Anaerobic Digestion Process - A Computational Tool to Estimate the Digester Volume and Biogas.

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Abstract

The anaerobic digestion process results in the formation of biogas, which serves as a renewable source of energy. Different types of feedstocks produce varying amounts of biogas. Many models have been programmed for the estimation of the volume of biogas produced during anaerobic digestion. This study develops a computational tool for the estimation of the volume of the anaerobic digester and the volume of the biogas produced. The computational tool utilizes three inputs, namely Retention time, daily feed, and type of feedstock, for the estimation. The estimation of biogas of this tool was compared to the model from the design procedures as provided in the literature. An overall gap of 10% (in the prediction of the biogas production) was shaved off from two of the three reported values of the case studies. The estimation of the volume of the digester (for the same case studies) was observed to be within $\pm 10\%$ of the reported values. These outputs can be critical for the evaluation of an anaerobic digestion plant as early as in the planning phase.

Statement Of Novelty

The article describes the development of a computational tool for the estimation of digester volume and biogas produced in an anaerobic digestion process. The computational tool is easy to operate as it receives three basic inputs, namely retention time, daily feed, and type of feedstock. The tool computes eight different types of feedstocks and delivers the output of the estimation. In comparison to a prior model, the tool exhibited an increase in accuracy for estimation of biogas volume, estimated digester volume, and dimensioned the digester for three fixed dome plant designs. The characteristic values of the feedstocks are the crux of the computational tool and are responsible for the accuracy increase.

1. Introduction

The anaerobic digestion (AD) process is a process of conversion of complex organic matter (proteins, carbohydrates, lipids, etc.) predominantly into simple end products of methane (CH_4) and carbon dioxide (CO_2) [1]. The conversion process is executed by microorganisms (in the absence of oxygen) to produce the end products [2]. The combination of gaseous end products is considered as biogas, which we can harness as a fuel [3]. Thus, the AD process grants the utilization of different types of organic feedstock (TOF) as a renewable source of energy [4]. The ability to employ different TOF is utilized for a dual purpose of reducing waste and generation of energy [5]. The energy generated from various TOF is variable, and Biochemical Methane Potential (BMP) can be used as an indicator. But the BMP value of a particular waste is an experimental estimation of the methane produced in the AD and can be influenced by various factors (physical conditions, chemical conditions, gas measurement systems, etc.) [6]. Hence, we can acquire an approximate estimation of the energy generated from the AD operation. This approximate estimation, with the use of experimentally attained values, can be facilitated by using the said values to develop a mathematical computational tool (CT) [7].

Studies have been conducted for the economical assessment of the farm-based AD. The financial feasibility and energy generation through the Combined Heat and Power unit were modeled for maximum profit [8; 9]. The AD calculator was developed for the calculation of daily biogas yield and economical aspects as an improvement to the fixed biogas yield calculators [10]. A software program was modeled which estimated the design and the construction costs of a biogas plant [11].

This study deals with mathematically developing a CT, which estimates the volume of the digester and the volume of the biogas produced due to various TOF. Based on the volume of the digester, the dimensioning of three types of biogas digester designs (BDD) (Fixed Dome Plant Designs – namely Chinese Design, Hemisphere Design, and Deenbandhu Design) have been computed.

2. Methodology

The mathematical CT was developed with the help of a Microsoft Excel worksheet. The tool consists of fundamental arithmetic equations, and the solutions of these equations are integrated to forge a chain of equations. Thus, a few selected parameter values are sufficient to generate a required solution as an output. The few selected parameters were retention time (RT, days), Daily Feed (DF, kg/day), and TOF. The input value of RT typically ranges from 10 to 40 days. The DF value is the total amount of feed that would be added to the digester daily. DF was converted from kg to Nm³ with the help of the typical density of the feedstock. The converted value was retained as Daily Feed Volume (DFV, Nm³/day). The selection of TOF describes a host of parameters related to a particular feedstock. Each feedstock has a characteristic value of percentage of total solids (TS, %), percentage of volatile solids to total solids (VS, % TS), and Biochemical Methane Potential (BMP, Nm³/kg VS_{added}).

2.1. Digester Dimensions

The input values of parameters, RT and DFV, facilitate the calculation of the volume of the digester (DV, Nm³).

$$DV = RT * DFV \quad (1)$$

The DV was considered to be 80% of the total volume of the digester (TDV). The volume for the gas storage (GSV) was allotted the remaining 20%.

$$TDV = DV + GSV \quad (2)$$

The TDV calculated from equation (1) was utilized as the volume of the digester in the three BDD as follows:

For Chinese BDD,

$$TDV = \frac{D^3}{2.2368} \quad (3)$$

Where, D is the diameter of the digester (m)

For Hemisphere BDD,

$$TDV = \frac{2}{3} \pi \left(\frac{D}{2}\right)^3 \quad (4)$$

Where, D is the diameter of the digester (m)

For Deenbandhu BDD,

$$TDV = \frac{2}{3} \pi r^3 + \frac{1}{6} \pi k(3r^2 + k^2) \quad (5)$$

Where, r is the radius of the digester (m), k is the depth of the curved base (m).

After attaining the fundamental values such as diameter and radius, dimensioning of other dependent values (such as height, dome height, base depth, etc.) was calculated for each digester. The fixed dome BDD was selected to be modeled for their advantages of simple design, absence of moving parts, and long-life span.

2.2. Methane Production

Methane production is directly proportional to the VS present in the feedstock. The CT was formulated to calculate the amount of methane produced every day based on the DF. The VS added to the digester was computed based on the TS and the VS of the given feedstock. For calculation of VS_{added} in kg/day, DF was multiplied with the TS and the VS to find its fraction in the DF by the following formula:

$$VS_{added} = DF * TS * VS \quad (6)$$

BMP of feedstock represents the maximum volume of methane produced per kg of VS present in the substrate. Hence, the total amount of VS_{added} to the digester on daily basis assists in the calculation of the total volume of methane produced daily (V_{MP}). The V_{MP} is expressed in the units of Nm^3/day .

$$V_{MP} = BMP * VS_{added} \quad (7)$$

The TS, VS, and BMP are the characteristic values that determine the volume of methane produced by a particular feedstock. Table 1 contains these characteristic values for a few TOF obtained from various studies. The values in Table 1 are the mean values of the data gained from the studies and are incorporated in the CT.

Table 1 The characteristic values of the various TOF used in the CT

TOF	TS (%)	VS (% of TS)	BMP (Nm ³ /kg VS _{added})	Reference
Food Waste	20.000	95.000	0.480	[12, 13]
OFMSW ^a	27.000	84.500	0.415	[14]
Dairy Manure	16.322	69.372	0.242	[15 – 18]
Dairy Slurry	7.593	77.707	0.211	[18, 19]
Poultry Manure	47.598	73.004	0.258	[15 – 20]
Pig Manure	26.704	75.366	0.263	[15, 18, 21, 22]
Maize Silage	32.094	93.706	0.417	[18, 23 – 26]
WWTP ^b Sludge	4.482	74.274	0.323	[18, 27 – 30]

^aOrganic Fraction of Municipal Solid Waste, ^bWastewater Treatment Plant

The composition of biogas generally contains 60% of methane in its total volume [31]. Hence, for computation of volume of biogas produced (V_{BP} , Nm³/day), V_{MP} was utilized as the following formula:

$$V_{BP} = \frac{V_{MP}}{0.6} \quad (8)$$

The V_{BP} indicated the estimated volume of biogas produced every day for the given input values.

2.3. Implementation of Co-digestion in the CT

Co-digestion is the process of anaerobic digestion of two or more TOF simultaneously. The CT was programmed for co-digestion of two TOF. Two separate DF input options were provided with the ability to select a TOF for each DF input option. The DFV was calculated by the addition of the two DF inputs. The V_{BP} of individual TOF was calculated independently with the help of the characteristic values from Table 1. The summation of individual V_{BP} of the two TOF resulted in the total V_{BP} .

3. Result And Discussion

The CT had been programmed to compute the DV and the V_{BP} with the help of three inputs: RT, DF, and TOF. These three inputs could be determined before the construction of the AD plant. The planning stage of the AD plant would be aided with this CT.

3.1. Estimation of the V_{BP}

Table 2 Comparison of V_{BP} estimation by the CT with a proposed model from the literature [10]

Case Study [32]	Copys Green Farm	Hill Farm	Lodge Farm
Feedstock [32]	DS ^a – 6.85 T/day MS ^b – 6.85 T/day	DS ^a – 4 T/day	DS ^a – 30 T/day PM ^c – 3 T/day
RT (days) [32]	45	26	28
V_{BP} Reported (Nm ³ /day) [32]	1680	100	1200
V_{BP} estimated by model of Wu (2016) (Nm ³ /day) [10]	1360 (-19%)	100 (~)	952 (-21%)
V_{BP} estimated by this study (Nm ³ /day)	1573.88 (-6.32%)	82.99 (-17%)	1078.48 (-10.13%)

^aDairy Slurry, ^bMaize Silage, ^cPoultry Manure

Table 2 compared the V_{BP} estimation of the CT with a proposed model of Wu (2016) [10]. All the case studies were farm-based AD plants. The CT was able to estimate the V_{BP} more accurately in two of the three case studies. In the first case study and the third case study, the increase in the accuracy of the estimate was observed to be 12.68% and 10.87%, respectively. In the second case study, 82.99 Nm³/day was estimated for 4 T/day of feedstock supply. This case study resulted in a decrease in the estimation accuracy by 17%.

3.2. Estimation of the DV

Table 3 Comparison of DV estimation by CT with the case studies

Case Study [32]	Copys Green Farm	Hill Farm	Lodge Farm
Feedstock [32]	DS – 6.85 T/day MS – 6.85 T/day	DS – 4 T/day	DS – 30 T/day PM – 3 T/day
RT (days) [32]	45	26	28
DV Reported (Nm ³) [32]	870	105	1100
DV estimated by this study (Nm ³)	924.75 (+6.29%)	104 (-0.95%)	1008 (-8.36%)

Table 3 compared the DV of the case studies and the estimation of the CT. The DV is critically dependent on the DF and the RT. The first case study showed a 6.29% overestimation of the DV. The second and the third case study showed underestimation of the DV by 0.95% and 8.36%, respectively.

3.3. Output of Digester Dimension Calculation.

The dimensions of the cylindrical digester of the Copys Green Farm were reported as 10 m in diameter and 10 m in height [32]. The tool estimated the DV of the Copys Green Farm as 924.75 Nm³ as reported in Table 3. From Eqn. (2), the TDV of the digester was calculated as 1,155.93 Nm³. Fig. 4 displays the output of the tool of digester dimensioning for the various BDD. The reported cylindrical digester was comparable to the Chinese BDD. The similarity was evidenced as the calculated dimensions for Chinese BDD were 13.725 m in diameter and 9.95 m in height (summation of H, f₁, and f₂).

4. Conclusion

The CT used three basic inputs (i.e. RT, DF, and TOF) which were utilized for modeling the entire tool. Other key parameters (such as pH, temperature, microorganisms, etc.) were unincorporated [33]. These key parameters are determined during the operation phase of the AD plant and have a dynamic nature (which varies throughout the phases of the AD process if not controlled). The CT attempts to estimate various output values to ease the pre-construction/planning phase. Hence, relatively fixed inputs (which can be determined in the pre-construction phase) were utilized for formulation of the CT. Notwithstanding this handicap, the CT was formulated for the calculation of DV and dimensioning of three different types of BDD. The CT also calculates the VS_{added} which facilitated the output of V_{BP}. The CT was able to increase the accuracy of the estimation of the V_{BP} when compared to a previously well-formulated model. The DV was within the ±10% range of the reported DV from the case studies. As the future scope of the CT, estimation of the energy output of the AD plant can be studied and integrated with this CT. This step will create a complex model for the construction and utilization of the AD technology.

Declarations

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Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dr. Prashant Bhawe and Pankaj Patil. The first draft of the manuscript was

written by Dr. Prashant Bhawe and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Figures

Figure 1

Line Diagram representing the shape and the dimension of the Chinese BDD

Figure 2

Line Diagram representing the shape and the dimension of the Hemisphere BDD

Figure 3

Line Diagram representing the shape and the dimension of the Deenbandhu BDD

Figure 4

Calculation output of the computational tool for all BDD based on input for the Copys Green Farm

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