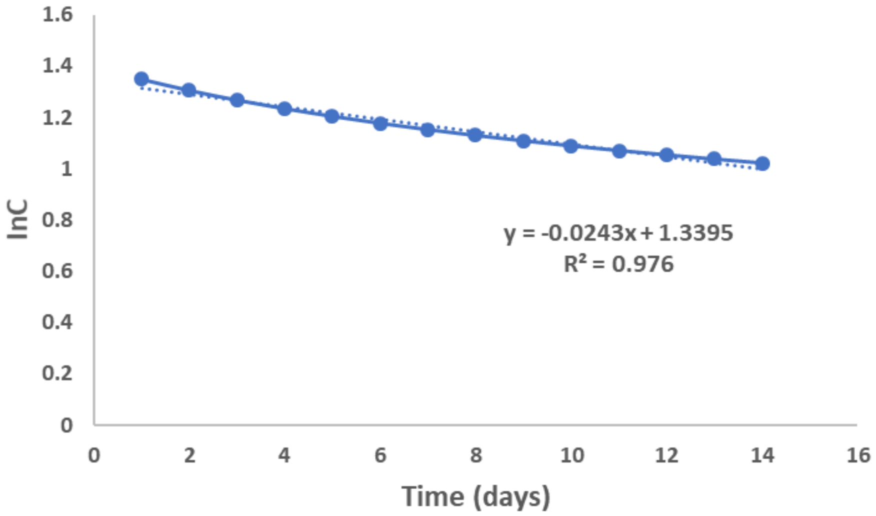

Figure 7. Determination of the coefficient in Power Model InC_s against Time (Excel Plot).

Both Figures 6 and 7 show that the power model though slightly less accurate when compared to the linear model in term of their regression can be used accurately to predict the production of biogas from spent grain with a steady decrease in the concentration of the biomass as time increase. Also, from Figures 6 and 7, it is clearly observed that at the last day (14th day) of the experiment, only about 45% of the biomass have been consumed which was also the case in Figures 4 and 5 indicating that the duration of the experiment can be increase to 30 days to allow complete biomass consumption and biogas production and clearly validates both models. Also, the MATLAB and Excel plot with the same slope and regression of –0.0367x and 1 respectively shows that for linear equations, the Excel plot is as accurate as the MATLAB plot.

GRD Model Coefficients

The constant, M, and the maximum specific rate constant, k, in the growth rate decay model were determined using Equations (25). According to the calculations, the highest rate constant, k, is –0.043g/ml/day, and the constant, M, is almost equal to 4.838g/ml. As a result, in terms of the substrate concentration, the rate of biogas production using the growth rate decay (GRD) model may be represented as:

$$r_{biog} = \frac{0.043C_s}{4.838 + C_s}$$

Figure 8 is a MATLAB plot of the relationship between the reaction rate and the concentration of the substrate. In this plot, it is clearly observed that at the beginning of the bio-reaction process with a high concentration of the biomass (spent grain), microbial activity was high and hence the reaction rate of the bio-reaction. Also, it can be observed that relationship between the rate of reaction and the concentration of the substrate is in a linear plot, so with a slope of 112.51x and a regression of 1, it can be stated that the rate of reaction is directly proportional to the concentration of the substrate which implies an increase in the concentration of the substrate will lead to a simultaneous increase in the rate of the bio-reaction.

Figure 8 validates Figures 4 and 5 and shows that the grow rate decay model with a regression 1 which is equal to that of the power model can be accurately used to predict the production of biogas from spent grain since the plot shows a direct proportionality between the rate of reaction and the and the concentration of the spent grain biomass.

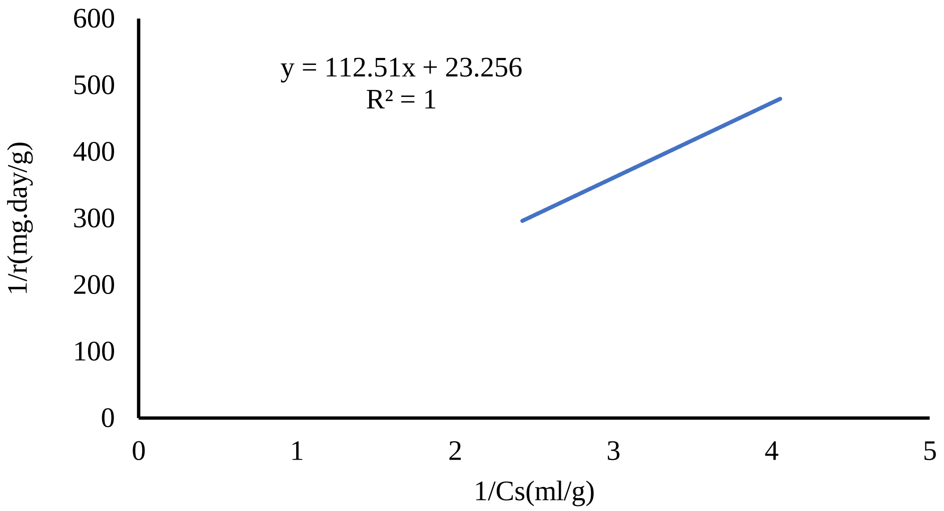

Figure 8. Determination of the Coefficient in GRD Model.

NER Model Coefficients

The non-elementary rate model's specific rate constant, k1, and second constant, k2, were derived using equation 36. The specific rate constant, k1, is 0.88g/ml.day, according to the calculations done, whereas the second constant, k2, is 2.650 (g/ml) 2day. To express the rate of biogas production as a function of the substrate concentrate, the non-elementary rate (NER) model can be employed as follows:

$$r_b = \frac{0.88C_s + 2.6503}{c_s}$$

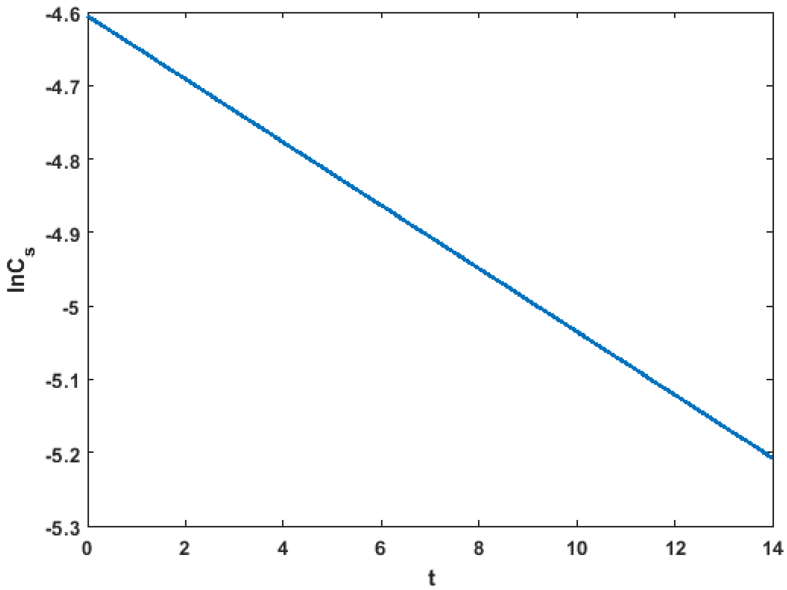

Figure 9. Determination of the coefficient in NER Model (MATLAB Plot).

Figure 9 shows that the non-elementary rate model can be used accurately to predict the production of biogas from spent grain with a steady decrease in the concentration of the biomass as time increases. Also, from Figure 9 it is observed that on the last day (14th day) of the experiment, the biomass has not been completely consumed which was also the case in Figures 2 and 3 indicating that the duration of the experiment can be increased to allow complete biomass consumption and biogas production and clearly validates both models.

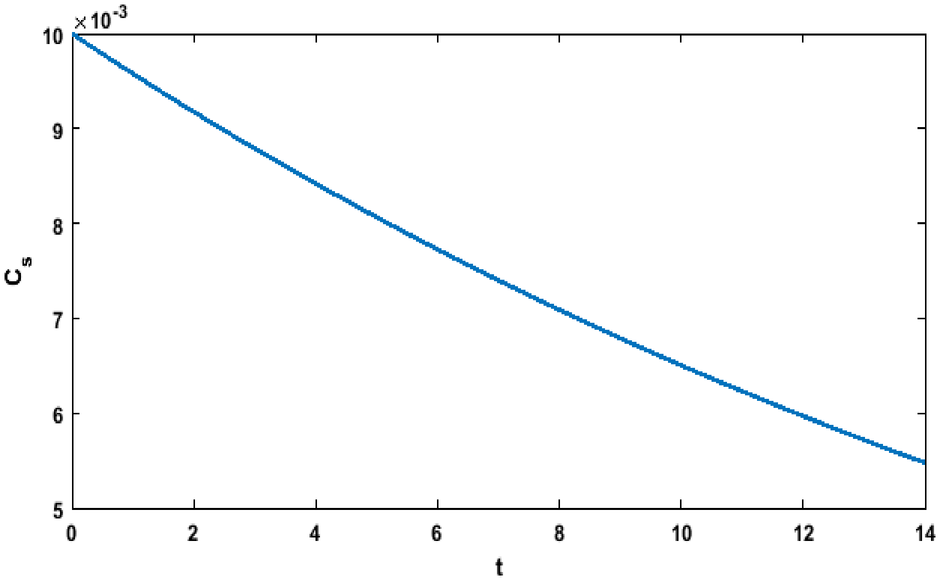

Figure 10. Determination of Substrate Concentration versus Time (MATLAB Plot).

Figures 10 and 11 are a MATLAB and Excel plot for the non-elementary rate model equation showing the relationship between the biogas concentration with increase in contact time or period of exposure. However, the investigation demonstrates a decrease in biomass concentration with an increase in time and this trend can be integrated to decline the substance, in which the products are obtained.

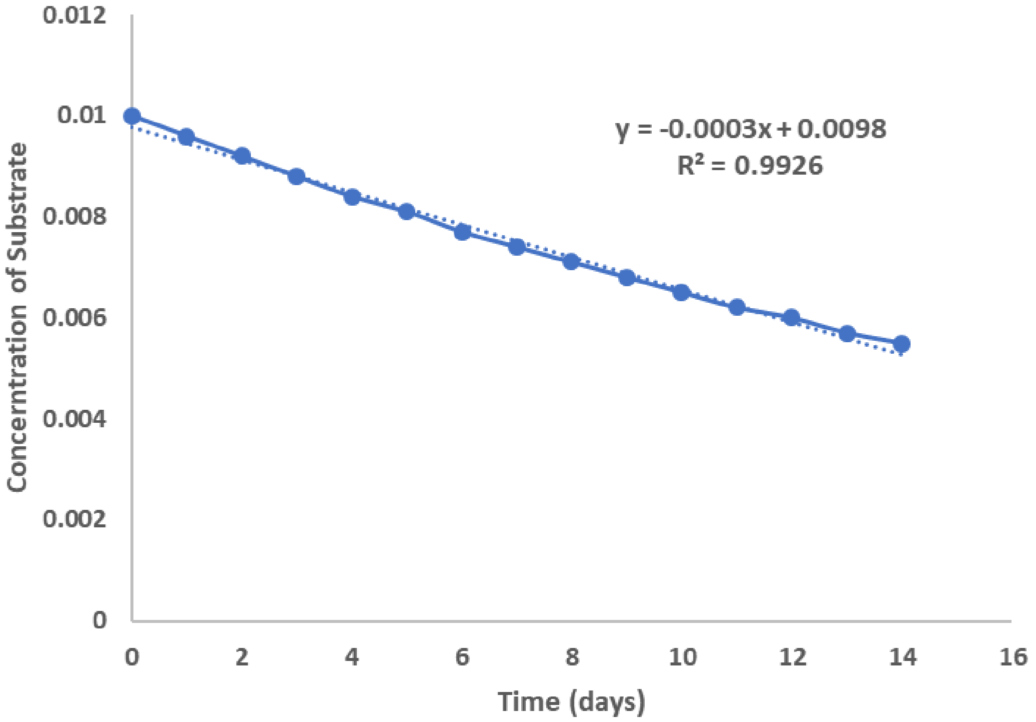

Figure 11. Determination of substrate concentration versus time (Excel Plot).

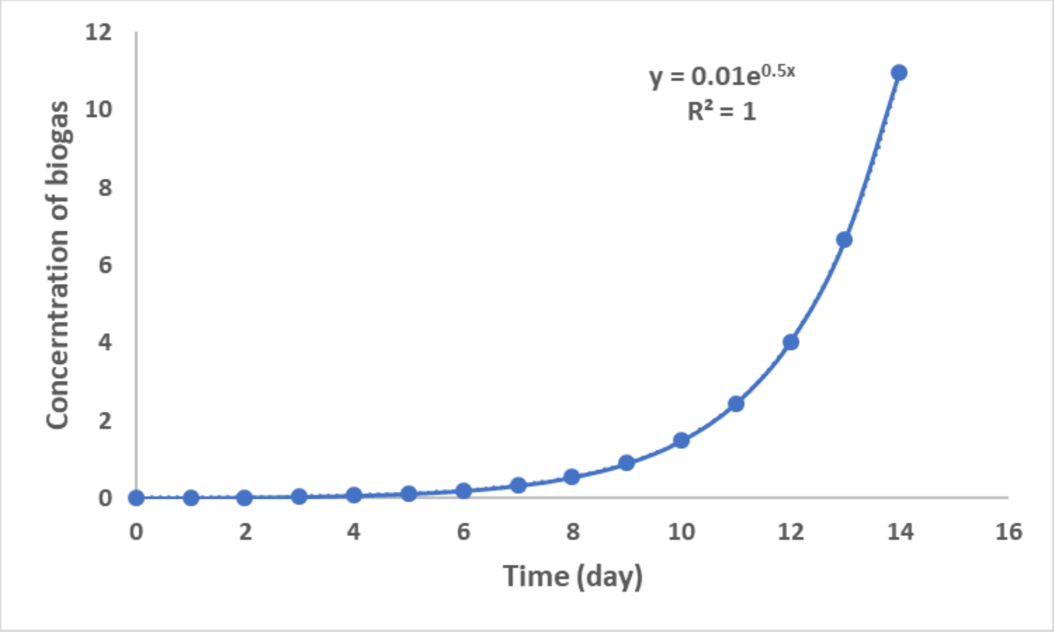

Figure 12. Determination of biogas concentration versus time (Excel Plot).

Finally, running Equations (37–39) on MATLAB, the plot as seen in Figure 12 was obtained which shows the change in the biogas concentration as time increased. For the first 4days, it is observed that the rate of biogas production was slow due to low microbial activity and as time increases, there is a rapid increase in the biogas production which indicates a high microbial activity. Furthermore, as stated earlier in the linear, power, GRD, NER models upon the 14th day of the experimental and modelling work, which is the chosen timeframe for the work, an incomplete consumption of the substrate is observed and hence incomplete biogas production.

CONCLUSION

This study looked at the production of biogas from fresh brewer’s spent grain at mesophilic temperatures of 28.10°C to 34.70°C. The collected biogas showed a rise in concentration and, as a result, the yield of biogas from the BSG, which if properly separated as seen in the GC analysis result, can be used significantly in food and beverage production and energy generation. Additionally, as the amount of biogas produced increased, the system pressure increased as well. This suggests that more biogas concentration was being produced as the fermented brewer’s spent grain released gas molecules, which raised the mean kinetic energy of the gases and, consequently, the system pressure.

From the experiment, a steady and continuous increase in the pressure of the system is observed even unto the 14th day indicating that the biomass is not completely consumed and there is room for further digestion reaction and production of biogas as the yield has not approached its maximum limit with respect to the chosen timeframe for the experiment. For an anaerobic digestion of BSG, it can be said that the yield of biogas in the bioreactor is proportional to the amount of pressure in the reactor since the yield of biogas increases as the pressure imposed by the gas produced in the reactor increases. It is also observed that the degradation is rapid due to favorable conditions experienced by the microbes in the bio-digester. Further examination of the biogas produced using a GC- Analyzer, indicates that methane makes up the majority with a relative abundance of (79.25 ppb), followed by carbon dioxide (45.53 ppb), then nitrogen (49.40 ppb), oxygen, hydrogen and trace constituents accounts for the remainder. This high methane content indicates that the gas is flammable and has the potential to be used as an alternative energy source on a modest scale, particularly for cooking and powering homes and similarly, the large amount of carbon (iv) oxide produced can be used in food and beverage manufacturing, processing and preservation.

On the other hand, research into biogas kinetics indicated that distinct kinetics can be used to interpret biogas output. Four different rate models were studied in this research work: linear, power, GRD, and NER models. All four models show high precision with a regression of approximately 1. Hence, we discovered that any of the rate models can be used to analyze biogas in a batch reactor.

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