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A review on the potential use of flammable gases from sewage systems as a source of energy

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Abstract: The demand for natural resources has increased exponentially due to the consistent growth of the global population and urbanization. This has resulted to considerable environmental challenges that are potentially affecting the global sustainable development goals. Therefore, it is important to develop sustainable strategies to manage urban wastes as well as produce and utilize energy. Flammable gases being generated from the sewage systems can be a prospective renewable resource of energy. However, existing studies suggest that the potential of sewage gas utilization for energy production has not been explored effectively. This paper focuses on identifying key design elements of sewage systems in an Anaerobic Digester (AD) to optimize the process of conversion of human waste into energy source. The paper uses a kinetic model to describe the fermentation process and thus evaluating the effect of key parameters on biogas (specifically methane) gases production in an anaerobic digester environment.

Keywords: Flammable Gases, Methane, Renewable Energy, Biogas, Sewage System**.**

1. Introduction

Due to the climate emergency, the use of renewable energy resources to address environmental pollution and reduction in use of fossil fuels has become necessary. Currently, the UK is mostly dependent on the natural resources of energy to operate households' appliances, power grids and transportation. Therefore, there is an urgent need to increase the utilization of renewable energy towards an improved sustainability and the achievement of net zero greenhouse gas emission target set for 2050. The Renewable Energy Action Plan (REAP) sanctioned in 2010 according to the Renewable Energy Directive 2009/28 EC (RED) specified that renewable energy should account for around 20% of the gross energy consumption in the UK. At the same time, the UK Government also made considerable attempts to achieve a 'zero waste' economy (e.g., The UK enshrines new target in law to slash emissions by 78% by 2035) (Government, 2021). One of the possible measures towards the zero waste target is the production of energy from waste through anaerobic digestion (AD), thus addressing organic waste disposal to some extent. The anaerobic digestion has the potential of being an effective and efficient method of treating organic disposal and producing biogas that can be used as an energy source for electricity and power generation. The biogas can also be used to convert bio-fuel into a gas grid (Commission, 2009). An additional advantage of AD is that it can be implemented in a variety of scales, from large facilities required for sewage sludge or bio-waste treatment, to comparatively smaller ones needed to handle materials from a specific company or an enclosed community (Pollitt, 2010). In July 2010, UK Government proposed a plan of action to incorporate methods and measures associated with AD and the production of renewable energy resources from bio-waste. In line to this, DEFRA has produced documentation designed to explore the necessary methods of extraction of increased amounts of energy from waste via AD in their published business plan of 30th November 2010. In regard to this, new pathways are explored to optimse the biogas production from organic matter/waste. This paper looks into the kinetic model used to describe the fermentation process in the AD systems and evaluate the effect of key parameters on biogas (specifically methane) production in an anaerobic digester environment.

2. Background

2.1. Anaerobic Fermentation Process

The fermentation process is an important aspect of methane production in an anaerobic digester and therefore needs to be investigated carefully. Numerous mathematical models have been developed to describe the fermentation process and quantify the production of flammable gases, including methane. During the multi-step process of AD, microorganisms break down organic matter in an oxygen-free environment. At the hydrolytic stage, the long carbon chains are broken down into short-chain acids. This leads to the acidogenesis process, where the short-chain acids are further converted into acetic acid by the action of acidogenic bacteria (fermentative microorganisms). The acetic acid is the most significant organic acid used as a substrate by methanogenic microorganisms, convertig the acetic acid into methane (methanogenesis stage) (Meegoda, 2018). A typical bacterial growth curve follows distinct phases of growth; initially, a lag phase where the microorganisms evolve slowly due to the extensive time needed for cells to adjust to a new environment; followed by growing exponentially where cell division proceeds at a constant rate; this leads to the stationary phase, when conditions become unfavourable for growth and bacteria stop replicating. The last phase is the death phase, when cells lose viability; this is then followed by a long-term stationary phase, which can extend for years (Roffe et al., 2012; Martins et al., 2018). The following section provides a brief overview of kinetic models used to describe AD processes.

2.2. Kinetic models

Mathematical models have been extensively used to predict the performance of the anaerobic digester to produce methane from sewage sludge and assist with the selection of appropriate design parameters for the operation and optimisation of the biological treatment plants to improve the efficiency of the processes (Memberea, 2018). In this paper Kinetic model has been used to describe the behavior of critical parameters to produce methane. Since even negligible system improvements can produce considerable financial benefits, mathematical modelling would remain essential for the production of biogas and bacterial growth (Pommier, 2007). As far as the kinetic model equations are concerned, for biogas production the focus is on the kinetics parameter such as the saturation constant rather than only the growth rate of bacteria (Velázquez-Martí, et al., 2018). Kinetic models also help in the estimation of a wide variety of kinetic structures. Studies have classified kinetic models into four main groups, briefly summarized in Table 1. Irrespective of their classifications, all the kinetic models depict the AD processes to predict biogas yield in the bio-digesters.

Table 1. Kinetic model classifications

Kinetic Model	Reference
Reaction in a single step with first-order kinetics	(Lima, et al., 2018)
Two-step reaction with first-order kinetics.	(Velázquez-Martí, et al., 2018)
Reaction in two speeds of a single step with first-order kinetics.	(Sales Morais, et al., 2020) (Kusch, et al., 2008)
Reaction in two speeds of two steps with first-order kinetics.	(Sales Morais, et al., 2020) (Brulé, et al., 2014)

3. Analytical method

In this study, a kinetic model by (Gompertz, 1825) was implemented to quantify methane production through AD technology. This is in a single-step reaction with first-order kinetics model in the presence of single-stage digester (Velázquez-Martí, et al., 2018), selected for its simplicity low equipment cost, and technological challenges associated with the design of the AD systems. The model was used to calculate the amount of methane produced in an AD under mesophilic conditions for a period of forty days. This time-period is essential in obtaining over 95% biogas (Meneses-Quelal, et al., 2021). Thus, the calculation of the kinetic constants was performed for the 40 days of digestion. Equation 1 calculates the highest amount of methane produced according to this model.

$$M = M_e.(1 - e^{k(t-t_{lag})}) \qquad \text{Eq. 1}$$

where, M stands for the amount of methane produced in a stipulated time (t); M_e, is the value of the final production of methane ($m^3/kg_{(vs))}$ and k refers to the constant 'saturation' (g/l). Equation 1 suggests that to produce methane two key factors contribute predominantly, i.e., the lag time and the saturation. The lag phase (t_{lag}) capitulates primarily all the negative impacts. In most of the researches, the gross lag time and the saturation constant (K_s) is maintained in between the 11to 15 days and 0.2 - 0.503 g/l accordingly. Hence, three different calculations were conducted to present an overview of the three different scenarios associated with the quantification of the production of methane. The first scenario constitutes of the consist at their minimum value while the second scenario is made of all the constituents at average level. The third and final scenario has the constituents at the maximum value. Table 2 shows the three different scenarios used for the analysis and quantification of the potential production of methane in the high, low and medium production process. At the end of the calculations, the digestion process was represented in graphs in section 4 below, demonstrating how the kinetic model scenarios and physical parameters are correlated to each other and how the parameters can create a strong influence on the process of methane production.

Table 2. List of Scenarios for Kinetic Model

Scenario	Parameter	Value	Reference
Scenario 1	K_s	0.20 g/l	(Doran, 2013)
	lag time	11 day	(Maria, et al., 2015)
Scenario 2	K_s	0.311 g/l	(Mardani, et al., 2011)
	lag time	14 day	(Velázquez-Martí, et al., 2018)
Scenario 3	K_s	0.503 g/l	(Ling, et al., 2016)
	lag time	15 day	(Crolla & Kinsley, 2013)

4. Results

Figure 1 shows the methane production rates over the 40-day period.

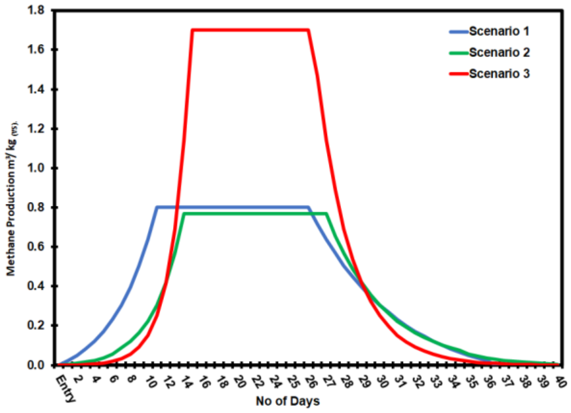

Figure 1. The Differences in the Production of Methane over a Period - The Three Scenarios

It can be seen that the rates of methane production in the first scenario slowly increased from 0.022m^3/ kg $_{(VS)}$ on the first day to 0.803m^3/ kg $_{(VS)}$ on the 11th day. Maximum rates were achieved between day 11 and day 27 with the highest production rate of 0.803 m^3/ kg $_{(VS)}$. There is a gradual reduction rate noticeable in the process which falls to zero on the 40th day. In the 2nd scenario, the production of methane slowly increases from 0.00365 m^3/ kg $_{(VS)}$ on the 1st day to 0.7678 m^3/ kg $_{(VS)}$ on the 14th day. Highest rates were also observed between day 14 and day 27 with the highest production rate of 0.7678m^3/ kg $_{(VS)}$. There is then a gradual reduction in the production rate; this falls to zero on the 40th day. As far as the 3rd scenario is concerned, the production of methane slowly increases from 0.0065 m^3/ kg $_{(VS)}$ on the 1st day to 1.7012 m^3/ kg $_{(VS)}$ on the 15th day. Highest rates were also achieved between day 15 and day 27 with the highest production rate of 1.7012 m^3/ kg $_{(VS)}$. There is a gradual reduction rate noticeable in the process which falls to zero on the 40th day.

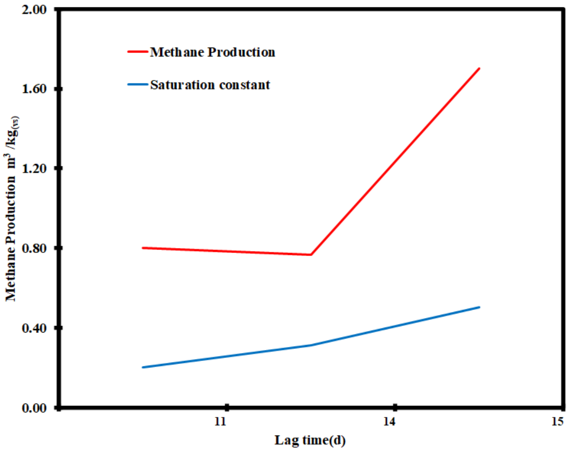

Figure 2. Relationships between the Essential Parameters in a Kinetic Model

Figure 2 demonstrates the non-linear relationship between the key parameters in a kinetic model. It can be seen that, when the saturation constant is altered from 0.2 g/l (Scenario 1) to 0.503 g/l (Scenario 3) within a lag time of 11 to 15 days, the production rate of methane will increase by 211%. The production rate for Senario 2 demonstrates a sharp drop of 3.27%. This drop is the result of the bare minimum increase in the saturation constant i.e. from 0.2 g/l to 0.311 g/l within three days increase in the lag time from 11 to 14 days. This indicates that the saturation constant would need to increase by approximately 250% for an enhanced methane production in a higher lag time. Figure 1 also indicates that all the scenarios are following the same pattern and can be categorised in 3 main stages, In the initial stages the saturation is very small, and the evolution of these microorganisms is slow because it requires time to adapt to the new environment (e.g., scenario 1; 11 days, scenario 2; 14 days and scenario 3; 15 days). 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 11 - 27 based on different scenarios). 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 saturation 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 based on different scenarios). Scenarios 1 and 2 have very close results, despite the saturation rate in scenario 2 being higher than scenario 1 by a ratio of 1.55, the lag time in scenario 2 is higher than scenario 1 by a ratio of 1.27, suggesting that lag time has a dominant effect on the final methane production in this process. Scenario 3 has a saturation rate that is higher than scenario 1 and 2 by the ratio of 2.51 and 1.617 and a lag time ratio of 1.36 and 1.07, respectively. The results of the 3 scenarios shown in figure 1 indicate that in cases where saturation has increased by a ratio more than 50% its effect on the final methane production is the dominating factor compared to the increase in lag time. The reason that Scenario 3 has increased of methane production by a ratio of 2:1 compared to scenarios 1 and 2 is the high level of saturation by more than 50% and therefore limiting the effect of increased lag time.

5. Conclusions

The paper implemented kinetic models to describe the anaerobic fermentation process for different scenarios, as a preliminary work for the development of optimised processes for methane production. Methane was shown to be produced between the ranges of 0.7678 and1.7012 m^3/ kg $_{(VS)}$ in a mesophilic condition i.e., between 30–37°C, the results are encouraging for potential energy generation from the sewage system. The process of digestion can be categorised further into three subsequent groups as per the capabilities to produce methane.

I. Low-Production Process: In this process, the methane production amount is less than $0.7678 m^3/kg_{(vs)}$

II. Medium-Production Process: In this process, the methane production amount is around $0.803 m^3/kg_{(vs)}$

III. High Production Process: In this process, the methane production amount is more than $0.803 m^3/kg_{(vs)}$

As it can be seen from the results and figures, in each scenario methane has been produced in AD but the rate of production is different during the fermentation process, and it depends on the time and saturation constant. However, the result shows there are few differences between them and therefore needs further investigation for the optimization of the two parameters. The optimum conditions can be accomplished when the gross lag time is 15 days, and the mean of the first-order kinetic constant is $0.503 d^{-1}$.

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