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A review of flammable gases from human waste sludge as a potential source of energy

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Abstract- For well over five decades, the world has experienced a significant population and urbanization growth rates and therefore resulting to an exponential surge in the demands of the natural resources like energy, water, land, and food, all of which not subjected to infinite growth. Increasing urbanisation has increased environmental challenges, that are associated with managing waste and emissions as part of global sustainable development objectives. This has become more important to contemplate different sustainable strategies to produce and utilise energy as well as manage waste. Based on a number of studies, one of the potential renewable sources of energy is the use of flammable gases generated from waste in human sewage system but this potential source of energy, which correlates with the human population, has not been effectively exploited as a renewable source due to the technological gap, economical obstacles, and regulations barriers. This paper analyzes and establishes the sewage system critical elements with effective potential of breaking down the organic matters in human waste to efficiently produce and extract flammable gases such as methane that can be used as an effective energy source. It also reviews the mathematical modelling of fermentation process to quantify of methane production in sewage system. This paper contributes to analysis the critical parameters that can directly effect on methane production and presents obstacles in implementing biogas from sewage systems. This technology can be improved to move towards the worldwide carbon footprint reduction.

INTRODUCTION

Bioenergy production from Anaerobic Digestion (AD) is a promising renewable technology that can contribute towards reducing Green House Gases (GHG) emissions. Bioenergy produced from AD can also be considered a reliable treatment technology that can be used for the treatment of wastewater. AD process using sewage sludge have many significant benefits to compare with other feedstock of AD; continues availability of feedstock, reduction in use of fossil fuel by utilising the bioenergy produced, reduction in residual volume and flexible and easy adoption to the climates of most countries. The net production rate of the technology has been considered to be positive in the process when biogas is produced in great amounts that can have the capability to replace non-renewable sources of energy. If the AD systems are appropriately handled, then there would be no risk around the aspect of health and safety for people living in proximity. According to (Angelidaki, et al., 2009), AD systems will significantly reduce carbon emissions and help reverse climate change. Biogas has gained the attention of several environmental scientists who have been involved in finding a substitute for fossil fuels. AD is dependent on effective and efficient conversion of the organic compound into biogas so that CH_4 or methane which is its primary combustible component can be efficiently produced. Biogas has been successfully used in lighting, home cooking, heating and starting electrical appliances (Bah , 2014). The process relies on mutual interaction between organisms so that the complex organic matter can be broken down into monomers like fatty acids, amino acids, glycerol and sugar. Even though there are some disadvantages of AD, weak operational efficiency and low awareness regarding the technology has hindered its adoption in the grassroots levels. Some factors are affecting the stability and performance of AD systems. These factors are part of biological and non-biological elements of components and are able to increase or decrease the interaction between microorganisms (Bayrakdar, et al., 2018). These factors can be considered as methods that can accelerate the reaction and improve the overall efficiency of the process. However, the AD systems have been surrounded by different controversies (Capson-Tojo, 2017). The overall impact of the interaction in the digestive process can be a topic of debate because there are several conflicting scholarly reports regarding their impact. The formation of biogas is considered to be the fermentation process as different microorganisms interact with one another to facilitate the process for greater methane production. Microorganisms have a key role to play to enhance the overall biogas produced. These microorganisms drive the AD process towards completion. To complete the digestion process, methanogenic microorganisms should have a physiological interaction of over 90%. The relationship and interaction between the microorganisms can be stimulated through temperature controls and fast feedstock biodegradation (Chinnasamy, et al., 2009). Several studies have been encouraged to review the different methods of fermentation in AD technology. These methods can contribute to critical factors that can increase the interaction process within the microorganisms. This research has critically analysed the effect of the fermentation process in the AD systems and review the method which can be used to optimise the overall productivity and the efficiency of the digestion process. The influence of models like Gompertz conductive materials process has also reviewed. The primary focus of this study is to enhance the interactions between methanogenic microorganisms so that efficient biogas production can be achieved through the digestion process. An overview of the AD process must be conducted followed reviewing the mathematical solution to quantify the biogas production via fermentation process.

OVERVIEW OF AD PROCESS

AD is a process where organic matter in the absence of oxygen is broken down into several gaseous components with the help of the interactions between several specific groups of bacteria. These gaseous components are known as biogas, which is formed by gases like carbon dioxide, methane, and hydrogen and in the digestate which is a mixture of mineral substances such as potassium, calcium and carbonate compounds which does not easily degrade in the environment (Cyprowski, 2018). One of the primary objectives of the AD process is the production of biogas which can be effectively used as a substitute for non-renewable sources of energy like petroleum and diesel. Biogas has been used as a fuel in several different countries (Fracchia, et al., 2006). AD is a very advantageous technology where the treatment of sludge residues and livestock manure is used to effectively produce biogas. The use of biogas as a substitute for petroleum and diesel is likely to reduce the adverse impact on the environment thus reversing the climatic change. The production of biogas has a long duration. However, organisations all over the world have been focusing on improving the efficiency of the biogas uses by researching on new raw materials that can be easily fermented so that biogas production can be quadrupled. Sludge is considered as an amalgamation of different organic compounds like oils, proteins, carbohydrates, fats and other living and non-living microorganisms. These organisms need to have high energy elements. The components of sewage can be highly unpredictable and inconsistent because the availability of biogas-producing compounds will be dependent on specific factors like wastewater treatment and the type of sewage. The climate has a huge role to play in the fermentation process. Higher the temperature faster is the fermentation process (Juárez, 2018). In this paper, the Gompertz model has been used to review fermentation process, and different adaptations have been obtained to fit the variables in the model to quantify the biogas production.

FERMENTATION PROCESS

To describe the biogas production through anaerobic fermentation many models have been suggested such as modified Gompertz model, kinetic models and cone models (Gompertz, 1825) (Bah , 2014) (Shin, et al., 2010) and identified different parameters aimed at increasing the biogas yield. In this paper modified Gompertz model has been used to identify the process of biogas production using AD technology. The model uses the hypothesis of microbial cellular production which is proportional to the cellular concentration and growth rate at that instant. The growth rate is considered to be constant in many cases (Fracchia, et al., 2006). The constant growth rate of the cell is considered to be normal. However, it moves away from the normal measurements especially when there is a lack of nutrients limiting the reproduction process. This leads to a sigmoidal variation in the cellular concentration. The Gompertz process is a model that considers the growth rate of cells as a variable (Knoblauch, et al., 2018). There are three stages in the AD process that leads to the decomposition of the organic matter. The first phase is known as the hydrolytic phase in which long carbon chains are broken down into short acid chains. This subsequently leads to the second phase which is known as the acidogenic phase. The short-chain acids are transformed into acetic acid in this second stage. Finally, the methanogenic stage arrives in which the acidic acid is converted into biogas. (Gompertz, 1825). Each of these phases is the primary stage for the next phase and produce the condition that bacteria can do their duty to digest the sewage sludge. Figure 1 shows the variation of cellular concentration of bacteria (CFU/m^3) (Colony-Forming Unit per cubic meters) in human sewage sludge in AD over the 40 days of digestion period.

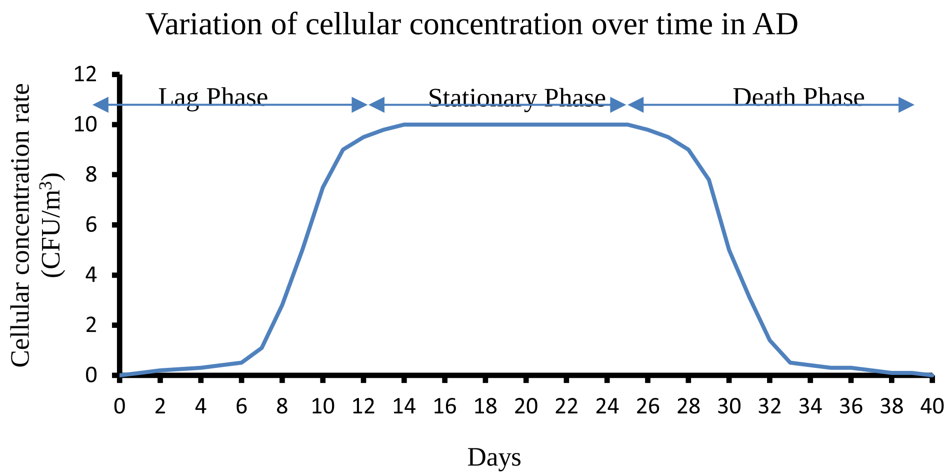

Figure 1 Variation of Cellular Concentration over time in AD (Velázquez-Martí, et al., 2018).

Figure 1 indicates that the typical human sewage sludge microorganism cellular concentration, it is dependent on the type of feedstock. In the initial stages the cellular concentration is very small, and the evolution of these microorganisms is slow because it requires time to adapt to the new environment (estimated up to day 14). This phase is considered to be the lag phase. Subsequently, there is an increase in the cellular action which takes in this phase. This phase ends when the rate of cell production is equal to cell deaths, so the number of living cells is stabilized. This phase is called the stationary phase (estimated around days 14 -26). The cells compete with each other which lead to subtraction. Cell replication takes place along with deaths of microorganisms. The subtraction point is reached when the number of deaths is higher than the rate of reproduction. The cellular concentration falls sharply. This is the final stage where the cells die. This is known as the cell death phase stage (estimated around days 25-40) (Martins, et al., 2018). In this paper mathematical analyses have been carried out to firstly, identified the critical parameters that potentially can have an impact on the biogas production and secondly, calculate the biogas production based on 40 days of digestion period in AD.

MATERIALS AND METHODS

To develop and analyse biogas production from sewage sludge in AD under atmospheric pressure and mesophilic condition (pH 3.85–11.40 and temp 30.0–37.0°C) a mathematical model has been produced with the help of the modified Gompertz equation. The calculations identify and predict the overall production of biogas. In the model different parameters have been incorporated, such as the lag time followed by the bacteria growth rate and finally, the bacteria cellular concentration rate.

MODEL OF GOMPERTZ

The available literature has provided enormous information regarding the bacterial behaviour that is facing the fermentation process. The behaviour of bacteria in this process has a huge impact on the biogas production (Angelidaki, et al., 2009). Model of Gompertz provides an equation that describes cellular concentration and bacteria growth rate over time in a fermentation process. both variables which are shown in Eq.1 (Chinnasamy, et al., 2009) (Anukam, et al., 2019).

$$\frac{d_x}{d_t} = \mu . x \qquad \text{Eq. 1}$$

Growth rate is identified by μ (d^{-1}) and the cellular concentration of bacteria is represented by x (CFU/m^3) (Anukam, et al., 2019). If there is a change in time from t_1 to t_2 then x_1 will be representing the cellular concentration that was in the initial stage of the process. x_2 will be representing the concentration of cells that changed from t_1 to t_2. When there is a change in time from t_1 to t_2 there is also a change in the cellular concentration rate of the bacteria from x_1 to x_2. The Eq.2 which is developed has shown that in the growth phase there is an exponential curve in the variation of cells (Bah H, 2014).

$$\mu = \frac{ln\frac{x_2}{x_1}}{t_2 - t_1} \qquad \text{Eq. 2}$$

Based on the variables of Eq.2, calculation of the growth rate can be done at any time during any given interval. For instance, to calculate the μ during the lag phase, the equation can be explained as Eq.3.

$$\mu = \frac{ln\frac{x_2}{x_1}}{t_{lag} - t_1} \qquad \text{Eq. 3}$$

The above equation is not satisfactory because the growth rate is not considered to be constant and as the time goes by the growth rate clearly varies (Barua & Dhar, 2017). To achieve a higher accuracy, it is important to understand when the maximum of μ and x can be achieved. Based on Eq. 3 when the $t_{lag} - t_1$ reaches to its minimum level and cellular concentration reaches at its maximum. Therefore, the constant values are identified in order to make a clear analysis of the situation. First is the maximum cellular concentration which is depicted by the variable **"**a**"** (Bayrakdar, et al., 2018). The cell growth rate value is depicted by the variable **"**c**"** where the growth rate is maximum and lag time is at the minimum. These parameters introduced to Eq.3 and the model has been modified to Eq.4 which provides a mathematical equation describing the maximum growth rate in the fermentation process. It is assumed that the fermentation process is happening at the normal atmospheric pressure where the temperature range is around 30° to 37°C.

$$\boldsymbol{\mu = c ln\left(\frac{a}{x}\right)} \qquad \text{Eq. 4}$$

By inserting Eq.4 into Eq.1 and solving the integration, x can be defined as shown in Eq.5.

$$\mathrm{x = x_0\ e^{ct}} \qquad \text{Eq. 5}$$

where (x_0) is initial cellular concentration, (x) cellular concentration, (t) time and (c) growth rate.

In Eq. 5 if (t) approaches zero (x) will be same as the initial cellular concentration rate (as shows in Eq.6) and when (t) approaches to t_{max} in this process (x) will be close to the maximum cellular concentration which is (a) (as shows in Eq.7).

$$\boldsymbol{\lim_{t\to 0} x = x_0\ e^{ct} = x_0} \qquad \text{Eq. 6}$$

$$\boldsymbol{\lim_{t\to t_{max}} x = x_0\, e^{ct} = a} \qquad \text{Eq. 7}$$

Therefore, to achieve the maximum (x) the Eq.5 can be explained as Eq.8.

$$\boldsymbol{x_{max} = a} \qquad \text{Eq. 8}$$

(Gompertz, 1825) has obtained that the maximum reproduction of biogas during fermentation process ($\vartheta_{\ Biogas\ max}$) can be defined as Eq.9. This equation has become popularized and explained the relation between biogas production and cellular concentration:

$$\boldsymbol{\vartheta_{\ Biogas\ max} = \frac{d_{x_{max}}}{d_t}} \qquad \text{Eq. 9}$$

Where the units for $\vartheta_{\ Biogas\ max}$ and x_{max} are m³/kg (VS) and CFU/m³ respectively. Also Eq.1 explained the relationship between growth rate and cellular concentration over the digestion period, so comparing Eq.1, Eq.4 can lead to a new equation Eq.10.

$$\frac{d_x}{d_t} = c\ ln(\frac{a}{x})\ x \qquad \text{Eq. 10}$$

(Winsor, 1932) proposed an adequate adjustment function on Eq.10 to obtain Eq.11. this equation Eq.11 considers the variables such as growth rate, cellular concentration rate in the time frame of $\mathrm{t_{lag} - t_1}$.

$$\boldsymbol{x = a\ e^{\left[-e^{\frac{\vartheta_{max}\, e}{a}\left(t_{lag}-t_1\right)+1}\right]}} \qquad \text{Eq. 11}$$

with respect to the Eq.11 (Chinnasamy, et al., 2009) and (Velázquez-Martí, et al., 2018) proposed Eq.12 , so the production of the biogas can be mathematically calculated during the digestion process in AD. Eq.12 has been identified as the modified Gompertz model. This equation Eq.12 has been used in the research such as (Bah H, 2014) , (Capson-Tojo, et al., 2017), (Bayrakdar, et al., 2018), (Mancini, et al., 2018), (Juárez, et al., 2018).

$$\boldsymbol{M = M_e\ e^{\left[-e^{\frac{\vartheta_{max\ e}}{M_e}\left(t_{lag}-t_1\right)+1}\right]}} \qquad \text{Eq. 12}$$

Eq.12 has been used to carry out the calculations in this study.

ANALYTICAL METHOD AND RESULTS

The equation which is used in the current paper is the modified Gompertz model that can identify the overall biogas production in the AD process. A spreadsheet was developed to perform these calculations considering various scenarios of biogas production. The results of the model have been presented with the help of table calculation and figures. Various comparisons between the results have been carried out to make an analysis of this model. The Gompertz model has provided an equation that describes the cellular concentration of cells over a time period in the fermentation process. To analyse this equation, it is important that three values are obtained. These three values are the maximum cellular concentration of the cells (a), the overall growth rate of the cells at the maximum growth velocity (c) and the lag time stage (t) (Dupla, et al., 2004) (Cyprowski, et al., 2018). Table 1 has collected the available literature data for these values. However even though most progress has been made the knowledge regarding the behaviour of the bacteria in different environmental situations is still limited. The data collected indicates that the critical parameters such as (a), (c) and (t) in fermentation process are likely to vary in different stages of digestion in AD (Gompertz, 1825) (Dupla, et al., 2004) (Fracchia, et al., 2006).

Table 1
Anaerobic Bacteria Specification in Human Sewage Sludge (Controlled Lab Environment Digester)

Parameters	Parameter range used in this study	Reference
Cellular Concentration of anaerobic bacteria (a)	10^1–10^4 CFU/m^3 *	(Fracchia, et al., 2006)
	0.15 - 10 × 10^6 CFU/m^3	(Crolla & Kinsley, 2013)
	1.12 – 4.06 × 10^3 CFU/m^3	(Cyprowski, et al., 2018)
Specific bacteria growth rate (c)	0.22 d^{-1}	(Chinnasamy, et al., 2009)
	0.038 - 0.091 d^{-1}	(Park, et al., 2010)
	0.05–0.39 d^{-1}	(Lim, et al., 2010)
	0.19 to 0.32 d^{-1}	(Yuan, et al., 2012)
	0.26 d^{-1}	(Wang, et al., 2013)
Lag time (t)	15 days	(Crolla & Kinsley, 2013)
	13 days	(Wang, et al., 2013)
	11 days	(Maria, et al., 2015)
	14 days	(Velázquez-Martí, et al., 2018)
*A colony-forming unit (CFU) is a unit used in microbiology to estimate the number of viable bacteria or fungal cells in a sample		
All the values are in mesophilic conditions (pH 3.85–11.40 and temp 30.0–37.0°C)		

Based on Figure 1 and relation of biogas production with the cellular concentration rate (x) identified in Eq.11 and Eq.12, it has been identified that the overall biogas production in digestion process can be divided into three major stages. Stage one refers to the low production process which starts either at the very beginning when the sewage is entering the digester and the cellular concentration rate of bacteria is very small or during cell death phase with a very rapid decrees in cellular concentration , stage two is during lag phase(lag time) also refers to medium production process when the cellular concentration is increasing but has not reached the maximum level, and the final stage refers to the high production process where the cellular concentration reaches its highest Level. Along with these information and deep undressing of the process and also the data collected from available literatures presented in Table 1 , the calculation has been carried out to consider three different scenarios to analyse and quantify the potential biogas production during the low, medium and high biogas production process. By studying Table 1, following assumptions can be extracted:

1. It has been identified that the bacteria cellular concentration rate has a range of 0.15-10×10^6 CFU/m^3. Therefore, to have a better understanding about the impact of this parameter on the biogas production, calculation has been carried out considering three different scenarios in the form of minimum, average, and the maximum cellular concentration rate value.
2. The growth rate of bacteria is between 0.038 to 0.39 d^{-1}. Minimum average and maximum growth rate have been considered under three different scenarios.
3. The lag time has been identified to a range of 11 to 15 days. Minimum average and maximum lag time have been considered under three different scenarios.

At the end to evaluate the result , the biogas production for each scenario have been compared with the biogas production in the previous research and thesis such as (Wang, et al., 2013) , (Maria, et al., 2015) , (Solé-Bundó, et al., 2018) (Velázquez-Martí, et al., 2018) and (Vassalle, et al., 2020).Table 2 briefly explained the different scenarios and assumptions for the mathematical calculation.

Table 2

List of Scenarios and assumptions for Mathematical Calculations

No. of Scenarios	Parameters	Value
Scenario 1	Cellular Concentration of anaerobic bacteria	10 CFU/m^3
	Specific bacteria growth rate	0.038 d^{-1}
	Lag time	11
Scenario 2	cellular Concentration of anaerobic bacteria	1,694,198 CFU/m^3
	Specific bacteria growth rate	0.21 d^{-1}
	Lag time	14
Scenario 3	Cellular Concentration of anaerobic bacteria	10×10^6 CFU/m^3
	Specific bacteria growth rate	0.39 d^{-1}
	Lag time	15

A spreadsheet was developed to perform these calculations considering various scenarios of biogas production identified in Table 2. Each calculation is concluded after a careful analysis of digestion process via bacteria that took place for 40 days. The Following Figure 3 is representing the biogas production in each scenario.

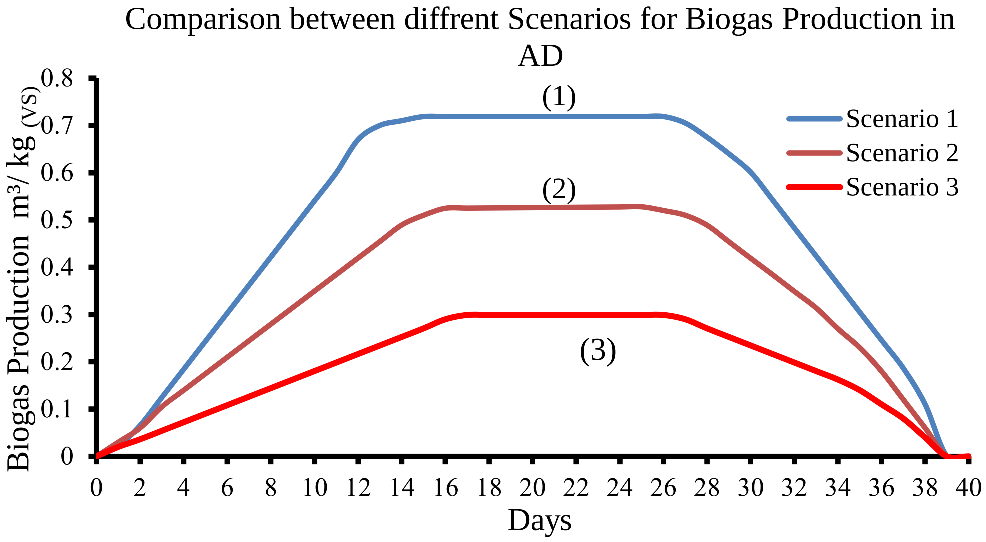

Figure 2 - Biogas Production considering three Scenarios (1,2&3)

Scenario 1 indicates that the rates of biogas production gradually increased from zero at day 1 to 0.659 $m^3/kg_{(VS)}$ at day 11, reached a shoulder between 11 and 27 days with the maximum production at 0.713 $m^3/kg_{(VS)}$, then gradually reduced to zero at day of 40. Scenario 2 indicates that the rates of biogas production gradually increased from zero at day 1 to 0.489 $m^3/kg_{(VS)}$ at day 14, reached a shoulder between 14 and 25 days with the maximum production at 0.524 $m^3/kg_{(VS)}$, then gradually reduced to zero at day of 40. Scenario 3 indicates that the rates of biogas production gradually increased from zero at day 1 to 0.207 $m^3/kg_{(VS)}$ at day 15, reached a shoulder between 15 and 26 days with the maximum production at 0.299 $m^3/kg_{(VS)}$, then gradually reduced to zero at day of 40. Figure 2 identifies that in Modified Gompertz Models; a low Lag time, high bacteria cellular concentration and high growth rate can increase the overall production of biogas. Also, the biogas production results in all scenarios from mathematical modelling approaches were in good agreement with the theoretical concept. Regarding previous research studies summarised in Table 3 the biogas production in AD is in the range of 0.11 - 0.68 $m^3/kg_{(vs)}$. The results from the calculations in this study indicates the accuracy of Modified Gompertz equation.

Table 3

Biogas Production within Sewage Sludge in AD at Mesophilic Condition

Parameters	Parameter range used in this study	Reference
Biogas production	0.11 – 0.16 $m^3/kg_{(VS)}$*	(Gunaseelan, 1997)
	0.15 – 0.65 $m^3/kg_{(VS)}$	(Velázquez-Martí, et al., 2018)
	0.47 $m^3/kg_{(VS)}$	(Wang, et al., 2013)
	0.30 - 0.33 $m^3/kg_{(VS)}$	(Díaz, et al., 2011)
	0.48 $m^3/kg_{(VS)}$	(Maria, et al., 2015)
	0.1 – 0.25 $m^3/kg_{(VS)}$	(Solé-Bundó, et al., 2018)
	0.36 – 0.46 $m^3/kg_{(VS)}$	(Solé-Bundó, et al., 2019)
	0.35 $m^3/kg_{(VS)}$	(Vassalle, et al., 2020)

*volatile solids (VS)- the portion of total solids present in sludge that have a calorific value

FURTHER ANALYSIS AND SUGGESTION

Despite there being progress in the literature concerning biogas production and physiological characteristics of the bacteria the overall knowledge regarding their working environment presence is still scarce (Solé-Bundó, et al., 2018).To mathematically calculate the production level of biogas through the Eq.12, the growth rate needs to be analysed. To calculate the growth rate the Eq.3 explained that the growth rate is not constant, and it is likely to vary over a certain time (Shin, et al., 2010). When $\frac{x_2}{x_1} < 1$ it means that the process is at the initial stage then μ will be at the minimum rage. When $\frac{x_2}{x_1} > 1$ it means that the process is at the growth phase and μ is reaching maximum rate. When $\frac{x_2}{x_1} = 1$ it means that the cellular concentration reached to the maximum so, μ reached to its minimum zero value. In summary when there is maximum cellular concentration of bacteria achieved, there is no growth of bacteria at all. Therefore, with above explanations and respect to Eq.3 to achieve a maximum growth rate two scenarios can happen: either cellular concentration of bacteria or $t_{lag} - t_1$ reach zero. The existence of bacteria in sewage sludge has been confirmed by other studies and research, therefore the $\frac{x_2}{x_1}$ can be at the minimum level but cannot be zero therefore $t_{lag} - t_1$ plays an important role so, t_{lag} should be limited to minimum valve to increase the potential of biogas production. However, the main question is how much time is required for bacteria to get ready to reduce the t_{lag}? The metabolic activity of the bacteria has a huge role to play in the extension of the lag phase. There are two reasons for the extension of the lag phase. First depends on the physiological changes that take place within the bacteria cells. The second reason for extension of the lag time is the division of the cells where one section of the bacteria is dying, and it is not multiplying. In both the cases cell count of the bacteria remains constant (Winsor, 1932).
Based on Eq.1 if only a fraction (F) of the cells is increasing during the process, then $x = (x - x_1)F$ by applying this assumption into the equation Eq.1 and solving the integration between t_1 to t_{lag} the Eq.1 can be written as Eq. 13.

$$\boldsymbol{t_{lag} - t_1 = \frac{1}{\mu.F}\, ln(x - x_1)} \qquad \text{Eq. 13}$$

where F is the fraction of the active cell population and where $\mu.F$ in the apparent growth rate. If x increases, then F will tend to 1 and $\mu.F$ will tend to μ. In this case the bacteria are likely to grow at an exponential rate and the process will not consist of any lag phase. To get the best result of the biogas production the bacteria need to be adapted to the new environment in AD and be prepared and highly concentrated before adding it to the digester so that the lag time can be effectively reduced. A good fermentation can only be achieved when the bacteria growth phase is optimised and ensure that the duration of the growth phase is more than the death phase and the lag phase. If there is higher cellular concentration in the growth phase, then there will be an increase in the overall bacteria age thus ensuring greater growth rate and more efficient production of the biogas. This result has also reported by (Khalid, et al., 2011) , (Korberg, et al., 2020) .

CONCLUSIONS

Anaerobic digestion is an established and effective method of producing biogas as renewable source of energy from sewage sludge. The challenging factors of an anaerobic digestor include the instability of time and space as well as being an inhomogeneous system. During the fermentation stage, the effectiveness of the anaerobic digester is influenced by multidimensional factors such as the bacterial cellular concentration rate, rate of growth and lag time. Due to this, the biogas production process in anaerobic digester does primarily depend on the environmental condition of the surroundings in order to facilitate successful growth of the bacteria and therefore enhancing an effective process. In this paper, a range of scenarios have been illustrated and analysed accordingly and the results show variation in the production of biogas in AD varying between 0.299 and 0.713 m^3 /$kg_{(vs).}$ The productions were simulated under a mesophilic condition, i.e. between 30 to 37°C. The digestion process, on the other hand, can be categorised further into three different groups depending on the potentials of biogas production. The lag time of this entire process ranged between 11-15 days. The results were as follow:

- Low Production Process: The first group of the digestion process is the low-production process which occurs when the produced biogas is less than 0.299 m^3 /$kg_{(vs)}$.
- Medium Production Process: The second group of the digestion process is the medium production process which occurs when the produced biogas is between 0.299 and 0.524 m^3 /$kg_{(vs)}$.
- High Production Process: The third group of the digestion process is the medium production process which occurs when the produced biogas is higher than 0.524 m^3 /$kg_{(vs)}$.

Although AD technology has experienced improvements through research and new environmentally sustainable waste management programmes, there are still knowledge gaps in order to understand fully the complexity of this process. Furthermore, various research identified the benefits and potential improvements that required to increase the efficiency of fermentation process in AD for improved biogas production. It is notable that UK has funded several AD projects all around the world. Therefore, the impact this funding has had through multidisciplinary research with the aim of progressing microbiological, operational as well as chemical aspects of the technology should be assessed in the future.

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