Anaerobic co-digestion of grass and cow manure: kinetic modeling comparison and GHG emission reduction

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Research Article

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Abstract

Grass is a highly desirable substrate for anaerobic digestion because of its higher biodegradability and biogas/methane yield. It contains a large amount of organic matter, which can be digested anaerobically to produce biogas. Anaerobic co-digestion of grass, cow manure and sludge was studied under mesophilic conditions for 65 days. Experiments were performed on a feed ratio of grass/manure 5, 10, 15, 20, 25%, respectively. During the experiments the volume and concentration of biogas and methane were recorded daily. The maximum cumulative biogas and methane yield was obtained as 331.75 mLbiogas/gVS and 206.64 mLCH$_4$/gVS for 25% ratio. Also, the results of the experiments were tested on the three different kinetics model which are the first order kinetic model, modified Gompertz model and Logistics model. As a result of the study, it was found that by using grass waste $1.2 \times 10^9$ kWh/year electricity may be produced and $1.1 \times 10^6$ tons/year CO$_2$ greenhouse gas emission may be reduced.

1. Introduction

Today, energy demand is constantly increasing due to the intense consumption of natural resources such as natural gas, oil and coal in the sectors such as industries, residences etc (Rathaur, 2018). Being dependent on fossil fuels as primary energy source has caused global climate change, environmental degradation and human health problems. When compared to energy sources such as fossil fuels, environmental protection concerns encourage renewable energy production, which is an alternative, cheap and sustainable energy (Pecar, 2020). Also, because of the increasing emissions of greenhouse gas emissions, the dependence of the fossil fuels has major negative effects on the environment. The high population and industrialization results to huge electricity demand all over the world with a significant challenge in reducing greenhouse gas (GHG) emission. Researchers around the world are concerned about reducing emission corresponding to electricity generation (Karmaker, 2020). For this reason, great importance is attached to greenhouse gas reduction on the agenda of policy makers. Therefore, the use of renewable energy sources can positively affect the green energy production and minimize negative effects caused by the use of fossil fuels (Tsapekos, 2019).

Anaerobic digestion (AD) is practiced in various processes and has become an important part of renewable energies (Tsapekos, 2019). It is an alternative energy source that is obtained from different organic sources and wastes during AD (Bücker, 2020). Every year, several million tons of organic waste are disposed by incineration, land applications, landfill, etc. in the world (Deepanraj, 2017). These wastes are agricultural residues, cattle manure, organic municipal solid waste, green biomass, etc. They are raw materials and exhibit a sufficiently high potential for biogas production (Yadvika, 2004). Microorganisms can consume organic matter through AD by producing biogas consisting of methane (50–70%) and carbon dioxide (30–50%). The use of fossil fuels can be reduced by evaluating the produced methane by cogeneration of heat and electricity or by injection into gas networks (Andre, 2019).

Interest in the use of grass silage as a raw material for bioenergy and bio-refining systems is due to its high yield potential in terms of methane production per hectare. But, the lignin and cellulose content makes it more suitable as energy sources (Korres, 2010; Nizami, 2011). In spite of the advantages given above, several difficulties must be encountered before using for industrial applications. For example, harvest stage technologies and pre-AD treatment methods should be carefully selected as they have important effects on the overall energy budget (Tsapekos, 2019; Svensson, 2005). During AD, methane yield is affected by the composition of lignocellulosic biomass and biodegradability. However, during AD the biodegradable nature of lignocellulosic biomass is hampered by the stubborn structure attributed to lignin around highly crystalline cellulose and carbohydrates (Frigon, 2010). Therefore, the use of lignocellulosic biomass is only economically possible after pretreatment in most cases. Pre-processes are thought to be important in facilitating technologies that allow these cheap and available raw materials to be used in the design of mass and economically efficient biofuels (Sun, 2015).

There are several pretreatment technologies in the literature about lignocellulosic materials. The main purpose of pretreatment is to decrease the strength of lignin and reduce the crystal structure, and then obtain more accessible
substrate to microorganisms in an anaerobic digestive system. Many promising pretreatment methods have been proposed so far to increase biogas production from lignocellulosic biomass. These methods can be classified as physical, physicochemical, chemical and biological pretreatment methods (Taherzadeh, 2008; Yang, 2008; Hendriks, 2009; Chandra, 2012). Between physical pretreatment methods milling is proved to be effective and increases hydrolysis efficiency by 5–25% by increasing the specific surface area, by reducing the degree of polymerization and also leading to shearing. This development depends on the type of biomass, the grinding time and the type (Zeng, 2007; Jin, 2006). So, it appears that in biofuel production, the smaller particle size of lignocelluloses yields higher biofuel yields (Kabir, 2015). Nizami (2009), reported that the grinding effect can increase the methane content from 5–25%, but higher parasite demands make grinding less attractive. He made sure that pre-processing techniques were suitable for heat treatment such as grass silage, size reduction, and liquid hot water, and that slurry coding could offer more stable processes that were more useful than grass or slurry mono digestion.

Tsapekos et al. (2019) investigated the production of biogas from AD of grass using two harvesters, a disc mower and an excavator. According to their study, single digestion of grass with a specific biomethane yield of 329 mLCH₄/gVS will not guarantee a long-term sustainable energy system. The combined digestion of grass and fertilizer will be a sustainable energy system. Bedoić et al. (2019) studied residue grass digestion on mono digestion system. They obtained the biochemical methane potential on uncultivated land, river bank highway boundary, between 0.192 Nm³/kg TS and 0.255 Nm³/kg TS. They estimated kinetic parameters in mathematical modeling using Anaerobic Digestion Model No. 1 (ADM1) and model results showed small deviations compared to experimental data. Andre et al. (2019) studied roadside grass cuts and solid cattle manure which are sources available for dry anaerobic digestion. They determined their methane potential at laboratory scale and showed a high degree of seasonality, such as 202.9 and 167.9 Nm³CH₄/tVS, respectively. In addition, these substrates were digested with dry reactors on a 60 liter pilot scale by dry treatment.

This study is about the valorization of grass by anaerobic digestion. The valuation of the grass was studied through digestion along with cow manure. Many studies have been done on co-digestion with plant residue and animal manures, but little information is available about the anaerobic co-digestion of cow manure with grass. The results were used to characterize anaerobic digestion using raw materials, investigate the quantitative relationship between the biogas potential and the organic content of sludge. Results from other references were analyzed and the effect of organic composition was discussed. Kinetic work on anaerobic co-digestion of grass with cow manure was carried out using three different models, the first-order kinetic model, the modified Gompertz model, and the Logistics model. Finally, energy production potential of grass and cow manure and an analysis of GHG emissions was carried out.

2. Materials And Methods

2.1 Materials

Grass waste was taken from the lawn mower of the university and collected from the surrounding garden. The waste was crushed using shredder, mixed and stored until use. The inoculum used in this study was collected fresh from the anaerobic wastewater treatment system of a yeast factory in Izmir and cow manure was taken from the university farm. Operational parameters of the digester content are given in Table 1.
### 2.2 Experimental design

For experiments, 10 liter laboratory scale batch glass digesters were used. The volume of the digester was kept at 7 liters. Anaerobic digestion was performed at mesophilic conditions (~35°C), maintaining the temperature constant. Figure 1 shows the simple scheme of one digester system. Details of the total laboratory scale and experimental setup can be found in the literature (Yilmaz, 2003; Ulukardesler, 2018).

### 2.3. Analysis

The properties of the digester raw materials can be found in Table 2. Total solids (TS) and volatile solids (VS) contents were determined by drying the substrates for 24 hours at 105°C and 2 hours at 550°C (APHA, 2005). The analyzes were performed once daily throughout the anaerobic digestion procedure and were performed in duplicate. The compositions of the produced biogas were measured using an infrared gas analyzer purchased from Geotechnical Instruments, UK.

### 2.4. Kinetic model

Three different kinetic models which are first order kinetic model, modified Gompertz model, and logistics model were applied to study the kinetics of methane production during anaerobic fermentation of grass waste and cow manure. Experimental cumulative methane yield values were used in order to estimate the kinetic parameters by using nonlinear least square regression analysis in the solver tool in MS Excel 2013. This method optimizes the value of kinetic parameters to minimize the sum of squares of differences between measured and simulated methane yield values (Pecar, 2020; Panigrahi, 2020). Models and equations are shown:

See formulas 1 - 3 in the supplementary files section.

where $C_{CH4}$ is the cumulative experimental methane yield (mole/gVS) for a digestion time $t$ (day); $r_{CH4max}$ maximum methane production rate (mole/gVS.day), $t_l$ lag phase time (day), and $e$ is exp(1) 2.7183. The validity of these models was evaluated by statistical indicators of coefficient of determination ($R^2$) and root mean square error (RMSE).

### 3. Results And Discussion
3.1 Volume of biogas and methane produced

The cumulative volume of biogas and methane produced at different ratios was measured for 65 days during anaerobic fermentation of cow manure, sludge and pretreated grass. The results are presented in Figure 2 and Figure 3. produced 51000 mL of biogas in total and other mixtures Exp2. 65600 mL; Exp3. 77200 ml; Exp4. 99850 mL and Exp5. produced 109500 mL, respectively. Based on the results obtained, Exp5. mixture produced more biogas than other mixes. It was obtained that the maximum methane volume was obtained in the Exp5 mixture. It is about 68000 mL.

Figure 4 shows that all mixtures have high methane content (about 70%) at many points in the biogas production curve. Biogas production in all digesters occurred immediately after the first day and markedly increased for the first 40-45 days, then decreased slowly. It is seen that peak values are between 35-40 days since daily biogas production. The results of daily methane production are given in Figure 5.

3.2 Biogas and methane production yield

Cumulative biogas yield and methane production yield are presented in Figure 6 and Figure 7, respectively. The final biogas and methane yield from each mixture are 216.42 mL biogas/gVS and 109.73 mLCH\(_4\)/gVS (Exp1.), 253.04 mLbiogas/gVS and 125.94 mLCH\(_4\)/gVS (Exp2.), 272.94 mLbiogas/gVS and 140.46 mLCH\(_4\)/gVS (Exp3), 325.82 mL biogas/gVS and 182.71 mLCH\(_4\)/gVS (Exp4.) and 331.75 mLbiogas/gVS and 206.64 mLCH\(_4\)/gVS (Exp5.), respectively. Specifically, the maximum biogas and methane yield was achieved in Exp5.

3.3 Model analysis and results of kinetic study

In order to obtain kinetic parameters which are maximum biogas production rate, biogas yield potential and duration of the lag phase of the reaction, experimental values obtained were fitted with kinetic models. The parameters of kinetic models may characterize the methane production process (Feng, 2020).

The calculated parameters of the analyzed kinetic models; the first order kinetic model, the modified Gompertz model and logistics model, are summarized in Table 3, respectively. The RMSE values was in the range of 0.827-3.384 for first order model while this value was between 0.82-14.3 for logistics model. It is seen from Table 3 that, the minimum RMSE values were obtained for the modified Gompertz model which were between 0.324-0.513.

|               | First order model | Modified Gompertz model | Logistics model |
|---------------|-------------------|-------------------------|-----------------|
|               | RMSE              | C\(_{\text{CH4max}}\) | k               | RMSE    | C\(_{\text{CH4max}}\) | r\(_{\text{CH4max}}\) | t\(_L\) | RMSE    | C\(_{\text{CH4max}}\) | r\(_{\text{CH4max}}\) | t\(_L\) |
| Exp1.         | 0.827             | 5.406                   | 0.093           | 0.513    | 1.970                   | 0.094       | 5       | 0.820   | 5.399                   | 0.516       | 0.217     |
| Exp2.         | 0.963             | 5.357                   | 0.095           | 0.655    | 1.957                   | 0.093       | 4.935   | 0.963   | 5.357                   | 0.513       | 0.001     |
| Exp3.         | 0.995             | 5.522                   | 0.096           | 0.707    | 2.021                   | 0.092       | 4.703   | 14.300  | 5.410                   | 0.418       | 0.001     |
| Exp4.         | 2.280             | 5.987                   | 0.096           | 0.914    | 2.228                   | 0.075       | 2.764   | 2.280   | 5.987                   | 0.096       | 0.001     |
| Exp5.         | 3.384             | 6.349                   | 0.119           | 0.324    | 2.407                   | 0.073       | 0.001   | 3.384   | 6.349                   | 0.119       | 0.001     |

Table 3. Results of kinetic study using three different models

Since the minimum RMSE values were in modified Gompertz model, the estimated cumulative biogas values were plotted against the experimental values and they were given in Figure 8 to Figure 12 for this model. The reliability of the model results is in reasonable agreement (R\(^2\)>97%).
3.4 GHG emission reduction

Biogas is a clean and sustainable energy generation option that can supply significant GHG savings compared to fossil fuels. The EU and its member states agreed to reduce their greenhouse gas (GHG) emissions with 40% by 2030 compared to 1990 levels.

Table 4 gives the biogas and energy equivalents produced according to grass. During the calculations, amount of grass was taken as the 7.9% of the total municipal waste of Turkey (EPA, 2021). The thermal value of the biogas was accepted as 22 MJ/m³ depending on the rate of methane and in accord with the reference value. Also, electrical energy equivalent was calculated as 1.9–2.2 kWh/m³ of biogas (Eryasar, 2009; Ulusoy, 2021). In 2018, the CO₂ emissions from different energy sources for Turkey are as follows: 161 Mt from coal, 115 Mt from oil and 93 Mt from natural gas (IEA, 2021). The greenhouse effect of electricity generation is reflected in the extent of the CO₂ emissions, which amount to 362-891 ton CO₂/GWh when the electricity is generated from natural gas, 547-935 ton CO₂/GWh for electricity generated from petroleum, and 756-1372 ton CO₂/GWh for that produced by coal (enerjiatasi.com, 2021).

| Municipal waste (tons/year) | Grass waste (tons/year) | Grass VS (tons/year) | Biogas (m³/year) | Electrical energy (kWh/year) | CO₂ release petroleum equivalent (tons/year) |
|----------------------------|-------------------------|----------------------|------------------|------------------------------|---------------------------------|
| 32,209,000                 | 2,544,511               | 1,908,383            | 631,674,773      | ~1,263,000,000               | ~1,073,000                      |

4. Conclusion

The co-digestion of different mixtures of grass, cow manure and sludge compositions was carried out successfully. The biogas production is dependent on various important parameters of substrates as well as the process parameters of AD. It can be concluded that, the amount of mixture influences the biogas and methane amounts obviously. As the grass amount increases, biogas yield was affected positively. According to the results obtained, 331.75 mL biogas/gVS is suitable to alternative other systems. The high lignin content in the substrates may cause less total biogas yield in this study, that's why pretreatment method was applied to increase biogas and methane yield.

The kinetic model studies showed that, the first order model and logistics model was not suitable for predicting biogas production because they had more fitting error values than the modified Gompertz model. The modified Gompertz model had fitting error value below 2%.

Various abatement procedures are presented to conclude that greenhouse gas emission can be significantly reduced by considering renewable sources. The technology consumes energy and increases the cost, which encourages it to choose an alternative way to reduce CO₂ emissions. In addition, the authors suggest that existing renewable sources would be a potential solution, effectively offering a significant reduction in greenhouse gas emissions. Although this research reflects
the example of Turkey, direct greenhouse gas emissions from electricity generation in the energy sector can be reduced by generating electricity from organic waste all over the world.

Declarations

-Ethical Approval Not applicable

-Consent to Participate Not applicable

-Consent to Publish Not applicable

-Author Contributions Not applicable

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-Competing Interests: The authors declare that they have no competing interests

-Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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**Figures**

Figure 1
Experimental set-up. (1) Laboratory digester (2) Mixer (3) Electrical motor (4) Gas bag (5) Gas analyzer

**Figure 2**
Cumulative biogas production

**Figure 3**
Cumulative methane production
Figure 4

Methane percentages

Figure 5

Daily methane production
Figure 6
Cumulative biogas production yield

Figure 7
Cumulative methane production yield
Figure 8

Results of models for Exp1. a) Cumulative methane production for all models b) Modified Gompertz model results

Figure 9

Results of models for Exp2. a) Cumulative methane production for all models b) Modified Gompertz model results
Figure 10

Results of models for Exp3. a) Cumulative methane production for all models b) Modified Gompertz model results

Figure 11

Results of models for Exp4. a) Cumulative methane production for all models b) Modified Gompertz model results
Figure 12

Results of models for Exp5. a) Cumulative methane production for all models b) Modified Gompertz model results

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