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A study on the effect of temperature and micro- nutrients in biogas production by dry anaerobic digestion of municipal solid waste

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Abstract

Energy scarcity is soaring due to the over exploitation of fossil fuel reserves in Bangladesh. On the contrary, a potential energy source i.e. organic municipal solid waste is creating a serious environmental hazard for municipalities ascribe to ineffective and commercially unviable waste management strategy. Therefore, the present study was performed on a dry anaerobic digestion process for biogas production from unsorted organic municipal solid waste. In batch digesters with a 5L effective capacity, the performance of the dry anaerobic digestion (DAD) process of solid waste was assessed during the period of 35 days of operation. Different factors i.e. temperature (35°C, 40°C, and 45°C), micro-nutrients (Na^{+}, K^{+}, Co^{+}) and inoculum mixing ratio (Anaerobic sludge: Cow manure = 1:2, 1:3 and 2:1) were analyzed to observe the biogas production. The results show that biogas production was comparatively higher (approx. 375 mL/day) for 35°C where anaerobic sludge (AS) to cow manure (CS) ratio more than 1. The obtained gas composition was analyzed further to compare the biomethane production depending on these factors. A machine learning (ML) algorithm i.e. Random Forest Regressor was implemented to predict the biogas generation considering different parameters. The model showed performance with more than 77.8% accuracy (R-squared value). Future research can be performed by conducting experiments considering other factors which affects biogas generation and a better model can be implemented to predict the nature of biomethane production.

Keywords: Anaerobic digestion, Biomethane production, Machine learning, Municipal solid waste, Renewable energy.

1. Introduction

Humans of all ages have an inherent requirement for energy. Fossil fuels, hydropower, thermal energy, electrical power, etc. are only few of the many types of energy sources available. Rapid economic development and population boom have led to a steady depletion of fossil fuel reserves. Over the past century, fossil fuels have supplied at least

85 percent of the world's primary energy consumption(Abanades et al., 2022; Ghasemian et al., 2020). Constant growth in worldwide energy use necessitates the development of sustainable alternatives. Greenhouse gas emissions are another issue that worries us. The excessive use of

fossil fuels is the reason of producing carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter and volatile organic compounds. So,it has become an urgent need to find any alternative source of renewable energy which can meet up the increasing energy demand all over the world.

Biofuel can be a potential alternative of fossil fuels and can be produced from biogas. Various waste biomass e.g. municipal solid waste (MSW), poultry feedstock, cow manure etc. are used as substrate for biogas generation (de Jong et al., 2008). On the contrary to fossil fuels, biogas is inherently renewable and naturally composed of biogenic materials. In 2020, the total amount of electricity generated from renewable sources was 7468 Terawatt hour (TWh) of which 584 TWh (8%) is from biological source(International Renewable Energy Agency, 2018). Biogas production can be achieved through anaerobic digestion (AD). It is a biological process which involves treating and stabilizing organic fractions of the biomass in the absence of oxygen. This process is accomplished by microorganisms consisting of four phases i.e. hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Zamri et al., 2021). Among these phases, the hydrolysis is the rate-limiting step. Biogas production depends on various factors e.g. substrate quality, design and selection of digestion process, pre-treatment process, and various process conditions such as, pH, temperature, carbon to nitrogen (C: N) ratio, organic loading rate and hydraulic retention time.

The rapid urbanization with economic and population growth has introduced an important drive of converting waste to usable energy. Waste is causing environmental, ecological and social problems including air and water pollution, bad odor, shortage of waste disposal area etc. So, the generation of municipal solid waste (MSW) is an alarming global issue contributing socio-economic and environmental problems. When wastes are sent to landfill, they can produce methane (CH_4) which is 34 times more potential than carbon dioxide (CO_2) responsible for global warming (Atelge et al., 2020). Though the amount of waste has been increased in recent times, little energy has been produced from the waste yet. Development of high energy fuels including bioethanol, biodiesel and biogas is needed to reduce carbon footprint, improve energy security, meet local energy demand and to make a sustainable alternative to fossil fuels (Uddin et al., 2021).

Machine learning (ML) model has been successfully applied in the anaerobic digestion field, mainly for predicting biogas yield. For instance, a two stage anaerobic digestion process of poultry manure was conducted and total ammonia nitrogen concentration was predicted using Support Vector Machine (SVM) model. Though there were limited data, the R-squared value for SVM was 0.898 (Alejo et al., 2018). Another study was performed for 50 samples of datasets from lab scale from 8 research groups where 6 ML models were compared for genomic data and operational parameters (volatile fatty acids, hydraulic retention time, temperature and organic load ratio. Random Forest (RF) model achieved prediction accuracy of 0.82 for the combination of genomic and operational factors (Long et al., 2021).

A feasibility study has been performed in Dhaka city, Bangladesh suggesting that waste to energy (WTE) conversion as a solution of waste management problem in Dhaka (Habib et al., 2021). Researchers found that 44% of the residents of Chattogram City, Bangladesh are agreed to pay USD 0.3 to 0.4 per month to the waste collector. This research adequately shows that household waste can be converted to resources they are segregated at the source (Habib et al., 2021). Similar study was performed in Rajshahi, Bangladesh which says that about 28.13 ton of solid wastes are handled in Rajshahi City Corporation area everyday (Habib et al., 2021). Most of the experiments are done on the sorted municipal solid waste(MSW) but only a few has focused on the biogas generation of unsorted MSW. Our study aims to measure the effect of temperature, micro-nutrients and inoculum mixing ratio in biogas generation on the unsorted MSW by varying different factors.

2. Material and Methods

2.1. Dry anaerobic digestion (DAD) process set up

The working volume is 3.5 L, whereas the digester's volume is 5.0 L. A flexible plastic tubing was used to connect it to a gas collector, which is a 2.0 L reservoir that was first filled with water (Fig. 1). Biogas was produced in the digester whose volume was measured by water displacement method. After feeding the digester with biomass, nitrogen gas was purged to create an anaerobic atmosphere. Using the nitrogen purging port, the pH of the digesting environment was periodically checked. The setup as a whole was made to remain airtight.

Figure 1: Process flow diagram of dry anaerobic digestion process (Hossain et al., 2022)

2.2. Waste collection and municipal solid waste feedstock preparation

The sample was made from waste items from the kitchen, including plastic, paper, cloth, and glass. These waste were collected from the nearby vegetable markets and students' dormitory. The feedstock was prepared in the following proportion: 900gm of organic waste, 100 gm plastics and 85 gm paper, 40 gm fabric , 40 gm glass and 35 gm metal wastes.

2.3. Inoculum preparation

Anaerobic sludge (AS) collected from sewerage drain and cow manure (CM) collected from cattle farm were used as inoculum in mixed mode in this study. Subsequently, the amassed anaerobic sludge and cow manure were combined in varying proportions (as delineated in Table 1) with 200 ml of water, resulting in the formulation of an inoculum slurry.

2.4. Experimental setup

During each experimental trial, a solution of alkali (NaOH) was meticulously blended with the biomass feedstock derived from municipal solid waste. Subsequently, the amalgamated mixture was introduced into the digester. Then the inoculum was flowed in a multilayer flow pattern throughout the whole biomass. The setup was hermetically sealed, and a stream of nitrogen gas was introduced into the digester at a rate of 1.5 L/min for a duration of 5 minutes. This procedure ensured the preservation of an anaerobic environment throughout the digestion process. Subsequently, the securely sealed anaerobic digester was upheld at a constant temperature for the entirety of the 35-day digestion period. The quantity of biogas generated was determined using the method of water displacement and recorded at intervals of 2 days. An analysis of the composition of the biogas was conducted to ascertain and compute the yield of biomethane.

2.5. Biomethane yield optimization

Temperature was varied from (35 – 45°C) at the thermophilic range to find out the optimum value for the digestion. The experimental designs for the optimization of temperature, nutrients and inoculum mixing ratio are presented in Table 1.

Table 1. Experimental design for different temperature, nutrients and inoculum mixing ratio

Digestion process parameter	**Temperature**			**Nutrients**			**Inoculation Mode**		
	35°C	40°C	45°C	Na^{+}	K^{+}	Co^{+}			
Amount of biomass (gm)	1200	1200	1200	1200	1200	1200	1200	1200	1200
Amount of NaOH (mL)	50	50	50	50	50	50	50	50	50
Digestion temperature	-	-	-	35°C	35°C	35°C	35°C	35°C	35°C
Inoculum flow pattern	Multi-layer	Multi-layer	Multi-layer	Multi-layer	Multi-layer	Multi-layer	Multi-layer	Multi-layer	Multi-layer
Amount of inoculum (gm)	100	100	100	100	100	100	33 gm AS + 67 gm CM + 200 mL water	25 gm AS + 75 gm CM + 200 mL water	67 gm AS + 33 gm CM + 200 mL water
Nitrogen purging (min)	5	5	5	5	5	5	5	5	5

2.6. ML Model Implementation

In this study, a dataset of (323 rows × 13 columns) was prepared from the experimental data. Among them (225 rows × 13 columns) are training dataset and the rest are validation dataset. The Random Forest Regressor model was implemented on the training and validation data. Then biogas generation was predicted by the model through providing the test dataset. Finally, the experimental data and the predicted data were compared graphically.

3. Results and discussions

Three sets of experiments were conducted at temperatures 35°C, 40°C, and 45°C respectively. It was seen that at 40°C and 45°C the overall gas production is low compared to other temperatures (Fig. 1). According to a study by (Rajagopal et al., 2019), it is concluded that the digester operating at low temperatures like 28°C obtained 50% higher specific methane yield compared to that at 20°C. Wang, et al. (2019) obtained the highest biogas production at 35°C for the co-digestion of cow manure and corn straw, and the biogas production decreased by about 22.4%, 36.2%, and 70.4% at temperatures of 25°C and 20°C, respectively. The higher temperature yielded an augmentation in the hydrolytic rate of municipal solid waste (MSW). Concurrently, proportional acidogenesis ensued, facilitating the generation of acetic acid, subsequently metabolized at a comparable rate during the methanogenesis stage, thereby resulting in an increased yield of biogas. Based on some previous research it was seen that the optimum temperature for the AD process is 35-37°C (Cioabla et al., 2012). Similar results have also been observed in our study where the multilayer flow pattern gave the highest yield at 35°C, so it can be concluded that this flow pattern and temperature are the optimum conditions for the anaerobic digestion of MSW.

The effects of micronutrients on biogas yield were observed by supplying $Na+$, $K +and$

$Co+$ as salt to the digester. It was observed that for $Co+$, the overall gas production is lower compared to other micro-nutrients (Fig. 3). Micro-nutrients show a greater effect on the production of biogas. Heavy metals inhibit the performance of methanogenesis bacteria significantly. Comparative lighter metals show better performance than that of heavy metals. Pretreatment with KOH in rice straw exhibits higher biogas production in anaerobic digestion (Luo et al., 2020).

The effects of different inoculum mixing ratio were observed through mixing AS and CM in multiple ratios (1:1, 1:2, 1:3, and 2:1). The similarity in the curves indicates the homogeneity in biogas production in the different fermenters through the gas production is higher in some and lower in others. The overall daily biogas production was higher for the inoculum mixture ratio (AS:CM) of 1:2 compared to the other mixed (Fig. 4). At the end of the 35th day, it was observed that the gas production was null in two fermenters and the experiments were continued for a few more days to see if there's any gas production but after this period the gas production ceased to exist. The AS inoculum employed in this investigation contains elevated concentrations of heavy metals such as copper (Cu^{2+}), zinc (Zn^{2+}), cadmium (Cd^{2+}), lead (Pb^{2+}), among others (Nsair et al., 2020). These heavy metal ions exert inhibitory and toxic effects on both acetogenic and methanogenic bacterial populations, leading to disruptions in enzymatic secretion and diminished activities of these bacterial types. Ultimately, the anaerobic digestion process utilizing the AS inoculum experienced a decline, marked by the absence of biogas production beyond the 25-day mark, attributed to the accumulation of volatile fatty acids (VFAs) (Hossain et al., 2022). The current study corroborates this observation, wherein the presence of heavy metals (Cu^{2+}, Zn^{2+}, Cd^{2+}, Pb^{2+}, etc.) within the AS inoculum initiates a suppression of biogas production from the onset, culminating in complete cessation after the 35-day threshold.

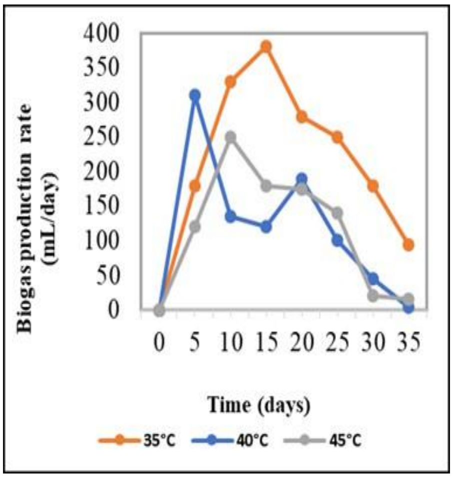

Fig. 2 Effect of temperature on biogas production rate

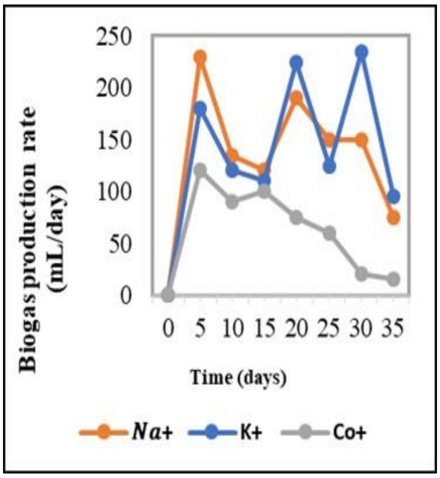

Fig. 3 Effect of nutrients (light & heavy metals) on biogas production rate

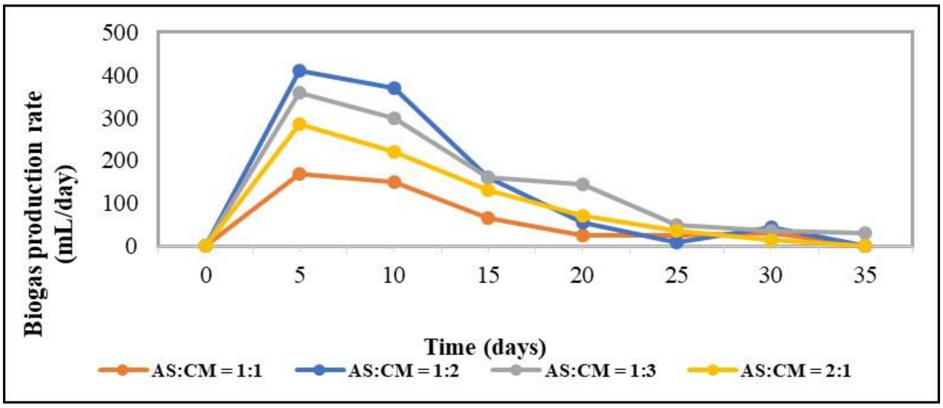

Fig. 4 Biogas production per day for the inoculum mixer ratios

4. ML Model Prediction

The code snippets for implementing the algorithm.

(a) Importing necessary libraries:

```
import pandas as pd import numpy as np
import matplotlib.pyplot as plt
from sklearn.ensemble import RandomForestRegressor
from sklearn.model_selection import train_test_split
from sklearn.model_selection import RandomizedSearchCV
```

(b) Importing dataset:

```
biogas = pd.read_csv("biogas_data.csv")
biogas.info()
```

(c) Splitting the data to training and validation set:

```
X = biogas.drop("target", axis =1)
```

```
y = biogas["target"]
train_split = round(0.7*(len(biogas)))
valid_split = round(train_split + 0.3*(len(biogas)))
X_train, y_train = X[:train_split], y[:train_split]
X_valid, y_valid = X[train_split:valid_split],
y[train_split:valid_split]
```

(d) Fitting ML model:

```
np.random.seed(56)
biogas_model = RandomForestRegressor()
biogas_model.fit(X_train, y_train)
biogas_model.score(X_valid, y_valid)
```

(e) Prediction using test dataset:

```
test = pd.read_csv("test.csv")
test_preds = biogas_model.predict(test)
df = pd.DataFrame()
df["days"] = test["days"]
df["biogas produced per day"] = test_preds
```

After implementing the model, it was found that the model shows an accuracy (R- squared value) of 0.778 which means that the model fits about 77.8% accurately with the training data. The model was evaluated with the test dataset and it could predict the amount of biogas generation/day. The experimental data was compared with predicted result illustrated in Fig.5.

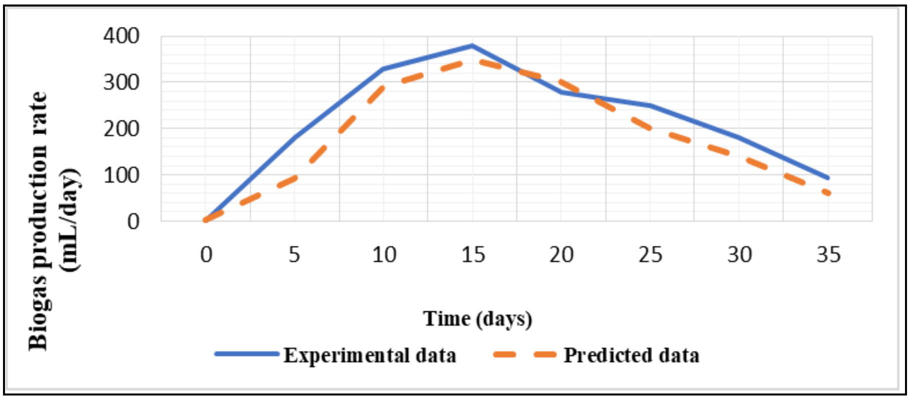

Fig. 5 Comparison of experimental and predicted data obtained from ML model

5. Conclusion

To meet the growing energy demand, it is necessary to intensify research on alternative energy sources. In our experiments, the temperature and effect of nutrient were optimized for biogas production from MSW using the method dry fermentation method. This process can be a promising method for the processing of MSW which can reduce the environmental impacts and also produce energy that can power up the local municipalities or even rural areas. An efficient way to handle organic waste, meet local energy needs, cut waste, increase energy security, and minimize air pollution is through anaerobic digestion (AD). Materials that would otherwise be considered garbage are given a second life by the AD technique. In addition to replacing fossil fuels for the production of heat and electricity, biogas can also be utilized as the fuel for vehicles. It is a versatile renewable green energy source. Analyzing and categorizing organic materials, biodegradability, involving numerous microbial activities, accessibility, and establishing the precise limiting elements and processes are the paradigms that the AD approach for organic waste finds fascinating. The large-scale AD process biogas plant must be adjusted for optimal operating conditions based on environmental considerations and the availability of raw materials. This is as a result of the varied feedstock composition. The local knowledge and data of the feedstocks, including their accessibility, degradability, and the design of all-purpose anaerobic reactors, are unavoidable in this situation. Biogas contains a number of undesirable substances and other gases that are regarded as biogas contaminants. In order to increase methane production and improve biogas quality and quantity, pre-treatment is typically necessary. The pre-treatment of organic waste is regarded as the key procedure in biogas producing facilities. This study can successfully speed up the use of renewable energy and utilization of available resources along with the concept of waste to wealth conversion. Future research can be conducted by considering more operational parameters of anaerobic digestion process and predicting a higher accurate score for most significant factor through ML models.

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