Modelling the Kinetics of Biogas Generation from Mesophilic Anaerobic Co-Digestion of Sewage Sludge with Municipal Organic Waste

G. K. Latinwo S. E. Agarry*
Department of Chemical Engineering, Biochemical and Chemical Engineering Biotechnology Laboratory, Ladoke Akintola University of Technology, P. M. B. 4000, Ogbomoso, Nigeria
*Corresponding author: sam_agarry@yahoo.com;

Abstract
This work investigated the effect of municipal organic waste as co-substrate in the anaerobic digestion of industrial sewage sludge for efficient and high biogas production. The biogas experiments were carried out in two different 30 L anaerobic digesters D1 and D2 which contained sewage sludge and mixture of sewage and municipal organic waste, respectively and were incubated for 25 days at ambient mesophilic temperatures (28 ^oC to 32 °C). The results showed that co-digestion of sewage sludge with municipal organic waste as co-substrate reduced start-up time for biogas generation and increased biogas yield by 132% as compared to sewage sludge alone. Peak biogas production was obtained for both digesters at pH of 6.85 and 7.85 as well as temperature of 30 and 31.5^oC, respectively. Modelling study revealed that exponential plot simulated better than the linear plot, the biogas production rates in digester D1 (sewage sludge) and D2 (mixture of sewage sludge and municipal organic waste), respectively. Logistic growth model and modified Gompertz plot showed better correlation of cumulative biogas production than exponential rise to maximum plot. These results show that biogas production can be enhanced efficiently through co-digestion process.
Keywords: Anaerobic digestion; Biogas; Municipal waste; Sewage sludge; Kinetic model.

1. Introduction

Biogas is a renewable substitute fuel for fossil fuel which is made from nontoxic, biodegradable renewable sources such as animal wastes, agricultural wastes, crop, domestic waste, and industrial waste (Omer et al., 2002). Biogas is produced by anaerobic digestion which is a multi-stage engineered biochemical process that mineralises organic substrates to methane and carbon dioxide through a series of reactions mediated by a consortium of micro-organisms under anaerobic condition (Joaquin et al., 2008; Colussi et al., 2012) and this involves four steps which are hydrolysis, acidogensis, acetogensis and methanogensis (Tiehm et al., 2001; Kim et al., 2003; Lo et al., 2010). The activity of anaerobic digestion process depends on various factors like temperature, pH, and concentration of substrate/nutrients, agitation, and pre-treatment of feedstock, hydraulic retention time and carbon: nitrogen ratio (Yadvika et al., 2004; Sreenivas et al., 2010; Umar et al., 2013). The anaerobic digestion process is slow, leading to relatively high retention time of about 20–50 days and a low overall degradation efficiency of about 20–50% in mesophilic digestion (Kim et al., 2010; Shehu et al., 2012).

Therefore, there is a need to improve the overall efficiency of anaerobic digestion process in the biogas plants. Significant effort to enhance biomass conversion efficiency and biogas yield in recent years through co-digestion with other substrates has been conducted by several researchers (Gelegenis et al., 2007; Lehtomaki et al., 2007; Iyagba et al., 2009; Aremu and Agarry, 2013; Ossai, 2013; Umar et al., 2013;). Co-digestion has been defined as the anaerobic treatment of a mixture at least two different substrates with the aim of improving the efficiency of the anaerobic digestion process (Neczaj et al., 2012). Anaerobic co-digestion is reported to offer several benefits over digestion of separate materials, such as increased cost-efficiency, increased biodegradation of the treated materials, as well as increased biogas production (Lehtomäki et al., 2007; Alvarez and Liden, 2008; Kangle et al., 2012; Neczaj et al., 2012).

Simulations of biogas, methane and hydrogen production rate and accumulation have been reported by (Kumar et al., 2004; Mu et al., 2007; Li et al., 2008; Bilgili et al., 2009; De Gioannis et al., 2009; Wang and Wan, 2009). Modeling of biogas production from anaerobic digestion has generally been based on kinetic models (Rao and Singh, 2004; Ueno et al., 2007; Nopharatan et al, 2007; Sosnowski et al., 2008; Boubaker and Ridha, 2008; De Gioannis et al., 2009; Derbal et al., 2009; Colussi et al., 2012; Wanasolo et al., 2013; Ghatak and Mahanta, 2014), while some were based on ADM 1 model, mass and energy conservation, fugacity and flow model, thermodynamic equilibrium model and MODUELO 2 model (Shafi et al., 2006; Pontes and Pinto, 2006; Oh and Martin, 2007; de Cortázar and Monzón, 2007). Due to the role of microorganisms in the anaerobic process, kinetic models particularly the first order kinetics were commonly applied to simulate the anaerobic biodegradation. Like the microbial growth phase, biogas production rate showed a rising limb and a decreasing limb which can be indicated by exponential and linear equation (Kumar et al., 2004; De Gioannis et al., 2009). In addition, exponential rise to maximum as well as modified Gompertz equations which were commonly used in the simulation of methane and hydrogen production (Li and Fang, 2007; Lin and Shei, 2008; Wang and Wan, 2009) could be used to simulate biogas accumulation (Lo et al., 2010; Ghatak and Mahanta, 2014).

In recent years, an increased attention has been carried out to minimize the amount of excess sludge, because it represents a rising challenge for wastewater treatment plants (WWTPs) due to economic, environmental and regulatory factors (Mahvi, 2008). The literature contains a number of interesting reports dealing with the application of co-digesting sewage sludge with other substrates such as crude glycerol (Fountoulakis et al., 2010), animals manure (Hassan, 2014) as well as agriculture wastes (Komatsu et al., 2007; Rughoonundun et al., 2012). While anaerobic co-digestion has been studied and practiced for a broad range of sewage sludge, however very few studies have been conducted on the co-digestion of sewage sludge and municipal solid waste as a co-substrate (Gomez et al., 2006; Agdag and Sponza, 2007; Lebiocka and Piotrowicz, 2012) and in these studies modelling of biogas production was not carried out. To bridge the existing gaps in the field of study, this work investigated the combined anaerobic digestion of industrial sewage sludge and municipal organic waste as well as evaluates the effects of municipal organic waste addition as a co-substrate on the overall stability and efficiency of the process. For this purpose, biogas production rates were modeled using linear and exponential equations. In addition, biogas production accumulation was simulated using logistic growth model, exponential rise to maximum and modified Gompertz models, respectively. This solution will allow developing a sewage sludge and municipal waste utilization technology enabling the production of bioenergy and wastes utilization.

2. Materials and Methods

2.1 Sample collection and preparation

Thickened sewage sludge was obtained from a full scale effluent treatment plant of a soft-drink bottling company located in Ibadan, Nigeria. The municipal organic waste (bio-waste) used as co-substrate (made up of vegetables) was collected selectively from households as well as institutions (restaurants, school canteens etc.) located in the vicinity of Ladoke Akintola University of Technology, Ogbomoso, Nigeria. A domestic food blender was used to homogenize the various components of bio-waste into particles smaller than 2 mm in diameter. Then, it was stored in a refrigerator at 15°C. Cow dung used as inoculums was obtained from cow sales point in Ogbomoso, Nigeria. The pH, total solids (TS) and volatile solids (VS) of sewage sludge and municipal organic waste samples were determined according to standard methods (APHA, 2000).

Table 1: Characteristics of sewage sludge and municipal organic waste (Dry weight basis)

Parameters	Sewage sludge	Municipal organic waste	Inoculum
pH	5.58	4.65	8.4
Total solid (%)	3.82	25.4	18.8
Volatile solid (%)	2.75	17.9	15.3
Total carbon (%)	37.6	52.8	31.5
Total nitrogen	4.65	2.74	2.20
Carbon: Nitrogen ratio	8.1:1	19.3:1	14.3:1

2.2 Preparation of the fermentation slurry

Two different fermentation slurry samples T1 (1500 g of sewage sludge + 100 g of inoculums + 18400 ml of water) and T2 (mixture of 1150 g sewage sludge + 350 g municipal waste + 100 g of inoculums + 18400 ml of water) were prepared according to the method of Ituen et al. (2007). According to the method, total solid (TS) content of the mixture is 8% of the fermentation slurry.

2.3 Biogas experimental procedure

Two improvised anaerobic batch digesters D1 and D2 each having a capacity of 30 L with 25 L working volume was used in this work. Nitrogen gas was purged through each of the digester to expel oxygen from the digester and make it air tight in order to ensure anaerobic conditions in the headspace of anaerobic digesters (Hassan et al., 2004). Round bottom flask which contained an acidified brine solution were fixed to each of the batch digesters as well as to a conical flask by means of connecting tubes and silicon sealant was applied to ensure no air entrapment. Each of the digesters was charged or seeded with each of the prepared fermentation slurry and was incubated for 25 days at ambient temperature (28 ± 2^{o}C). The initial pH of the fermentation slurry made from sewage sludge alone and mixture of sewage sludge and municipal organic waste was 5.91 and 6.75, respectively. The digesters were manually agitated daily for a minute to ensure homogenous dispersion of the constituents of the mixture and to enhance the digestion process by transferring heat throughout the digester as well as to prevent formation of surface crust and scum (Sulaiman et al., 2009). The generated biogas from the digester was collected continuously into a round bottom flask by the down displacement of acidified brine solution; and this was measured daily by reading the volume of acidified brine solution displaced in the round bottom flask which is equal to the volume of gas generated. Also, the temperature and pH of the fermented slurry in each of the digester was measured at interval of 3 days.

2.4 Kinetic modelling of biogas generation

The biogas production kinetics for the description and evaluation of methanogenesis was carried out by fitting the experimental data of biogas production to various kinetic equations. Biogas production rates of sewage sludge alone and sewage sludge co-digested with municipal organic waste was simulated using linear plots. The linear equation of the biogas production rate in the ascending and descending limb can be expressed by Eq. (1) (Kumar et al., 2004; Lo et al., 2010). It is assumed that biogas production rate will increase linearly with increase in time and after reaching a maximum point after sometime it would decrease linearly to zero with increase in time.

$$y = a + bt \qquad (1)$$

Where, y, biogas production rate in dm^3/gm/day; t, time in day for digestion; a (dm^3/gm/day) and b (dm^3/gm/day) are the constants obtained from the intercept and slope of the plot of y vs t. For the ascending limb, b is positive and it is negative for the descending limb.

The exponential plot for the ascending and descending limb can be presented by Eq. (2) (De Gionnis et al., 2009). Here it is assumed that biogas production rate will increase exponentially with increase in time and after reaching the high point it would decrease to zero exponentially with increase in time.

$$y = a + b\exp(ct) \qquad (2)$$

Where, y, biogas production rate in dm^3/gm/day; t, time in day for digestion; a and b (dm^3/gm/day) are the constants; c = constant (day^{-1}). For the ascending limb, c is positive and it is negative for the descending limb.

In addition, cumulative biogas production was simulated using logistic kinetic model, exponential rise to maximum and modified Gompertz kinetic model. Logistic kinetic equation is shown in Eq. (3):

$$C = \frac{a}{1 + b\exp(-kt)} \qquad (3)$$

where, C, cumulative biogas production (dm^3/gm); k, kinetic rate constant (day^{-1}); t = hydraulic retention time (Days); a, b are the constants. Exponential rise to maximum is presented in Eq. (4) (De Gioannis et al., 2009; Lo et al., 2010):

$$C = A(1 - \exp(-kt)) \qquad (4)$$

Modified Gompertz kinetic model equation is a modified form of the Gompertz equation which is commonly used to simulate the cumulative biogas production (Lo et al., 2010). This model assumes that cumulative biogas production is a function of hydraulic retention time. The modified Gompertz equation can be presented as follows (Budiyono et al., 2010; Yusuf et al., 2011):

$$P = A\exp\{-\exp[\frac{r_m e}{A}(\lambda - t) + 1]\} \qquad (5)$$

Where, P is the cumulative of the specific biogas production (dm^3/gm), A is the biogas production potential (dm^3/gm), r_m is the maximum biogas production rate (dm^3/gm/day), λ is the lag phase period or the minimum time required to produce biogas (day).

3. Results and Discussion

3.1 Biogas production rate and accumulation

The biogas production rate and accumulation from sewage sludge (digester D1) and sewage sludge co-digested with municipal organic waste (digester D2) are shown in Fig. 1(a) and 1(b).

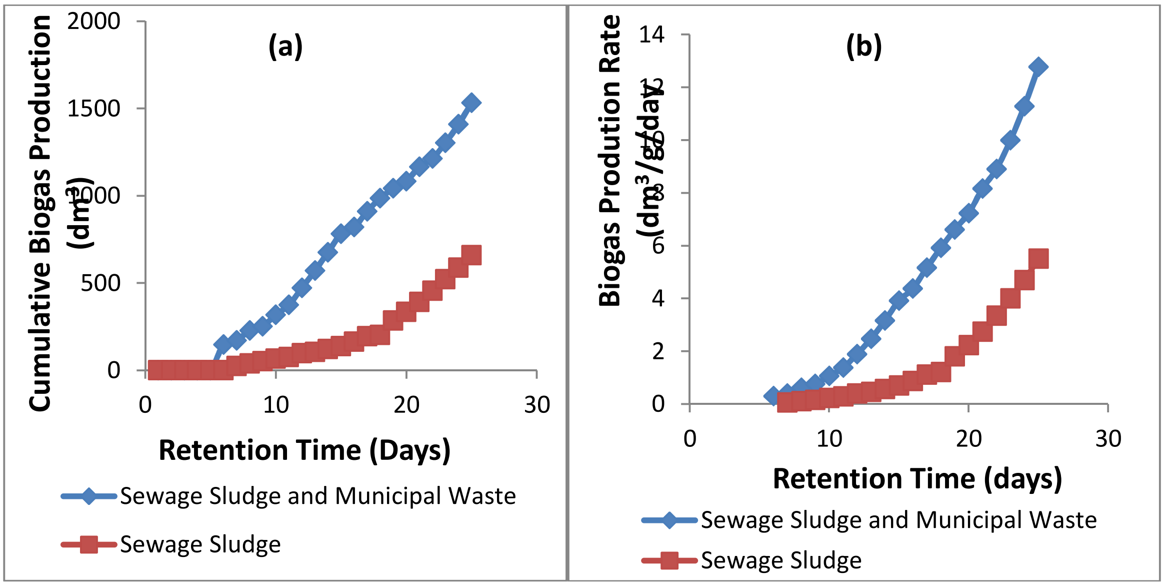

Fig. 1: (a) Cumulative biogas production (b) biogas production rate from sewage sludge and sewage sludge co-digested with municipal wastes.

It could be seen from Fig. 1 that digesters D1 (100% sewage sludge) and D2 (50% sewage sludge + 50% municipal wastes) started the generation of biogas on the 6th and 5th day of anaerobic digestion, respectively. This observation indicates that biogas production started early for digester D2 and thus a reduction in start-up time as compared to digester D1. As biogas started generating from digesters D1 (100% sewage sludge) and D2 (50% sewage sludge + 50% municipal organic waste), the results show increase in biogas production rate and accumulation throughout the retention period. This might be as a result of acclimatized methane forming bacteria activities as they overcome the protective barrier that initially prevented degradation by fungi and bacteria for conversion of substrate to energy (biogas) (Angelidaki and Ellegaard, 2003; Ossai, 2013). The maximum cumulative biogas yield at day 25 was 660.2 dm^3 for digester D1 (100% sewage sludge) and 1532.2 dm^3 for digester D2 (50% sewage sludge + 50% municipal wastes), respectively. The biogas yields from co-digestion are significantly higher than that of mono-digestion of sewage sludge alone. The observed phenomenon could be attributable to additional nutrients availability (feedstock composition) and improved carbon-to-nitrogen ratio (C:N) provided by the municipal organic wastes. Similar observations have been reported (Murto et al., 2004; Eze et al., 2007; Iyagba et al., 2009; Ossai, 2013). This study shows co-digestion in digester D2 to be capable of improving the efficiency of biogas production by 132% higher than digestion of sewage sludge alone (D1). This result supports the observation by Murto et al. (2004) and Umar et al. (2013) who reported that co-digestion could improve biogas production by 50- 200%, depending on the operating condition and substrates used.

Furthermore, it was observed that pH of the fermentation slurry was changing in the course of biogas production from the anaerobic digestion of sewage sludge and sewage sludge co-digested with municipal organic waste as shown in Fig. 2(a) and 2(b).

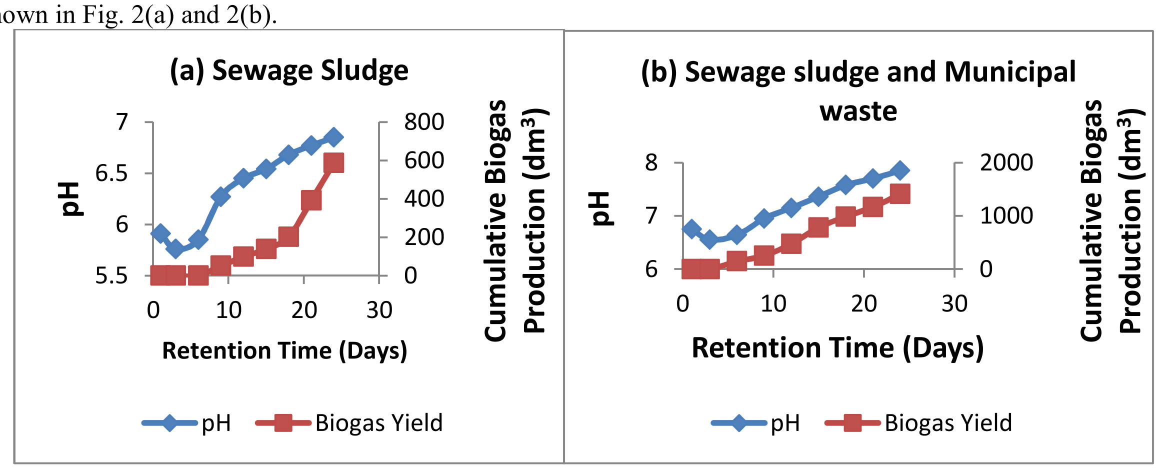

Fig. 2: Changes in pH and biogas production in (a) digester D1 that contained sewage sludge alone (b) digester D2 that contained sewage sludge and municipal wastes

pH is an important factor that affects anaerobic digestion (Rabah et al., 2010). Fig. 2(a) and 2(b) shows that there was a sharp decrease in the pH of the fermenting medium in the first 3 days of anaerobic digestion in both digester D1 (sewage sludge alone) and D2 (sewage sludge and municipal organic waste), respectively. However, the decrease was more pronounced with the mixture of sewage sludge and municipal organic waste. The observed differential in pH change may be due to the high volatile solids in the sewage sludge and municipal organic waste mixture which were converted more intensely into volatile fatty acid and other acidic metabolites by the activities of aerobes and facultative aerobes that were subsequently metabolized by methanogenic bacteria to generate biogas (Dennis and Burke, 2001; Iyagba et al., 2009). The initial pH decrease was responsible for low biogas production on the first 6 and 7 days in the digester D1 and digester D2, respectively. Low pH as been reported to inhibits methanogenic bacteria that are responsible for biogas production (Chynoweth and Isaacson, 1987; Mahanta et al., 2004). pH value less than 5 or greater than 8 has been reported to rapidly inhibits methanogenesis (Garba and Sambo, 1992).

In addition, it could be seen that high cumulative biogas yield was attained after day 6 (Fig. 2(a)) in digester D2 and day 7 (Fig. 2(b)) in digester D2 respectively as pH started to increase. Similar observations have been reported (Nagamani et al., 1992; Ilaboya et al., 2010). This observation of increased biogas yield due to increase in pH may be as a result of increased metabolic activity of the microbial community present in the digester (Lyberatos, 1999). It has been reported that anaerobic bacteria required a natural environment and thus a pH ranging from 6.4-7.2 is needed for optimum biogas production (Garba and Atiku, 1992; Rabah et al., 2010).

Similarly, marginal variation in temperature (26.5 – 31.5^{o}C) was observed in the course of biogas production from the anaerobic digestion of sewage sludge and sewage sludge co-digested with municipal organic waste as shown in Fig. 3. Fig. 3 shows that biogas production in both digester D1 and D2 took place under mesophilic temperature. Moreover, it is seen from Fig. 3(a) and 3(b) that the relation between the temperature and gas production rate is proportional because as temperature of fermentation slurry increased the cumulative biogas production also increased.

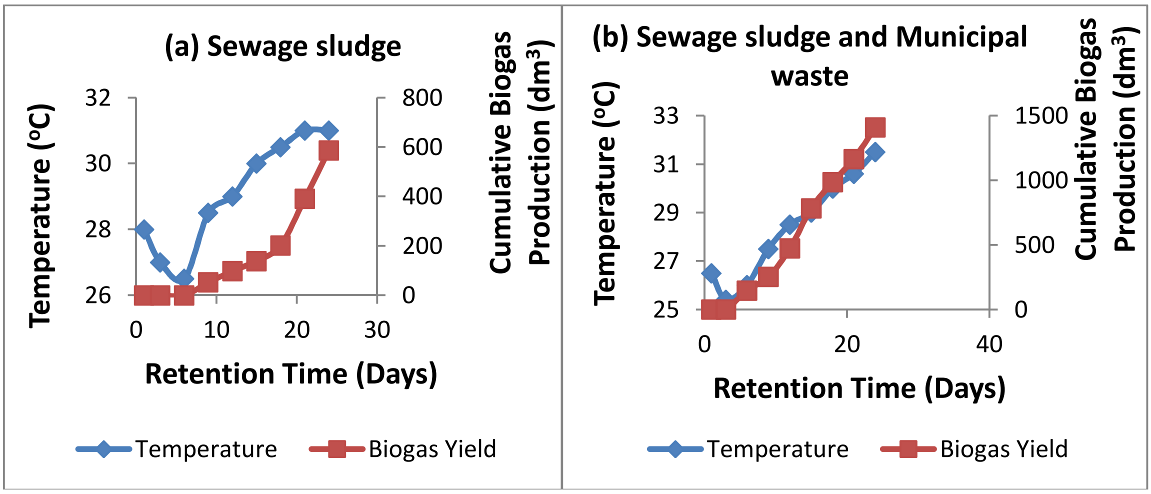

Fig. 3: Changes in temperature and biogas production in (a) digester D1 that contained sewage sludge alone (b) digester D2 that contained sewage sludge and municipal wastes.

3.2 Modelling

Fig. 4(a) and 4(b) shows the linear plots of biogas production rates for sewage sludge and sewage sludge co-digested with municipal organic waste, respectively. Coefficient of determination (R^2) was found to be 0.8410 and 0.9560 for sewage sludge and sewage sludge co-digested with municipal organic waste, respectively.

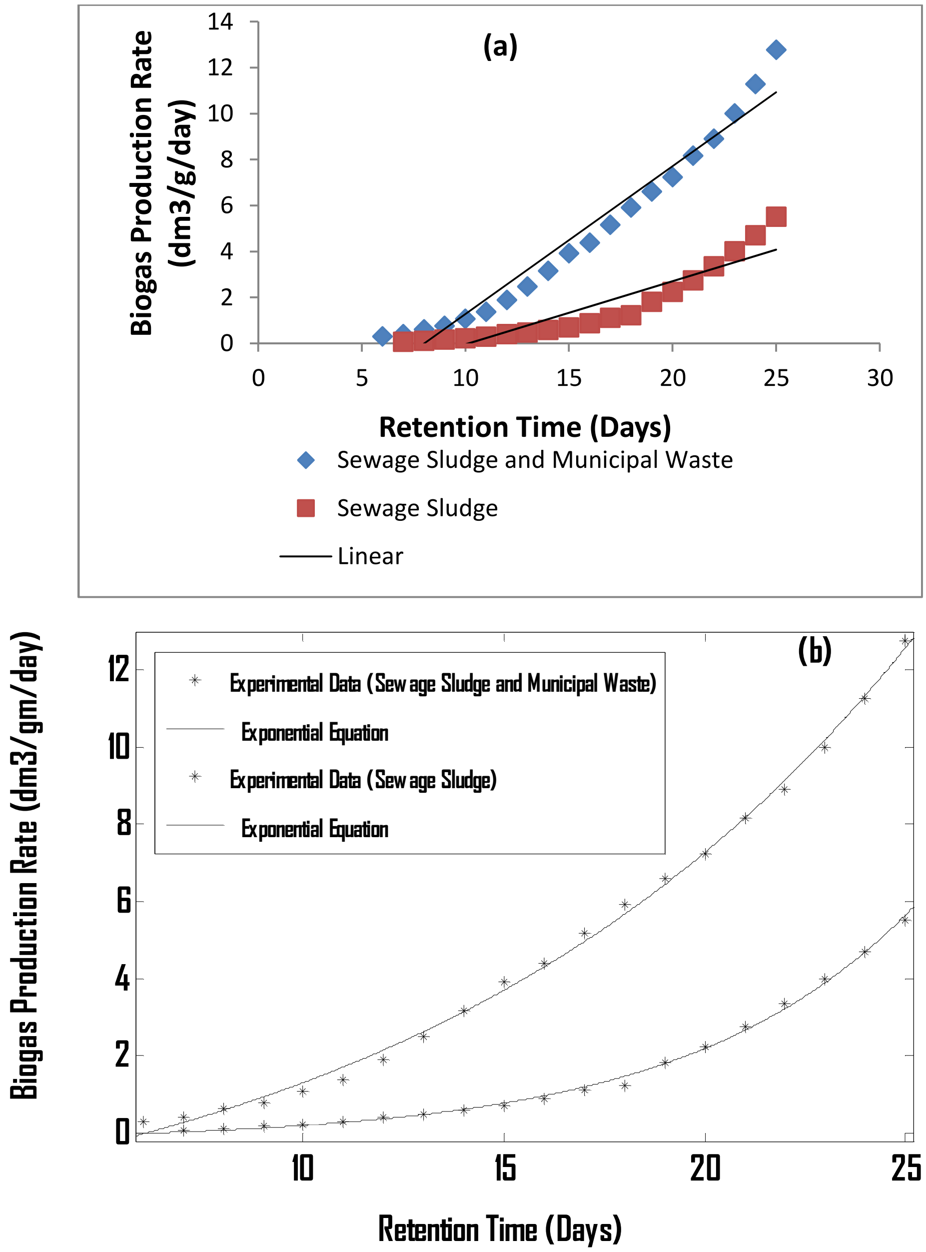

Fig. 4: (a) Linear plots of biogas production rates from sewage sludge and sewage sludge co-digested with municipal organic waste (b) Exponential plots of biogas production rates from sewage sludge and sewage sludge co-digested with municipal organic waste

Fig. 4(c) and 4(d) shows the exponential plot of biogas production rates in the ascending limb from sewage sludge alone and sewage sludge co-digested with municipal organic waste. The R^2 was 0.9971 for sewage sludge alone and 0.9975 for sewage sludge co-digested with municipal organic waste, respectively, and these were found to be slightly better simulation than that of the linear regression.

Fig. 5(a) and 5(b) shows the experimental cumulative biogas production data as well as the cumulative biogas production simulation using exponential rise to maximum, logistic and modified Gompartz kinetic models for sewage sludge alone and mixture of sewage sludge and municipal organic waste, respectively. The coefficient of determination (R^2) was higher for modified Gompertz kinetic model (0.9947-0.9961) and Logistic kinetic model (0.9886-0.9959) than that of the exponential rise to maximum model (0.9141-0.9959) as shown in Table 2. Thus both the logistic and modified Gompartz kinetic model can be used to simulate biogas production from sewage sludge alone and its co-digestion with municipal organic waste, respectively. In modified Gompertz equation, the values of biogas production potential (A = 0.6469 dm^3/gm) and the biogas production rate (μ_m =

0.6212 dm^3/gm/day) for biogas produced from sewage sludge and municipal organic waste was found to be relatively higher with lower lag phase period (λ = 6.47 days) than the values of (A = 0.3075 dm^3/gm, μ_m = 0.1747 dm^3/gm/day, and λ = 8.98 days) obtained for biogas produced from sewage sludge alone. Also, in the Logistic kinetic equation, the kinetic rate constant (k = 0.2455 day^{-1}) was found to be relatively higher for biogas production from sewage sludge co-digested with municipal organic waste than that obtained for biogas production from sewage sludge alone (k = 0.2062 day^{-1}).

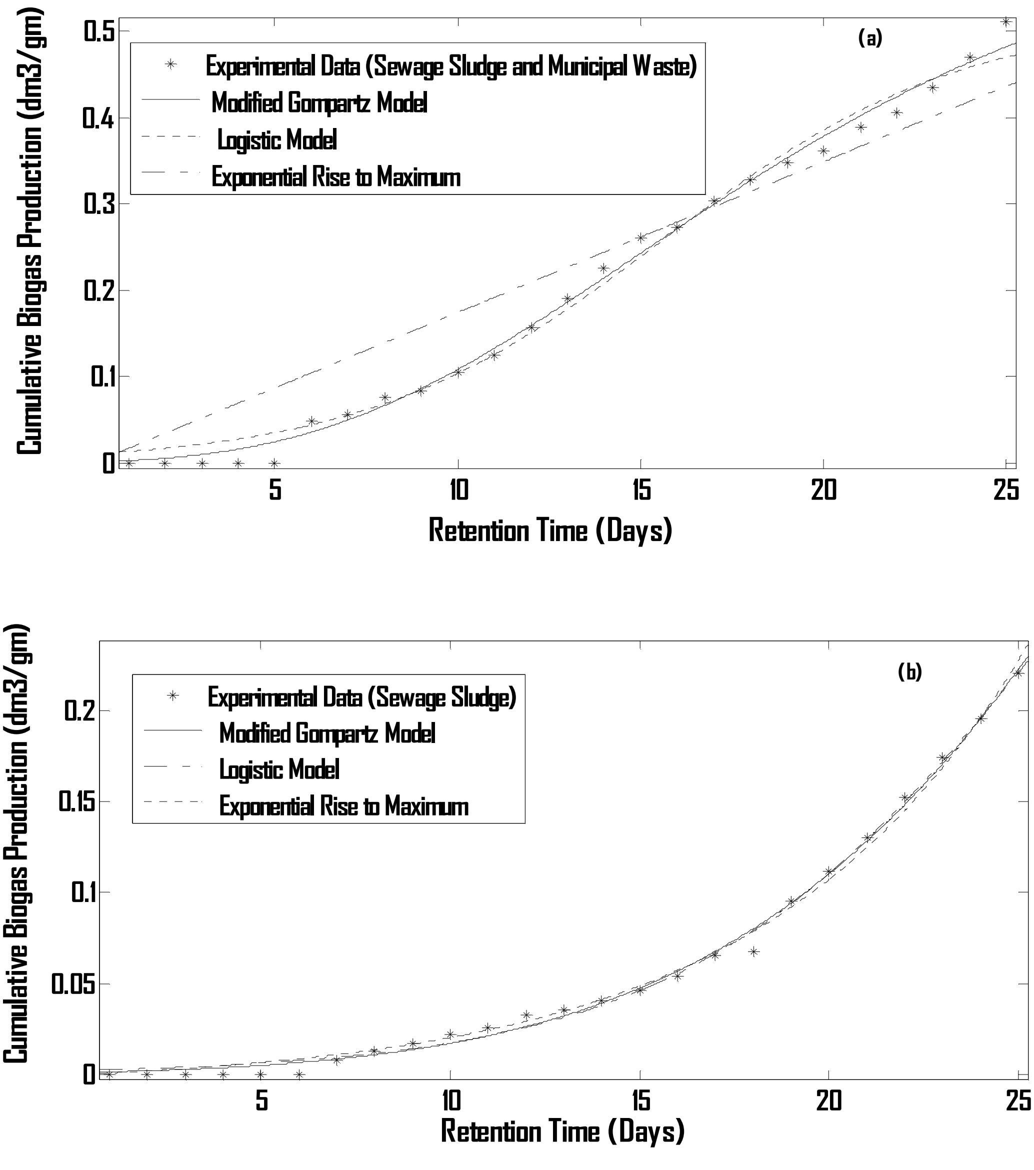

Fig. 5: Kinetic growth models of experimental rise to maximum, modified Gompartz and logistic fitted to the cumulative biogas generation data of (a) sewage sludge and municipal organic waste and (b) sewage sludge.

Table 2: Values of model constants and coefficient of determination (R^2) obtained from kinetic models fitted to cumulative biogas production data of sewage sludge and mixture of sewage sludge and municipal organic waste

Models	Sewage Sludge	Sewage Sludge and Municipal Waste
Exponential Rise to Maximum		
A (dm^3/gm)	-0.0063	4512
k (day^{-1})	-0.1449	3.873×10^{-6}
R^2	0.9959	0.9141
Logistic		
a	0.4952	0.5161
b	215.1	46.13
k (day^{-1})	0.2062	0.2455
R^2	0.9959	0.9886
Modified Gompartz		
A (dm^3/gm)	0.3075	0.6469
μ_m (dm^3/gm/day)	0.1747	0.6212
λ (day)	8.975	6.493
R^2	0.9961	0.9947

4. Conclusion

It can be concluded from the anaerobic digestion of sewage sludge and municipal organic waste as co-substrate that the addition of co-substrate has the potential of increasing biogas yield and have a positive influence on early biogas production. pH range of 6.27 to 7.85 and mesophilic temperature range of 26.5 to 31.5 ^oC resulted in higher biogas production for both digesters. The maximum cumulative biogas yield was 660 dm^3 for digester D1 (100% sewage sludge) and 1532.2 dm^3 for digester D2 (50% sewage sludge + 50% municipal organic waste), respectively. Exponential plot simulated biogas production rate better than that of linear plot. Modified Gompertz plot and Logistic growth plot both had higher correlation than exponential rise to maximum plot for simulating cumulative biogas production. Therefore, arising from the increasing environmental concern and prevailing wastes management crises; optimizing biogas production by co-digestion of industrial sewage sludge and municipal wastes represents a viable and sustainable energy option.

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