Non-Linear Regression Models for Predicting Biogas Yields from Selected Bio-wastes.

Abstract

The benefits of biogas as alternative energy to other fossil fuel sources, due to its renewability, environmentally friendly nature, health benefits, etc., cannot be overemphasized. There are numerous models for predicting biogas production rate from bio-materials, including the modified Gompertz equation. These models are primarily dependent on specific biomass parameters. When any of these parameters, like the slurry volume, changes, another round of experiments must be conducted and curve fitted before biogas yield predictions can be made. This could be time-consuming and costly. Using experimentally published data, simple empirical models can be developed for predicting biogas yields over a range of input parameters. This will eliminate the need for always performing experiments before biogas yield predictions can be made. In light of this, scarce literature provides explicit models for predicting biogas yield over a range of parameters based on published data. This study developed non-linear regression models using published data on parameters that affect biogas yields, like the slurry volume, carbon-to-nitrogen ratio, temperature, total solids, volatile solids, hydraulic retention time, and pH. The data covered seven readily available bio-wastes, including cow dung, cow dung with plant waste, cow dung with poultry dung, poultry dung with grass, pig dung, and plant wastes. On validation of the models, the results showed that the models had a relatively low standard error of estimates, Akaike information criterion, Schwarz criterion, and Hannan-Quinn information criterion. Furthermore, the coefficients of determination, $R^{2,}$ were between 89.52 and 98.93%. The percentage average absolute deviation (% AAD) for each model was less than 7 %. The non-linear models were found to adequately predict the biogas yields within the limits of the available data set.

Keywords: Biogas, non-linear models, bio-wastes, renewable energy.

1. Introduction

Sustainable development has become a global priority. Global prosperity and human development have always been tied to energy. But the health threat imposed by fossil fuel, its non-renewable nature, the environmental pollution from the constant release of carbon dioxide, etc., a cause for global concern, has necessitated the search for alternative renewable and cleaner energies with a less negative effect on the environment. Unfortunately, only about 20 percent of the global energy requirement is met by renewable sources like solar, wind, biomass, etc., of which energy from biomass has gained significant importance due to its waste volume reduction and energy recovery. Consequently, the need for a sustainable supply of clean energy has increased the quest for alternatively cleaner and renewable energy sources that can mitigate climate change effects [1]. To achieve this goal, the contribution of renewable energy to the total energy supply mix must continue to increase significantly and ultimately be the sole energy source in the future. Many developed countries increasingly utilize solar, wind, nuclear, biomass, and geothermal energy sources. Their contribution to the total energy mix in those countries is increasing significantly. However, this is not the case in many developing countries where the primary energy source remains fossil fuels and biomass.

Biomass is a common bio-energy source, especially in many developing countries' rural communities. This is due to its availability, scalability, abundance, and cost-effectiveness in generating clean and renewable bio-energy compared to other renewable energy sources [2]. Another advantage of biomass clean energy sources is that they can valorize plant and animal waste (which could pose environmental and public health issues when not properly disposed of) for effective waste management. Many biomass fuels produce biogas, such as wood, charcoal, agricultural residues, household waste [3], animal waste, and energy crops [4]. Biogas production, one of the most environmentally beneficial technologies for bioenergy production [5], plays an essential role as an energy source capable of increasing the supply stability of gaseous fuels. As a source of renewable natural gas, it has been adopted as one of the best alternatives for fossil fuels after the 1970s world energy crisis. Biogas is a clean and renewable fuel produced through a natural process in which bacteria convert organic materials into a mixture of methane and carbon dioxide gases with traces of ammonia and hydrogen sulfide [6]. It is a colorless, odorless, and flammable gas. It can be collected, with special installations, from landfill sites [7]. Many technologies, such as incineration and refuse-derived fuel (RDF), etc., produce energy from solid wastes. Among them, anaerobic digestion has become a promising technology, particularly for recovering energy from the organic fraction of solid wastes. According to the department of alternative energy development and efficiency [8], one cubic meter (m^3) of biogas comprises 60% methane, with a heating value of around 21 mega-joules, an equivalent of 0.6 liters of diesel oil or 0.67 liters of gasoline, 0.55 liters of fuel oil, 0.46 kg of LPG or 1.2 kWh of electricity. As a result, biogas is used for cooking, heating, and fuel sources for electric generators, automobiles, etc., in many households, farms, and public utility systems.

Due to its numerous applications, the need to accurately predict the amount of biogas obtained from a given mass or volume of a substrate cannot be overemphasized. Predicting biogas yields from the various types of available biomaterials is helpful for the efficient design and construction of biogas digesters and other equipment used for biogas generation. Accurate biogas prediction from different biomaterials helps optimize the production value chain, reducing the associated costs and maximizing biogas yield. Consequently, many scholars have tried to find the best ways to optimize the biogas yield of different substrates. Unbiased decisions in biogas production optimization are guided by the development of models commonly referred to as Decision support tools (DST). Some of these models include the Modified Gompertz model, widely used to study growth rate (i.e., used to fit growth data), and the first-order kinetic model used to model batch Biochemical Methane Potential (BMP) data to obtain valuable interpretation about hydrolysis kinetics. The Logistics model used to predict the methane production potential as a function of time, the 3-D numerical simulation model based on the conservation of mass and energy, and the species transport model that predicts biogas production from plug-flow anaerobic digesters [9]. Also, the Buswell Formula has been used to forecast the BMP of various substrates.

However, these models for biogas prediction have one common limitation. Experimentation must be conducted to furnish the models with the essential information to estimate biogas production yield. This means that for any change in substrate properties like slurry volume and temperature, new sets of experimental analyses must always be performed to generate data for model curve fitting. This will increase the overall costs and time. Furthermore, models for predicting biogas yields without recourse to experimentation, e.g., regression models based on available data, are scarce in the open literature. Therefore, this study aims to develop time and cost-saving regression models from published data for predicting the biogas yields of common substrates found in our everyday lives without regular experimental analysis. The regression models utilize seven parameters that significantly influence biogas yields from various biomaterial substrates. They include the slurry volume, temperature, carbon-nitrogen ratio, total solids, volatile solids, pH, and hydraulic retention time. Most of the parameters influencing biogas yields are presented in the next section.

2. Optimal Production of Biogas

The use of biogas has attracted attention in the processing industry due to its renewable raw materials and environmentally friendly products. The current demand for renewable energy sources instead of non-renewable ones has increased the research interest in optimizing biogas production technologies. The increase in biogas efficiency depends mainly on the concentration of the raw material, the process temperature, the hydraulic residence time, pH value, the organic matter loading rate, the volatile fatty acids, the particle size, the crystallinity of the raw material, etc. and these numerous factors makes the biogas optimization decisions difficult [10]. The prediction of biogas yields from readily available raw materials has taken on a new dimension from using traditional statistical methods to applying mathematical techniques and artificial intelligence (AI) strategies. This has improved offset data decision-making in the biogas production and strategic planning phase. Models based on mathematics and statistics can provide vital information for the intellect, analysis, and prediction of the processes' yields [11]. These are necessary to select the essential parameters for optimizing the final product and process [12].

According to Kunatsa and Xia [13], optimization is "the determination of the maximum or the minimum values of a specific function that is subject to a specific constraint." Hagos et al. [14] emphasized that more research is needed to optimize and improve the biogas production process and yields. Using mathematical techniques and tools can significantly increase and enhance biogas yields. Various optimization approaches have been described in the literature to obtain the best reaction conditions that favor biogas yield, that is, the best reaction parameters and the best substrate ratios for different raw materials, to improve and optimize the biogas production process. Traditional methods for optimizing the production process include batch laboratory experiments with varying proportions of constituent components to assess the degree of digestion of the substrate. The process shows that the potential for improved biogas production can be achieved compared to mono-digestion of single substrates [15]. Mathematical techniques are potential tools for modeling and optimizing biogas production processes.

In addition to the undeniable contribution of experimental activity in biogas optimization processes, mathematical modeling, and simulation techniques have been proposed to support further development and growth. Literature has shown that process development and operations become more efficient and reliable when reliable mathematical models that determine transfer phenomena and process dynamics can support experimental data [16]. In addition, the availability of such models is beneficial for predictive design, performance analysis, and process modeling, eliminating dependence on long, energy-intensive experiments [17]. The mathematical models also render a better understanding of various details about the process and procedures involved through the interpretation of existing data. An effective mathematical model or simulation tool can be used to study and optimize the effect of functional parameters on biogas process performance and yield [18]. Based on the review of various pieces of literature, the mathematical modeling and simulation of the biogas production process provide information on the critical factors involved.

2.1 Factors that Influence Biogas Yields

2.1.1 Effect of co-digestion/co-digestion ratio

Anaerobic digestion of biomass waste can be performed with mono-digestion or co-digestion. Anaerobic co-digestion improves digestion and energy production by increasing microbial nutrient availability and organic matter load while reducing inhibitory chemical toxicity by diluting the co-substrate [19]. Mono-digestion is commonly used to digest manure in small biogas plants, while co-digestion is used in larger biowaste plants of different origins (farms, urban areas, industry). Co-digestion occurs when different raw materials are simultaneously digested in the same reactor [20]. Anaerobic digestion technology was earlier designed for a single feedstock. Still, it has recently been recognized that the co-digestion of different substrates simultaneously results in more stable anaerobic digestion. Simultaneous co-digestion of different substrates improved the biogas production capacity compared to a single substrate [21].

The main advantage of co-digestion is the improvement of biogas yield and its methane content. Animal manure is digested with other biodegradable materials to increase economic efficiency and ensure the stability of the anaerobic digestion system on an industrial scale [22]. Much literature on laboratory studies and small bioreactors has shown that anaerobic co-digestion is the best approach for biogas production and optimization [13]. Studies have also shown that most commercial reactors use mono-digestion, mainly due to the large amount of a given substrate in close proximity to the geographical location of the digester [13], [21]. Other reasons for not applying anaerobic co-digestion include ignorance, lack of technical knowledge about co-digestion, reluctance to change and adopt new techniques, and avoiding co-digestion's disadvantages. Some of the main disadvantages of co-digestion that prevent the application of this technique to large commercial reactors are the accumulation of refractory solids in the digester, large amounts of nitrogen, and other related substrates, including acid accumulation from co-substrate [23].

The synergistic effects of the co-substrate mixture caused by the dynamics of the co-digestion process and the microorganisms involved will outweigh the shortcomings of the technique. Technological advancement, including process regulation and control, pre-treatment, and other means, can improve the utilization of anaerobic co-digestion. However, research and development into the co-substrate mixing ratios require further investigation in a wide range of co-curing substrates.

Weerayutsil et al. [24] experimented with a 48-day HRT to study the effect of co-digestion of poultry manure and Napier grass at co-digestion ratios of 3:1, 1:1, and 1:3. They observed that the biogas produced was highest in 1:1 poultry manure to Napier grass, and the percentage of gas produced from 3:1, 1:1, and 1:3 of poultry manure to Napier grass were 88%, 110%, and 123% to gas produced from mono digestion of Napier grass and 75%, 0% and100% to mono digestion of poultry dung respectively

In a similar work, Miah et al. [25] conducted an experiment to know the effect of co-digestion of cow dung and poultry dung on biogas production for a 50-day HRT at a temperature of 32^{o}C. Their result showed that biogas production was 85% when poultry dung was digested with cow dung at 1:1 and 66% at a co-digestion ratio of 3:1. Other works buttressing the significance of co-digestion and the co-digestion ratio of substrates have been reported in the open literature [26 – 28].

2.1.2. Effect of volatile solids (VS) and total solids (TS) on biogas production

The initial and final properties of the digestates and feedstock provide better performance indicators of the biogas production process. An overall volatile and total solids profile is essential for understanding production process dynamics [6]. The co-digestion provides a more balanced ratio of carbon to nitrogen (C/N) in the feed, increases system buffering capacity, avoids the accumulation of volatile fatty acid, and accelerates the optimal pH maintenance for the methanogenic process [29]. The substrate's total solids content significantly affects methane formation [30]. Abbassi-Gendowes et al. [31] reported that the cumulative yield of methane decreased when the total solids content increased from 10% to 25%, which is attributed to the decomposition of the mesophilic digestion of the feedstock. They identified mass transfer limitations at high total solid levels as the factor contributing to the low production of methane.

The production of biogas from volatile solids in the sludge by anaerobic digestion is slowed towards the end of the process. The limiting factors include increased pH associated with ammonia accumulation, poorly digestible biomaterials, and high total solids contents [32]. The concentration of volatile solids decreases during anaerobic digestion due to biogas production, concentrating the toxic and even inhibitory substances in the waste stream and intermediates of microbial metabolism [33]. The accumulation of inhibitory compounds can ultimately prevent the production and yield of biogas, including inorganic ions, heavy metals, ammonia, and hydrogen that affect the pH.

The work of Miah *et al.* [25] on poultry dung, cow dung, and poultry liter showed that peak gas generation occurred earlier when the volatile solids concentration was higher. At volatile solids of 49, 50.5, 61, and 52g/l, the peak gas generation was observed on days 34, 30, 27, and 24. They concluded that the lower the initial VS concentration, the more time is required for peak gas production in the reactor. Also, Ardaji et al. [34] studied the effect of 5%, 10%, 15%, 20%, 25%, and 30% total solid on biogas production. They observed that the higher the percentage of total solids in the slurry, the higher the amount of biogas produced.

2.1.3. The Effect of slurry pH

Anaerobic digestion is characterized by a series of biochemical transformations caused by the breakdown of organic matter. This process involves four distinct stages: hydrolysis, acid production, acetic acid production, and methanogenesis [2]. In the first step, fats, complex carbohydrates, and proteins are hydrolyzed in their monomeric form by appropriate enzymes. In the second step, the monomer is further cleaved into short-chain acids. These short-chain acids are then converted to hydrogen, carbon dioxide, and acetate intermediates in the third step. With the help of methanogens, the final intermediates are converted to methane and carbon dioxide. However, to produce methane, the average pH of the flammable gas must be attained to produce methane [35].

Jayanth et al. [36] noted that maintaining neutral pH is one of the major driving forces of the anaerobic digester process. Often, acidic pH necessitates using a lower quantity of lime to maintain a neutral environment. Maile et al. [3] used cow dung, tomato waste, spinach, and food waste to study the effect of pH on the biogas produced. With the lowest pH of 4.9, tomato waste recorded the lowest biogas production. In contrast, cow dung and food waste with pH values of 7.2 and 7.1 (a neutral range that favors methanogenic bacteria) gave higher biogas production. Other studies showing the effect of slurry pH on biogas yields are available elsewhere [38].

2.1.4. The Effect of Carbon to Nitrogen (C/N) Ratio

Optimizing methane production requires a balanced ratio of carbon to nitrogen (C/N). The high C/N ratio means that there is not enough nitrogen for the cells to function properly. This reduces the growth of microorganisms and reduces biogas production and yield [39]. Higher C/N ratios also reduce the formation of volatile butyric acid and ammonia (lower levels of free ammonia and total ammonium nitrogen in the system); lower C/N ratios accumulate large amounts of ammonia. However, the risk is ammonia inhibition is increased. Ammonia is toxic to methanogens, so biogas yield and production are significantly reduced by ammonia accumulation [40]. Therefore, for maximum performance and efficiency, it is recommended to set the C/N ratio to 20-35. Bacteria use carbon 30 times faster than nitrogen, so the carbon-to-nitrogen ratio should be maintained between 20 and 30 for better biogas conversion. The optimum thermophilic temperature is 50-60 ° C, and the pH should be maintained at 6.7-7.5. Dioha et al. [39] further conducted a study on the effect of the C/N ratio on biogas production using ten different substrates of different C/N Ratios. Their result showed that the least biogas production was from the substrate with a low and high C/N ratio of 10 and 82, respectively. Also, a C/N ratio reference value of 20 - 30 gave the optimum biogas yields. Other studies on the effect of the C/N ratio on biogas yields can be found in the open literature [41 43]. According to Jayanth *et al.* [36], a C/N ratio of 24 states that the raw material is suitable for anaerobic digestion, whereas the C/N ratio of 15.3 infers that the digester should be carefully monitored for any ammonia (NH_3) buildup that could lead to the inhibition of methanogens resulting in lower biogas production.

2.1.5. Effect of temperature

The process of anaerobic digestion is performed by a delicately balanced population of different bacteria. These bacteria can be susceptible to environmental changes, of which temperature is a prime factor. Two types of bacteria that are actively involved in anaerobic digestion (acid-producing and methanogen-producing bacteria) operate at three different temperatures: psychrophiles or ambient temperature (< 25 °C), medium temperature bacteria (25 - 40 °C) and thermophiles (45 - 60 °C) [44]. Temperature fluctuations can lead to reduced bacterial activity or death, followed by reduced biogas production and yield. At ambient temperature, anaerobic digestion is strongly influenced by earth/ atmospheric temperature, resulting in reduced yield in biogas production [45]. Surface digesters enhance this effect in the form of concrete, metal prototypes, or commercially available plastics. Chang et al. [46] observed that a reduction in the temperature of the thermophilic condition system from 55 °C to 20 °C at different retention times almost stopped the production of biogas formation, and the free fatty acids' rapid accumulation caused a drop in pH. Anaerobic digestion for optimum biogas yield and output depends on temperature.

The experiment conducted by Wang et al. [40] at temperatures of 20, 30, 40, 50, and 60 ^oC for 30 days to study the effect of temperature on methane production of co-digested substrate cow manure, poultry manure, and rice straw, showed that as the temperature increased, methane potential continuously improved. Still, the increasing rate was lower under thermophilic than mesophilic conditions. For the co-digestion of cow manure, poultry manure, and rice straw, the methane production temperatures of 20, 30, 40, 50, and 60^oC were approximately100 180, 260, 300, and 310mL/gVS, respectively. Their work further corroborated the position of Al Seadi et al. [7].

2.1.6. Effect of Hydraulic Retention Time (HRT)

Hydraulic retention time is an important operating parameter of anaerobic reactors that can affect the conversion of volatile solids into biogas. It is one of the factors to be optimized and analyzed in the biogas production process [47]. Anaerobic digestion of lignocellulosic waste usually requires a relatively long hydraulic retention time because this type of substrate is resistant to anaerobic microorganisms [48]. Baâti et al. [49] observed from the study that hydraulic retention time significantly influenced the conversion of organic load and, therefore, the production of biogas. Reducing hydraulic retention time is desirable, as it is directly related to reducing capital costs and improving process efficiency. However, the literature still lacks sufficient information on the effect of Hydraulic retention time on anaerobic digestion [50]. Methanogens usually have a longer regeneration time than hydrolyzing acid-producing bacteria. The Hydraulic retention time must be optimum and long enough to hold the methanogens and prevent them from being washed out of the reactor.

Onthong et al. [51] investigated the effect of hydraulic retention time on biogas production of five substrates (Soybean residues, Papaya peels, Sugarcane bagasse, Rice straw, and greater galangals) at five different hydraulic retention times of 15, 20, 25, 30 and 35 days under a mesophilic temperature range of 34 – 37 ^{o}C. The results showed that the highest biogas generation of 560.47 ml, 404.24 ml, 263.20 ml, 4.26 ml, and 45.83 ml from soybean residues, papaya peels, sugarcane bagasse, rice straws, and greater galangals was observed at the HRT of 25, 15, 25, 30, and 25 days, respectively. With papaya peels having the shortest HRT of 15 days, Soya bean residue gave the highest biogas production of 560 ml at a 25-day HRT, while rice straw gave a very low biogas production of 4.26 ml at 30 days HRT. Other studies on the effect of HRT on biogas yield can be found elsewhere [52 – 54]. Their works' results clearly show HRT's influence on biogas yields.

2.1.7. Effect of Slurry Volume

The slurry volume of the substrate mainly plays a role in the overall value of the biogas potential. Smaller slurry volumes tend to have lower biogas potentials and vice versa. HRT depends largely on the slurry volume, temperature, percentage of total solids, organic loading rate, etc. Other factors that can affect biogas yields include the type of substrate, organic loading rate, digester design [55], salinity [56], and agitation [57]. Figure 1 shows the main factors affecting biogas yield.

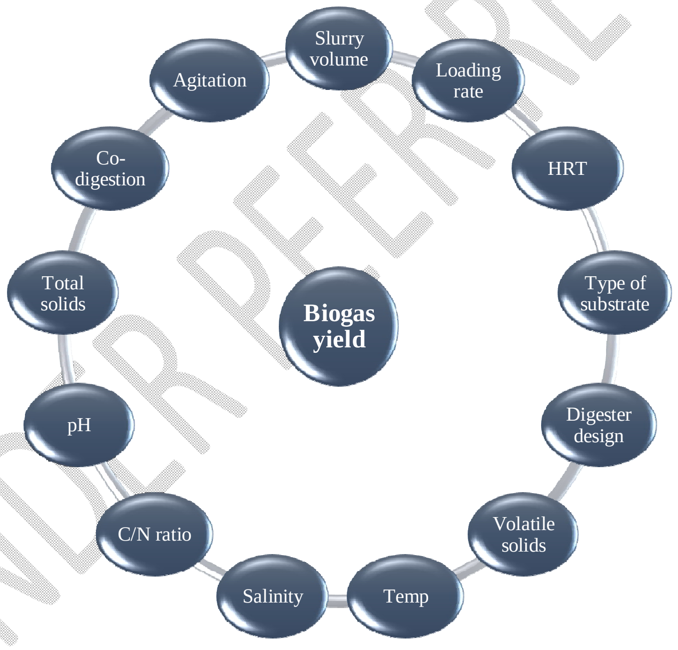

Fig. 1. Factors affecting biogas yield

3. Materials and Method

This study involved the development of non-linear regression models using published biogas data from the open literature (see Appendix A). The biogas data was obtained for seven different substrates, including cow dung, cow dung with fruit vegetable and plant waste, cow dung with Poultry dung, Poultry dung with grass, Grass and Fruit Vegetable, and Plant waste. The input parameters used for the prediction of biogas yield include the volume of slurry (L), volatile solids (%), temperature (^{o}C), pH, total solid (%), carbon-nitrogen ratio, and hydraulic retention time (days). The developed models were validated using published empirical results different from those used in building the models. The E-view 9 statistical package was used for the analysis.

3.1 Descriptive statistics of the input data.

Table 1. Descriptive statistics of the data used in the model development.

Substrate		Slurry (L)	C/N	T (^oC)	TS (%)	VS (%)	HRT (days)	pH
Cow dung	Min	0.15	8.10	25.00	1.40	1.10	7.00	6.20
	Max	17.50	24.00	53.00	87.00	78.85	62.00	9.20
	Mean	3.20	15.3	34.90	31.10	46.39	34.38	7.19
Cow dung + Plant waste	Min	0.30	8.50	31.00	5.70	9.50	7.00	5.50
	Max	5.00	40.00	37.00	75.60	91.00	75.00	7.80
	Mean	1.69	16.58	35.00	42.38	58.04	46.38	7.02
Cow dung + Poultry dung	Min	2.00	15.00	32.00	30.00	20.80	30.00	6.50
	Max	15.00	26.30	35.00	95.50	65.70	56.00	8.70
	Mean	4.86	19.44	34.15	63.16	51.24	42.93	7.28
Poultry dung	Min	0.50	3.30	26.00	6.93	14.30	7.00	6.25
	Max	36.70	19.80	38.00	72.80	86.40	63.00	8.40
	Mean	17.77	12.20	31.07	37.10	49.73	34.14	7.12
Poultry dung + Grass	Min	0.13	11.80	28.00	9.10	19.24	20.00	6.30
	Max	5.00	36.54	38.00	78.00	96.35	90.00	8.60
	Mean	1.51	18.04	33.13	37.72	64.87	39.75	7.18
Pig dung	Min	0.20	5.50	28.00	7.80	8.50	14.00	6.20
	Max	17.50	22.00	52.00	91.00	93.00	80.00	8.10
	Mean	6.25	12.85	34.46	27.02	45.80	44.15	6.76
Plant waste	Min	0.02	10.49	30.00	7.70	6.00	12.00	4.00
	Max	4.00	61.17	60.00	81.08	90.29	77.00	8.20
	Mean	1.49	18.79	39.14	18.25	35.07	31.14	5.74

3.2 Model Development

Considering the relationship

$$Y = F(X_1 X_2 X_3 \dots\dots\dots\dots.) \tag{1}$$

Where Y is the dependent variable and $X_1X_2X_3\ldots\ldots$ are independent variables. This expression could be narrowed down to linear and non-linear expressions, as shown below;

For linear expression, we have

$$Y = (a_0 + a_1X_1 + a_2X_2 + a_3X_3 \ldots\ldots\ldots..) \tag{2}$$

While non-linear expression can be polynomial, logarithmic, exponential, or sinusoidal, and the simplest logarithmic form is given as:

$$logY = (a_0 + a_1logX_1 + a_2logX_2 + a_3logX_3 \ldots\ldots\ldots..) \tag{3}$$

The logarithmic function was chosen for this study due to its numerous advantages. The logarithmic function is represented as:

$$logY = a_0 + a_1logX_1 + a_2logX_2 + a_3logX_3 + a_4logX_4 + a_5logX_5 + a_6logX_6 + a_7logX_7. \tag{4}$$

Where Y is the volume of biogas produced and $X_1X_2X_3X_4X_5X_6X_7$ are volume of slurry (L), carbon/nitrogen ratio (C/N), temperature (T), total solid (TS), volatile solids (VS), hydraulic retention time, and pH, respectively.

3.3 Model Validation

The developed models in this study were validated using experimental data from other authors. The validation data set differs from the ones used in developing the models in this study. The statistical error models selected for this study include absolute and average absolute errors. The error models are given as follows:

$$\text{Absolute deviation \%} = \left|\frac{V_{exp}-V_{cal}}{V_{exp}}\right|100 \tag{5}$$

and

$$\text{Average absolute deviation \%} = \frac{1}{n}\left|\frac{V_{exp}-V_{cal}}{V_{exp}}\right|100 \tag{6}$$

4. Results and Discussion

Table 2 shows the correlation coefficients developed for the various substrates in this study. Appendix B shows the statistical analysis results for the developed models. The statistical results show that the coefficient of determination for the seven models was between 0.90 and 0.99. The goodness of fit for cow dung, cow dung with plant waste, and cow dung with poultry dung were 0.99. That of poultry with grass, pig dung, and plant waste was 0.95, 0.95, and 0.96, respectively. Poultry dung had the least goodness of fit of 0.9. The goodness of fit indicates how well the model can match the given data. From the results, the regression models for cow dung, cow dung with plant waste, and cow dung with poultry had the best goodness of fit compared to the other models. The fact that the coefficient of determination for all the models was 0.9 and above indicates that the models could predict the biogas yield for 90% and above of the given data. Furthermore, the statistical analysis results showed low values of the standard error of estimate or regression for all the models. The standard error of estimate or regression tells us how wrong or right the regression model is on average. The smaller the values of standard errors of estimate, the better the model. For this study, the standard error of estimate of the regression models for cow dung, cow dung with plant waste, cow dung with poultry dung, poultry dung, poultry dung with grass, pig dung, and plant waste were 0.35, 2.16, 0.18, 1.52, 0.52, 0.34, and 1.62, respectively. These results indicate that the model for cow dung with poultry dung gave a better prediction (least standard error of estimate of 0.18), followed by the pig dung and cow dung models, respectively. The model for the cow dung with plant waste gave the highest standard error of estimate (2.16).

Table 2. Model coefficients

Substrate	**Model Coefficients**							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
Cow dung	-1.8616	1.2021	-0.7865	0.4741	1.5192	-0.7914	-0.3818	1.1585
Cow dung + Plant waste	-2.0738	3.3394	-0.3048	0.5264	-0.1882	1.5840	0.5149	-2.1537
Cow dung + Poultry dung	-2.4304	1.8770	0.9456	-0.9709	0.1040	1.9646	0.0474	-2.0036
Poultry dung	0.1082	0.4804	-0.5226	0.4332	-0.0716	1.7866	0.0412	-3.4867
Poultry dung + Grass	0.2610	0.5528	1.6154	-0.3107	-0.2084	0.1877	0.8529	-3.5323
Pig dung	0.4208	1.1156	-0.5791	-0.0101	-0.1101	0.3071	-0.0171	-0.3208
Plant waste	8.7733	0.6039	-3.4020	1.2024	-1.4337	-2.2955	1.3134	-5.2441

To further ascertain the accuracy and reliability of the developed models, the Akaike information criterion (AIC), the Schwarz criterion (SC), and the Hannan – Quin criterion (HQC) were calculated for each model. The AIC and HQC allow us to ascertain the model with a better fit. The lower the AIC and HQC, the better the fit. The SC helps screen and select the best model among several models. The lower the SC, the better the model. For this study, the AIC for the models was 1.04 for cow dung, 4.69 for cow dung with plant waste, -0.25 for cow dung with poultry dung, 3.82 for poultry dung, 1.84 for poultry dung with grass, 0.97 for pig dung, and 4.10 for plant waste. Likewise, the HQC for the models was 1.01 for cow dung, 4.71 for cow dung with plant waste, -0.28 for cow dung with poultry dung, 3.80 for poultry dung, 1.87 for poultry dung with grass, 0.99 for pig dung, and 4.12 for plant waste. Also, the SC results for the models were 1.41 for cow dung, 5.07 for cow dung with plant waste, 0.12 for cow dung with poultry dung, 4.12 for poultry dung, 2.24 for poultry dung with grass, 1.35 for pig dung, and 4.49 for plant waste. The AIC, HQC, and SC results show a similar trend with the standard error of estimate results for the models developed in this study. These results indicate that the model for cow dung with poultry dung gave a better prediction (least standard error of estimate, AIC, HQC, and SC), followed by the pig dung and cow dung models, respectively. The model for the cow dung with plant waste gave the highest standard error of estimate AIC, HQC, and SC. The relatively low standard errors of estimate, AIC, HQC, and SC indicate that the developed models in this study are adequate and reliable for predicting biogas yield from the bio-materials considered, given the data set limits from which the models were developed.

Figure 2 shows the SER, AIC, HQC, and SC variation for the various biomaterials materials considered in this study.

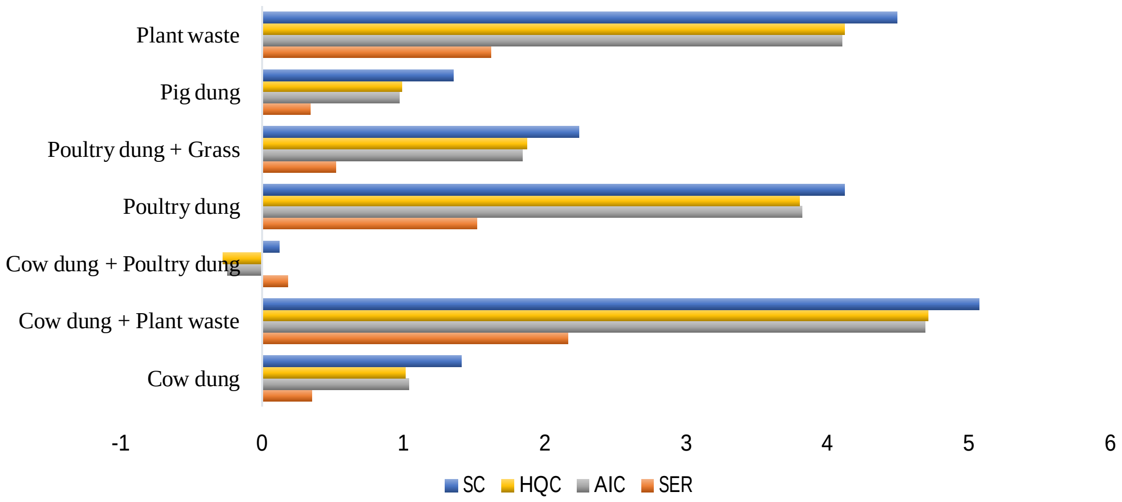

Fig 2. Schwarz criterion (SC), Hannan-Quin criterion (HQC), Akaike information criterion (AIC), and standard error of regression for the various bio-material models.

The models' reliability in this study was further ascertained by comparing the estimated biogas yields with published experimental results. The results of the validation are presented in Tables 3 to 9. From the results, the biogas yield models had average absolute deviations of less than 7 %, indicating that they are relatively accurate, reliable, and adequate for predicting biogas yield from the biomaterials considered in this study.

Table 3. Validation of the cow dung model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AAD (%)
[58]	4.5	18.1	35	22.4	46.4	30	9.2	0.73	0.74	**1.37**

Table 4. Validation of the cow dung with plant waste model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AAD (%)
[59]	2.0	16.0	35	62.0	45.0	60	7.2	5.500	5.510	**0.18**

Table 5. Validation of the cow dung with poultry dung model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AD (%)
[28]	3.0	20.0	34	95.4	65	56	7.	2.24	2.31	3.12
[58]	4.5	22.0	35	83.16	39.2	30	7.0	1.86	1.88	1.08
									% AAD	**2.10**

Table 6. Validation of the poultry dung model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AD (%)
[25]	0.4	9.2	35	28.0	19.0	75	7.2	0.23	0.22	4.35
[60]	4.0	10.1	35	12.0	50.8	35	7.6	2.94	3.20	8.84
									% AAD	**6.60**

Table 7. Validation of the poultry dung with grass model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AD (%)

[61]	0.50	17.7	28	9.1	79.6	52	7.5	1.550	1.549	0.06
[62]	2.50	14.8	30	62.0	85.0	35	6.4	2.280	2.230	2.19
									% AAD	**1.13**

Table 8. Validation of the pig dung model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AAD (%)
[63]	7.0	9.8	35	22.5	28.2	60	6.3	6.22	6.03	**3.05**

Table 9. Validation of the plant waste model

Authors	Slurry (L)	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (days)	pH	Actual (L)	This study (L)	AD (%)
[64]	0.30	14.0	37	11.0	84	50	8.2	0.0093	0.0094	1.08
[65]	0.20	19.1	60	15.0	14	30	7.0	0.2140	0.2090	2.34
									% AAD	**1.71**

5. Future Perspective

Modeling biogas yield from various biomass substrates requires a good amount of quality data. The significance of developing such models is the low cost and response time needed to estimate the amount of biogas generated from a particular substrate without recourse to experimental analysis. One limitation of this study is the small volume and range of available data for developing and validating the correlations. This was mainly because experimental works on biogas production considering the slurry volume, carbon to nitrogen ratio, temperature, percentage volatile solid, percentage total solid, hydraulic retention time, and pH in one fell swoop are very limited in the open literature. These factors are known to affect biogas yields and should be included as independent variables for biogas yield modeling. Consequently, researchers should be more inclined to conduct biogas yield experiments incorporating measurable factors like slurry volume, carbon to nitrogen ratio, temperature, percentage volatile solid, percentage total solid, hydraulic retention time, and pH for each biomass used. This will further increase the amount of data output required for building new models and tuning the coefficients of existing ones.

Also, the interdependency of the seven independent variables (slurry volume, carbon to nitrogen ratio, temperature, percentage volatile solid, percentage total solid, hydraulic retention time, and pH) should be investigated. This study is necessary to understand how specific parameters influence biogas production in the presence of others, and as such, the highly influential parameters responsible for biogas production could be identified. Identifying such parameters could help optimize the biogas yield model while reducing the independent variables required for biogas prediction.

Furthermore, an artificial intelligence (AI) model can be developed for predicting biogas yield from various biomass waste materials. Presently, literature on AI-based models for predicting biogas yield from multiple substrates is not only limited but is very scarce. AI models are better than regression models and could help deepen the frontiers of biogas prediction modeling. Artificial intelligence can play an essential role in ensuring the efficiency and sustainability of biogas production. The simulation and optimization of the biogas production process improve the understanding of the process parameters for optimal efficiencies and production rates. Artificial intelligence models show that reliability can be improved by modeling complex, non-linear relationships between input and output sets (system responses) and revealing hidden patterns between data sets. AI models have been observed to exhibit human characteristics acquired through learning.

6. Conclusion

The benefits of biogas as an alternative to fossil fuel due to its renewable sources, environmentally friendly nature, health benefits, etc., cannot be over-emphasized. In this study, seven (7) non-linear regression models for predicting biogas yields from a wide variety of commonly available and abundant waste biomaterials, including cow dung, cow dung with plant waste, cow dung with poultry dung, poultry dung, poultry dung with grass, pig dung, and plant waste were developed. Factors affecting biogas yields like slurry volume, carbon to nitrogen ratio, temperature, percentage of volatile solids, percentage of total solids, hydraulic retention time, and pH were the independent variables for the model development. The relatively low values of the AIC, SC, HQC, and SER statistical criteria for ascertaining the reliability of regression models indicated that the models in this study are adequate. Furthermore, the model validation results showed that all the models had a percentage average absolute deviation (AAD) of less than 5%. The low percentage AAD shows that the models are relatively accurate. However, the developed models are valid for the input data ranges from which they were developed.

References

1. Nasir I. M., Ghazi T. I., Omar R. and Idris A. ‘Batch and Semi-Continuous Biogas Production from Cattle Manure’ International Journal of Engineering and Technology, 2013, 10(1), 16-21.

2. Chowdhury, T., Chowdhury, H., Hossain, N., Ahmed, A., Hossen, M.S., Chowdhury, P., Thirugnanasambandam, M., Saidur, R. Latest advancements on livestock waste management and biogas production: Bangladesh’s perspective. Journal of Cleaner Production 2020, 272: 122818.

3. Maile I., Muzenda 1. E., and Mbohwa C. Optimization of Biogas Production through Anaerobic Digestion of Fruit and Vegetable Waste: A Review’ International Conference on Biology, Environment and Chemistry (ICIET’2016). 2016, 98 (16).

4. Sawyerr, N. Trois, C. Workneh, T. Okudoh, V. An Overview of Biogas Production: Fundamentals, Applications and Future Research. International Journal of Energy Economics and Policy. 2019, 9(2), 105-116. DOI: https://doi.org/10.32479/ijeep.7375

5. Gadde, B., Menke, C., Wassmann, R. Rice straw as a renewable energy source in India, Thailand, and the Philippines: overall potential and limitations for energy contribution and greenhouse gas mitigation’ Biomass and Bioenergy Journal, 2009, 33(11):1532-1546.

6. Giwa, A.S., Ali, N., Ahmad, I., Asif, M., Guo, R.-G., Li, F.-L., Lu, M. Prospects of China’s biogas: Fundamentals, challenges, and considerations. Energy Reports, 2020, 6: 2973-2987.

7. Al Seadi,T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T. Biogas Handbook;’ University of Southern Denmark Esbjerg, Niels Bohrs Vej 2008, 9-10, DK-6700 Esbjerg, Denmark.

8. Department of Alternative Energy Development and Efficiency. 2018 Annual Report. Available at http://e-lib.dede.go.th/mm-data/BibA9434_2018.pdf

9. Wu B., Bibeau E. L. and. Gebremedhin K. G. Three-Dimensional Numerical Simulation Model of Biogas Production for Anaerobic Digesters," American Society of Agricultural and Biological Engineers, ASABE, 064060, 2006 ASAE Annual Meeting.

10. Escamilla-Alvarado C., Ríos-Leal E., Ponce-Noyola M.T., Poggi-Varaldo H.M. Gas biofuels from solid substrate hydrogenogenic-methanogenic fermentation of the organic fraction of municipal solid waste". Process Biochem. 2012, 47 (11):1572-1587, https://doi.org/10.1016/j.procbio.2011.12.006.

11. Ray S., Reaume S.J., Lalman J.A. Developing a statistical model to predict hydrogen production by a mixed anaerobic mesophilic culture". Int. J. Hydrogen Energy, 2010, 35 (11):5332-5342, https://doi.org/10.1016/ j.ijhydene.2010.03.040

12. Olatunji K.O., Ahmed N.A., Madyira D.M., Adebayo A.O., Ogunkunle O., Adeleke O. Performance evaluation of ANFIS and RSM modeling in predicting biogas and methane yields from Arachis hypogea shells pretreated with size reduction". Renewable Energy, 2022, 189:288-303

13. Kunatsa, T., Xia, X. A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement". Bioresource Technology 2022, 344:126311.

14. Hagos, K., Zong, J., Li, D., Liu, C., Lu, X. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives". Renew. Sust. Energ. Rev. 2017, 76, 1485–1496. https://doi.org/10.1016/j.rser.2016.11.184

15. Bong, C.P.C., Lim, L.Y., Lee, C.T., Klemeˇs, J.J., Ho, C.S., Ho, W.S. The characterisation and treatment of food waste for improvement of biogas production during anaerobic digestion–A review". J. Clean. Prod. 2018, 172, 1545–1558. https://doi. org/10.1016/j.jclepro.2017.10.199.

16. Hosseini S.S., Denayer, J.F.M. Biogas upgrading by adsorption processes: Mathematical modeling, simulation and optimization approach – A review". Journal of Environmental Chemical Engineering 2022, 10: 107483.

17. Leflaive P., Pirngruber G.D., Faraj A., Martin P., Baron G.V., Denayer J.F.M. Statistical analysis and Partial Least Square regression as new tools for modelling and understanding the adsorption properties of zeolites". Microporous Mesoporous Mater. 2010, 132:246–257, https://doi.org/10.1016/j.micromeso.2010.03.004.

18. Aminian D.J., Hosseini S.S., Kundu P.K., Tan N.R. Mathematical modeling of natural gas separation using hollow fiber membrane modules by application of finite element method through statistical analysis". Chem. Prod. Process Model, 2016, 11:11–15, https://doi.org/10.1515/cppm-2015-0052.

19. Maragkaki, A., Vasileiadis, I., Fountoulakis, M., Kyriakou, A., Lasaridi, K., Manios, T. Improving biogas production from anaerobic co-digestion of sewage sludge with a thermal dried mixture of food waste, cheese whey and olive mill wastewater. Waste. Manage. 2018, 71, 644–651. https://doi.org/10.1016/j.wasman.2017.08.016.

20. Vivekanand, V., Mulat, D.G., Eijsink, V.G., Horn, S.J. Synergistic effects of anaerobic co-digestion of whey, manure and fish ensilage". Bioresour. Technol. 2018, 249, 35–41. https://doi.org/10.1016/j.biortech.2017.09.169

21. Lee, J., Hong, J., Jeong, S., Chandran, K., Park, K.Y. Interactions between substrate characteristics and microbial communities on biogas production yield and rate". Bioresour. Technol. 2020, 303, 122934 https://doi.org/10.1016/j. biortech.2020.122934.

22. Hegde, S., Trabold, T.A. Anaerobic digestion of food waste with unconventional co-substrates for stable biogas production at high organic loading rates. Sustainability 2019, 11, 3875.

23. Sembera, C., Macintosh, C., Astals, S., Koch, K. Benefits and drawbacks of food and dairy waste co-digestion at a high organic loading rate: A moosburg wwtp case study. Waste Management 2019, 95, 217–226.

24. Weerayutsil P., Khoyun U., Khuanmar K. Optimum Ratio of Chicken Manure and Napier Grass in Single Stage Anaerobic Co-Digestion' 3rd International Conference on Power and Energy Systems Engineering, 2016, 100, 22 – 25.

25. Miah M. R., Rahman A. L., Akanda M. R., Pulak A., Rouf A. Production of Bio-Gas from Poultry Litter Mixed with The Co-Substrate Cow' Journal of Taibah University for Science 2016, 10, 497–504.

26. Kasisira, L.L., Muyiiya, N. D. Assessment of the Effect of Mixing Pig and Cow Dung on Biogas Yield. Agricultural Engineering International, CIGR E journal. 2009, 11.

27. Oleszek M.,and Krzeminska I. Enhancement of Biogas Production By Co-Digestion Of Maize Silage With Common Goldenrod Rich In Biologically Active Compounds.' Bioresource Technology. 2014, 12(1):704-714.

28. Chomini, M.S., Ogbonna, C.I.C., Falemara, B.C., Thlama D.M.Comparative Effect of Co-Digestion of Some Agricultural wastes on Biogas Yield and Some Physical Parameters' IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS). 2014, 8(11): 48-56.

29. Mishra, A., Kumar, M., Bolan, N.S., Kapley, A., Kumar, R., Singh, L. Multidimensional approaches of biogas production and up-gradation: Opportunities and challenges. Bioresource Technology 2021, 338: 125514

30. Wang, Z. Jiang, Y., Wang, S., Zhang, Y., Hu, Y., Hu, Z., Wu, G., Zhan, X. Impact of total solids content on anaerobic co-digestion of pig manure and food waste: Insights into shifting of the methanogenic pathway. Waste Management, 2020, 114: 96-106.

31. Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenès, J.P., Steyer, J. P., Escudié, R. Total solids content drives high solid anaerobic digestion via mass transfer limitation. Bioresour. Technol. 2012, 111, 55–61. https://doi.org/ 10.1016/j.biortech.2012.01.174.

32. Jeppu, G.P., Janardhan, J., Kaup, S., Janardhanan, A., Mohammed, S., Acharya, S. Effect of feed slurry dilution and total solids on specific biogas production by anaerobic digestion in batch and semi-batch reactors. J Mater Cycles Waste Manag 2022, 24, 97–110. https://doi.org/10.1007/s10163-021-01298-1

33. Kouzi, A., Puranen, M., Kontro, M.H. Evaluation of the factors limiting biogas production in full-scale processes and increasing the biogas production efficiency". Environ Sci Pollut Res 2020, 27, 28155–28168. https://doi.org/10.1007/s11356-020-09035-1.

34. Ardaji V. G., Radnezhad H., Nourouzi M. Improving Biogas Production Performance From Pomegranate Waste, Poultry Manure And Cow Dung Sludge Using Thermophilic Anaerobic Digestion: Effect Of Total Solids Adjustment.' Department of Environmental Science, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran. 2017, http://www.ijeehs.org

35. Zainudeen, M.N., Kwarteng, M., Nyamful, A., Mohammed, L., Mutala, M. Effect of temperature and pH variation on anaerobic digestion for biogas production. Ghana Jnl. Agric. Sci. 2021, 56 (2), 1 – 13.

36. Jayanth, T.A.S., Naveen K.M., Sameena, B., Vijayalakshmi, A., Sudharshan, J., Shruthi, A., Sandeep, K.D., Gangagni, R.A. Anaerobic mono and co-digestion of organic fraction of municipal solid waste and landfill leachate at industrial scale: Impact of volatile organic loading rate on reaction kinetics, biogas yield and microbial diversity. Science of the Total Environment, 2020, 748: 142462.

37. Maile I. I., and Muzenda E. Production of Biogas from Various Substrates Under Anaerobic Conditions.' 7th International conference on Innovative Engineering Technologies. ICIET, 2014, Bangkok

38. Muvhiiwa Rf., Chafa, PM, Chikowore, N, Chitsiga T, Matambo, TS, and Low M. Effect of Temperature and PH on Biogas Production from Cow Dung and Dog Faeces. Africa Insight, 2016, 45,4.

39. Dioha I. J., Ikeme C.H., Nafi'u T., Soba N. I. and Yusuf M.B.S. Effect Of Carbon To Nitrogen Ratio On Biogas Production' International Research Journal of Natural Sciences. 2013, 1 (3): 1-10.

40. Wang X., Lu X., Li F, Gaihe Y. Effects of Temperature and Carbon-Nitrogen (C/N) Ratio on the Performance of Anaerobic Co-Digestion of Dairy Manure, Chicken Manure and Rice Straw: Focusing on Ammonia Inhibition.'National Center for Biotechnology Information (NCBI), United States of America, 2013.

41. Jos B, Hundagi F, Wisudawati RP, Budiyono, Sumardiono S. Study of C/N Ratio Effect on Biogas Production of Carica Solid Waste by SS-AD Method And LS-AD. MATEC Web of Conferences 2018, 156, 03055. https://doi.org/10.1051/matecconf/201815603055.

42. Wang X, Lu X, Li F, Yang G. Effects of Temperature and Carbon-Nitrogen (C/N) Ratio on the Performance of Anaerobic Co-Digestion of Dairy Manure, Chicken Manure and Rice Straw: Focusing on Ammonia Inhibition. PLoS ONE 2014, 9(5): e97265. doi:10.1371/journal.pone.0097265.

43. Shahbaz, M., Ammar, M., Korai, R.M. et al. Impact of C/N ratios and organic loading rates of paper, cardboard and tissue wastes in batch and CSTR anaerobic digestion with food waste on their biogas production and digester stability. SN Appl. Sci. 2020, 2, 1436. https://doi.org/10.1007/s42452-020-03232-w

44. Uzodinma, E.O.U., Ofoefule, A.U., Eze, J.I., Onwuka, N.D. Optimum Mesophilic Temperature of Biogas Production from Blends of Agro-Based Wastes". Trends in Applied Sciences Research, 2007, 2: 39-44.

45. Dioha, I.J., Eboatu, A.N., Sambo, A.S., Kebbi, A.M.B., Tung, U.S., Okoye, P.A.C. Investigation of the effect of temperature on biogas production from poultry droppings and neem tree leaves. Nig. J. Solar Energy, 2006, 16: 19-24.

46. Chang, W.M., Wei, S.K., Yong, Z. Influence of temperature fluctuations on thermophilic anaerobic digestion of municipal organic solid waste". J. Zhejiang Univ. Sci., 2006, 7, 180-185.

47. Nelabhotla, A.B.T., Khoshbakhtian, M., Chopra, N., Dinamarca, C. Effect of Hydraulic Retention Time on MES Operation for Biomethane Production. Front. Energy Res, 2020, 8. https://doi.org/10.3389/fenrg.2020.00087.

48. Dareioti, M.A., Kornaros, M. Effect of hydraulic retention time (HRT) on the anaerobic co-digestion of agro-industrial wastes in a two-stage CSTR system. Bioresource Technology, 2014, 167:407–415.

49. Baâti, S.,Benyoucef, F., Makan, A., El Bouadili, A., El Ghmari, A. Influence of hydraulic retention time on biogas production during leachate treatment. Environ. Eng. Res. 2018, 23, 3.

50. Shi, X.-S., Dong, J., Yu, J., Yin, H., Hu, S., Huang, S., Yuan, X. Effect of Hydraulic Retention Time on Anaerobic Digestion of Wheat Straw in the Semicontinuous Continuous Stirred-Tank Reactors. BioMed Research International, 2017, 2457805. https://doi.org/10.1155/2017/2457805.

51. Onthong U, Juntarachat N. Evaluation of Biogas Production Potential from Raw and Processed Agricultural Wastes, Energy Procedia, 2017, 138, 205-210, https://doi.org/10.1016/j.egypro.2017.10.151

52. Kim, J. K., Oh, B. R., Chun, Y. N., & Kim, S. W. Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. Journal of Bioscience and Bioengineering, 2006, 102(4), 328–332. doi:10.1263/jbb.102.328.

53. Haryanto, A., Triyono, S., & Wicaksono, N. H. Effect of Hydraulic Retention Time on Biogas Production from Cow Dung in a Semi Continuous Anaerobic Digester. International Journal of Renewable Energy Development, 2018, 7(2), 93. doi:10.14710/ijred.7.2.93-100.

54. Musa MA, Idrus S. Effect of Hydraulic Retention Time on the Treatment of Real Cattle Slaughterhouse Wastewater and Biogas Production from HUASB Reactor. Water, 2020, 12(2), 490. doi:10.3390/w12020490

55. Nwokolo N, Mukumba P, Obileke K, Enebe M. Waste to Energy: A Focus on the Impact of Substrate Type in Biogas Production. Processes, 2020, 8, 1224; doi:10.3390/pr8101224.

56. Li, Huang, Liu, Huang, Maurer, Kranert. Effects of Salt on Anaerobic Digestion of Food Waste with Different Component Characteristics and Fermentation Concentrations. Energies, 2019, 12(18), 3571. doi:10.3390/en12183571

57. Mantovan FM, Zenatti DC, Burin ELK. Effect of Agitation on Anaerobic Co-Digestion of Swine Manure and Food Waste. Braz. arch. biol. technol. 2021, 64 https://doi.org/10.1590/1678-4324-2021200102.

58. Nnabuchi, M. N., Akubuko, F. O, Augustine, C. Ugwu G. Z. Assessment of the Effect of Co-Digestion of Chicken Dropping and Cow Dung on Biogas Generation' International Research Journal of Engineering Innovation. 2012, 1(9):238-243.

59. Yao Y., Wei Y., An L., Zhou J. Effect of Inoculum on Anaerobic Co-digestion of Vegetable Processing Wastes and Cattle Manure at High Solids Concentration.' Department of Biological Systems Engineering, Washington State University, 2017, Pullman, WA, USA.

60. Wang C., Hong F., Lu Y., Li X., and Liu H.. Improved Biogas Production and Biodegradation of Oilseed Rape Straw by Using Kitchen Waste and Duck Droppings Co-substrate in Two-Phase Anaerobic Digestion. Journal pone, 2017, 0182361.

61. Okewale, A. O. and Babayemi, K. A.Anaerobicco–digestion of pig and poultry droppings with elephant grass for the production of biogas. Journal of Renewable Energy and Smart Grid Technology, 2018, 13(1).

62. Mei Z.,Liu X.., HuangX., Li D., Yan Y., Yuan Y. and Huang. Anaerobic Mesophilic Co-digestion of Rice Straw and Chicken Manure: Effects of Organic Loading Rate on Process Stability and Performance.' Journal of Applied Biochem Biotechnol. 2016, 179(5):846-862.

63. Song X., Zhang K., Han B., Liang J., Zhai Z., and Du L. Anaerobic Co-digestion of Pig Manure with Dried Maize. Bioresource Technology, 2016, 11(4): 8914-8928.

64. Parawira W., Murto M., Zvauya R., Mattiasson B.Anaerobic Batch Digestion of Solid Potato Waste Alone and In Combination With Sugar Beet Leaves' Renewable energy journal. 2014, 29(11),1811-1823.

65. David A. Thermophilic Anaerobic Digestion: Enhanced and Sustainable Methane Production from Co-Digestion of Food and Lignocellulosic Wastes. Department of Chemical and Biological Engineering, South Dakota School of Mines and Technology, 2018, USA.

66. Qiao W., Yan X., Ye J., Sun Y., Wang W., Zhang Z. Evaluation of Biogas Production from Different Biomass Wastes With/Without Hydrothermal Pre-treatment' Renewable Energy. 2011, 36:3313- 3318.

67. Tetteh E., Amano K. A., Asante-Sackey D., Armah E. Response Surface Optimisation of Biogas Potential in Co-Digestion of Miscanthus Fuscus and Cow Dung. International Journal of Technology 2018, 944-954.

68. Theresia M. and Priadi C.R. Optimization of Methane Production by Combining Organic Waste and Cow Manure as Feedstock in Anaerobic Digestion. American Institute AIP Conference Proceedings, 2017, 1826.

69. Abebe M. A. Characterization Peal of Fruit and Leaf of Vegetable Waste with Cow Dung for Maximizing the Biogas Yield. International Journal of Energy and Power Engineering 2017, 6(2): 13-21.

70. Eyalarasan K., Tewelde S, Yohannes A, Habteslasie T, Karthikeyan K. Anaerobic Co-Digestion of Cafeteria Wastes And Cow Dung Mixtures For Biogas Production. International Journal of Engineering Research and Technology. 2013, 2(3).

71. Lami M., Chimdessa M. Biogas Production from Co-Digestion of Poultry Manure and Orange Peel through Thermal Pre-Treatments in Batch Fermentation. American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS). 2018.

72. Sunada N., Orrico C. A., Orrico(Jr) M. A. P., Miranda de Vargas (Jr) F., Garcia,R. G. and FernandesA. R. M. Potential of Biogas and Methane Production from Anaerobic Digestion of Poultry Slaughterhouse Effluent' Revista Brasileira de Zootecnia, 2012, 41(11):2379-2383.

73. Alfa M.I. Comparative study of Biogas Production from Cow Dung, Chicken Droppings and Cymbopogoncitrarus as Alternative Energy Source in Nigeria, 2013, Department Of Water Resources And Environmental Engineering, Ahmadu Bello University, Zaria Nigeria.

74. Oyewole, O. A. Biogas Production from Chicken Droppings.' Science World. 5(4) 2010.

75. Bhatnagar N., Ryan D.1, Murphy R. And Enright A. Effect of Co-Digestion Ratio and Enzyme Treatment on Biogas Production from Grass Silage and Chicken Litter. 2017, 15th International Conference on Environmental Science and Technology.

76. Li Y, Zhang R., He Y, Zhang C, Liu X., and Chen C. Anaerobic Co-Digestion of Chicken Manure and Corn Stover in Batch And Continuously Stirred Tank Reactor (CSTR) Bioresource Technology 2014,156, 342–347.

77. Sara E. . Evaluation of a biogas process co-digesting slaughterhouse waste and swine manure Impact of increased organic loading and addition of iron. Faculty of Natural Resources and Agricultural Sciences Department of Molecular Sciences Swedish University of Agricultural Sciences, 2017, 10 (9):4390-4417.

78. Luna-delRisco M, Norma A. and Orupõld K. Biochemical Methane Potential of Different Organic Wastes and Energy Crops from Estonia.' Agronomy Research, 2011, 9 (1–2): 331–342.

79. Bouallagui H, Lahdheb H Romdan H B., Rachdi B., Hamdi M. Improvement of Fruit and Vegetable Waste Anaerobic Digestion Performance and Stability with Co-Substrates Addition.' Journal of environmental engineering, 2009, 90(5):1844-1849.

80. Niyonsaba, O. Effect of Substrate Improvement on Optimizing Biogas Yield from Anaerobic Digestion. University of Agder, 2014.

APPENDIX A

Table A1. Data for cow dung with poultry dung as co-substrate correlation.

CD	CO	Slurry volume	C/N	T(^{o}C)	TS (%)	VS(%)	HRT(D)	PH	BP (L)	Authors
CD	**PD**									
1	3	2.0	17.00	32	34.0	52.0	50	6.9	0.902	[25]
1	1	2.0	20.88	32	36.0	52.0	53	8.7	0.800	[25]
3	1	2.0	17.00	35	38.0	65.0	50	7.0	0.906	[25]
1	3	2.0	20.88	35	34.0	58.0	50	7.0	0.800	[25]
1	1	3.0	20.00	34	95.5	65.7	50	6.5	2.960	[28]
1	2	3.0	21.00	34	95.0	65.0	56	7.5	2.050	[28]
1	1	3.0	21.00	34	95.0	62.0	56	7.1	2.200	[28]
1	1	4.5	18.60	35	65.3	20.8	30	8.3	0.320	[58]
1	4	4.5	26.30	35	79.7	42.5	30	7.1	2.800	[58]
9	1	4.5	15.20	35	63.2	32.0	30	7.6	0.800	[58]

Table A2. Data for cow dung correlation

Slurry volume	C/N	T(^{o}C)	TS (%)	VS (%)	HRT (Days)	PH	BP (L)	Authors
4.00	15.0	33	37.0	17.0	14	6.2	0.51	[3]
3.00	18.1	34	61.5	75.7	56	7.4	2.07	[28]
2.00	12.0	35	45.2	73.0	60	6.8	0.42	[59]
2.00	17.0	35	42.0	78.3	60	7.1	0.38	[59]
2.00	17.2	35	87.0	63.3	60	7.5	1.26	[59]
0.25	8.2	37	34.1	19.5	14	7.2	0.182	[66]
0.25	8.2	37	34.1	19.5	14	8.5	0.234	[66]
0.80	12.8	30	9.2	71.4	20	6.8	0.167	[67]
0.80	18.2	30	10.9	70.4	20	6.8	0.17	[67]

Table A3. Data for cow dung with fruit/vegetable/plant waste as co-substrate correlation

CD	CO	Slurry volume	C/N	T(^{o}C)	TS (%)	VS (%)	HRT(D)	PH	BP (L)	Authors
CD	**FVW**									
3	1	2.0	13.10	35	65.4	62.2	60	6.2	9.00	[59]
3	1	2.0	8.50	35	63.5	67.3	60	7.1	10.70	[59]
1	1	2.0	13.10	35	75.6	53.0	60	7.3	6.50	[59]
1	1	2.0	16.10	35	67.2	61.2	60	7.2	7.56	[59]
3	1	0.3	16.0	35	62.5	45.0	60	7.5	0.12	[59]
1	3	0.7	11.40	35	26.5	52.1	35	7.4	0.20	[68]
1	6	0.7	18.14	35	25.8	52.3	35	7.6	0.18	[68]
1	9	0.7	15.40	35	24.8	52.1	35	7.6	0.12	[68]
1	12	0.7	12.60	35	26.6	52.2	35	7.2	0.15	[68]
1	1	2.5	40.00	31	28.0	91.0	75	6.5	2.75	[69]

Table A4. Data for poultry dung correlation

SLURRY	C/N	T(^{o}C)	TS (%)	VS(%)	HRT(D)	PH	BP (L)	AUTHORS
3	10.3	32	12	54.7	56	7.8	2.6	[28]
4	10.5	35	37	25.2	34	8.4	0.381	[60]
4	10.5	35	37	25.2	34	8.4	0.381	[60]
0.5	15.14	38	24	14.3	21	7.5	0.095	[71]
36.7	15	28	63.8	40.76	21	7.2	9. 95	[72]
36.7	15	26	68.5	55.56	7	7.6	5.69	[72]
36.7	15	28	69.8	62.6	14	7.5	8.89	[72]
36.7	15	28	72.8	65.5	28	7.0	10.86	[72]
4	3.3	32	50.1	38.8	35	6.4	0.21	[73]
15	10.3	28	50.5	64.3	18	6.4	3.7	[74]

Table A5. Data for poultry dung with grass as co-substrate correlation

CD	**CO**	**SLURRY**	**C/N**	**T(^{o}C)**	**TS (%)**	**VS(%)**	**HRT(D)**	**PH**	**BP (L)**	**AUTHORS**
PD	GRASS									
3	2	0.50	15.9	28	9.1	77.10	52	7.3	1.33	[61]
3	2	0.50	14.8	28	9.1	77.60	52	7.5	0.93	[61]
1	1	2.50	17.8	37	50.0	89.00	35	7.1	2.36	[62]
1	2	2.50	22.4	37	78.0	83.00	35	7.6	2.00	[62]
3	1	0.50	18.2	38	23.8	19.24	20	6.8	0.77	[71]
1	1	0.50	15.0	30	25.1	20.50	20	6.3	0.60	[71]
1	3	0.50	11.8	30	25.9	21.13	20	6.6	0.33	[71]
1	2	0.13	12.0	37	56.0	51.00	30	8.6	0.17	[75]
3	1	5.00	36.5	37	33.5	96.35	36	7.0	0.48	[76]
2	1	2.50	19.5	37	71.0	79.00	90	7.4	0.46	[76]

Table A6. Data for pig manure (dung) correlation

SLURRY	**C/N**	**T(^{o}C)**	**TS (%)**	**VS (%)**	**HRT(D)**	**PH**	**BP (L)**	**AUTHORS**
0.50	22.0	30	9.1	68.0	52	7.0	0.235	[61]
0.50	22.0	30	9.1	64.5	52	6.8	0.240	[61]
7.00	9.8	35	26.3	25.0	40	6.2	7.230	[63]
7.00	9.8	35	26.5	25.0	80	8.1	4.100	[63]
0.25	5.5	37	23.0	20.0	14	6.9	0.250	[66]
0.25	5.5	37	28.0	22.0	14	6.5	0.385	[66]
5.00	8.1	52	7.8	8.5	29	6.5	5.300	[77]
0.20	10.0	36	91.0	93.0	38	6.5	0.125	[78]

Table A7. Data for fruit/vegetable/plant waste substrate correlation

SLURRY	**C/N**	**T(^{o}C)**	**TS (%)**	**VS (%)**	**HRT(D)**	**PH**	**BP (L)**	**AUTHORS**
4.00	10.49	33	12.0	73.0	14	5.2	0.260	[3]
4.00	14.70	33	7.7	26.4	14	7.1	0.294	[3]
4.00	13.50	37	9.1	26.0	35	5.2	7.240	[60]
4.00	13.00	37	8.0	30.0	35	5.6	4.840	[60]
0.20	17.10	60	15.2	13.8	30	6.9	0.322	[65]
0.25	14.79	37	9.2	18.7	14	5.6	0.443	[66]
0.25	11.30	37	19.7	18.8	14	4.8	0.783	[66]
0.25	12.80	38	19.7	17.0	14	4.5	0.781	[66]
2.50	16.00	30	18.0	20.0	77	5.7	2.690	[69]
0.25	34.00	35	8.3	53.0	42	5.0	0.403	[79]
0.02	11.08	37	21.6	6.0	12	4.0	0.003	[80]