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Design of Biomethane and Organic Waste Storages for Anaerobic Digestion

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Industrialization and rapid development surged the energy demands and landfill usage required to cater ~~to~~ for the increase in waste disposal. Organic wastes valorization can alleviate the adverse impacts on the environment and can convert wastes to value-added products. Organic waste varies in availability and composition, which can be generalized to carbon-rich and/or nitrogen-rich. The carbon-to-nitrogen (C/N) ratio is one of the significant factors for biomethane production and must be considered during system design. This research proposed a numerical framework for targeting waste-to-energy system taking into consideration the inconsistency of daily organic wastes availability (C/N ratio), volatile solid percentage (VS%), and total solid percentage (TS%). The methodology from previously established Electric System Cascade Analysis (ESCA) was adopted and applied to design the waste and product storage. The developed methodology implemented in a case study comprises of 50 houses with a total energy demand range from 1,095 to 1,290 kWh/d. A 49.01 m^3 biogas storage was equipped into a biomethane energy system with 115.93 m^3 CH_4 daily production to satisfy the energy demand. The identified organic wastes storages capacity was 2,695.17 m^3 for swine manure and 416.17 m^3 for rice straw.

1. Introduction

Organic wastes are found in various compositions across different industries such as the plantation industry, pastoral farming industry, and food and beverage industry. Organic wastes should be properly handled as they tend to putrefy to release greenhouse gas, and spread unpleasant odors when biodegrading. According to Oliver (2013), the heat-trapping ability of CH_4 is 34 times more than CO_2. The valorization of organic wastes as renewable energy can reduce the emission of CH_4 to the atmosphere and lessens fossil-based energy consumption. The bioconversion of organic wastes into biomethane requires specific substrates compositions and optimum operating conditions in order to maximize yield. Co-digestion is an approach to comprehending the carbon-rich organic wastes with nitrogen-rich organic wastes to fulfill the C/N ratio required to maximize biomethane production (Guo et al., 2012). According to Ivan et al. (2016), co-digestion of several organic wastes together at a certain proportion could maximize the biomethane yield. Wang et al. (2012) discovered that the substrate mixtures with a C/N ratio of 27.2 comprised of dairy manure, chicken manure, and wheat straw produced the most methane. Tanimu et al. (2014) obtained the maximum methane production from food waste mixture with a C/N ratio of 30 via anaerobic digestion in that study. Among the studied food wastes, the substrate with a C/N ratio of 25 has the highest methane potential (Xue et al., 2020).
For the biogas system design, Rupf et al. (2017) developed an optimal biogas system design model (OBSDM). The factors such as energy demand, feedstock biodegradability, plant location, and economics were considered while designing the biogas system. Kasaeian et al. (2019) developed a biogas system equipped with a fermentation tank, gas storage, and biogas generator to valorize the biomass resources. The authors focused on operating conditions such as hydraulic retention time, operating temperature, and operation efficiencies while designing the biogas generator. Zhang et al. (2019) developed and simulated a hybrid renewable energy system

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comprised of solar and biomass. The authors focused on thermodynamic and operating conditions during the design of the anaerobic digester.
Pinch Analysis is one of the energy resource optimization tools initially developed to maximize heat energy utilization for a series of process streams and minimize external heat energy required via a graphical approach (Flower and Linnhoff, 1979). Cascade table analysis was derived from the Pinch analysis to optimize resources utilization such as water and electricity while designing the system. Water cascade analysis was developed by Manan et al. (2004) to minimize the water and wastewater targets for continuous processes. To address the fluctuation of energy demands, Ho et al. (2012) developed Electric System Cascade Analysis (ESCA) to determine the optimal power generators and energy storage capacity. The ESCA technique was then applied to optimize the capacity of an energy generator powered by intermittent resources such as solar energy (Ho et al., 2014).
The existing studies assumed steady operation without considering fluctuation of resource supplies and demands simultaneously. It is essential to fill the gaps as it determines how fluctuated resource demand and supply sides impact the design of the biogas system. This study aims to design the biogas system to satisfy the energy demand while focusing on the C/N ratio required during biomethane production. The methodology and optimization approaches from previously established cascade table analysis by Ho et al. (2012) in the ESCA was adopted and applied to determine the capacity of biomethane and organic wastes storage. In addition to the energy balance that was introduced in ESCA, this work considers mass balance instead. The novelty of this this work also include the consideration of C/N ratio, VS%, and TS% during the targetting.

2. Case study

2.1 Illustrate the energy demands for a hypothetic case study

This paper tested a microscale biomethane digester feed on swine manure and rice straw to valorize the local urban organic wastes as energy supply for an illustrated case study with 50 houses in the urban area (Figure 1). The mass flowrate availability of swine manure and rice straw was inconsistent, and the case study's energy demands fluctuated every day. The fluctuation trend of supply and demand sides was assumed to repeat for every cycle (7 d). The energy and organic waste storage were required to tackle the fluctuation of daily energy demands and mass flowrates of organic wastes available.

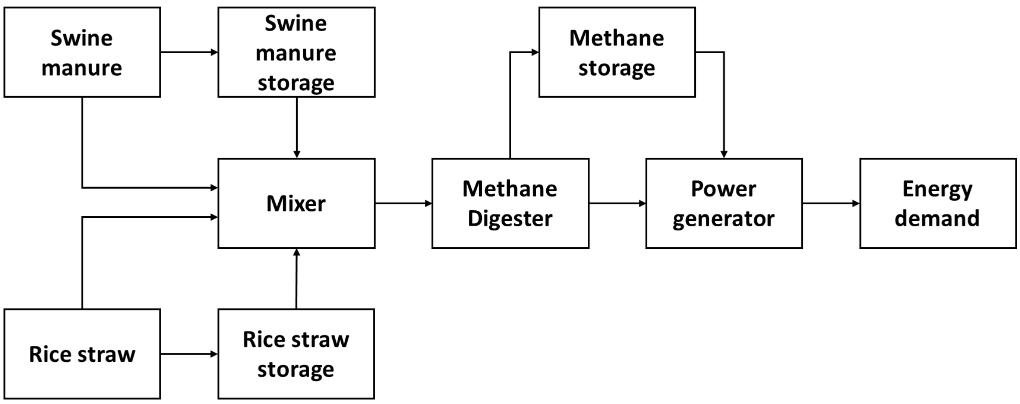

Figure 1 Illustrated case study comprised of biomethane digester, organic wastes and biomethane storage

Ahmed et al. (2017) reported the averaged energy demand for a house ranging from 21.9 kWh/d during weekday to 25.8 kWh/d on the weekend. Based on the average energy demand aforementioned, the hypothetical total daily energy demands, D_{energy} (kWh) for 50 houses were as illustrated in Figure 2. The time frame of this study started with weekdays from Day 1 to Day 5 (denoted as Monday to Friday), followed by weekends for Day 6 and 7 (denoted as Saturday and Sunday). Suhartini et al. (2019) stated that 10 kWh of electricity is equivalent to 1 m^3 of CH_4. Eq(1) was used to calculate the daily CH_4 demand required, $D_{methane}$ (m^3 CH_4) to satisfy the daily energy demands.

$$D_{methane} = D_{energy} \times \frac{1\ m^3\ CH_4}{10\ kWh} \qquad (1)$$

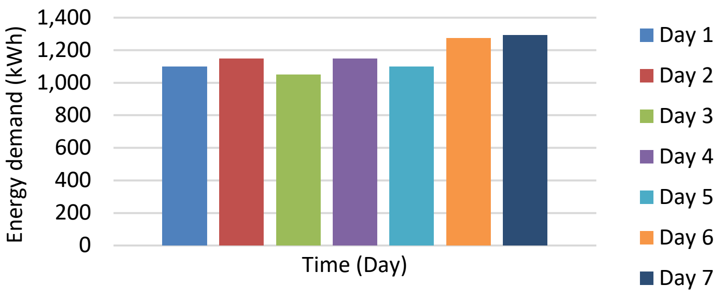

Figure 2 Energy demand of 50 houses

2.2 Cascade table analysis to determine maximum biomethane accumulation in storage

The net CH_4, $N_{methane}$ (m^3 CH_4) was calculated by deducting the daily biomethane demand, $D_{methane}$ (m^3 CH_4) from the daily biomethane production, $P_{methane}$ (m^3 CH_4). The positive value of $N_{methane}$ indicates that CH_4 is supplied in excess and will be stored into the biomethane storage tank, denoted as CH_4 loading, $L_{methane}$ (m^3 CH_4). The negative value of $N_{methane}$ indicates insufficiency of CH_4 supply. The biomethane previously stored in the biomethane storage tank will be unloaded for energy generation and denoted as CH_4 unloading, $UL_{methane}$ (m^3 CH_4). To determine the capacity of the biomethane digester, an initial guess of the daily biomethane production, $P_{methane}$ was assumed and then the new daily biomethane production, $P_{methane,\ new}$ was calculated via Eq(2) where the $C_{methane,\ final}$ is the cumulative biomethane in the storage tank on the last day of the current cycle period, $C_{methane,\ initial}$ is the cumulative biomethane in the storage tank that is carried forward from the last day of the previous cycle period and T is the time duration for a cycle period, which is 7 d in this case study.

$$P_{methane,\ new} = P_{methane} - \left(\frac{C_{methane,\ final} - C_{methane,\ initial}}{T} \right) \quad (2)$$

The calculation of new daily biomethane production, $P_{methane,\ new}$ was repeated by using Eq(3) until the percentage error, E (%) is less than 0.05 % to verify the accuracy of the analysis.

$$E = \frac{|\ P_{methane,\ new} - P_{methane}|}{P_{methane}} \times 100\ \% \quad (3)$$

From the cascade table analysis for the biomethane production (Table 1), the maximum cumulative of biomethane that will be stored was 24.64 m^3. According to Amon et al. (2007), biomethane only accounted for part of the total biogas produced. The ultimate biogas storage was determined using the empirical formula of the biomethane feedstock mixture.

Table 1: Cascade table to determine capacity for biomethane storage

Time	D_{energy} (kWh)	$D_{methane}$ (m^3 CH_4)	$P_{methane}$ (m^3 CH_4)	$N_{methane}$ (m^3 CH_4)	$L_{methane}$ (m^3 CH_4)	$UL_{methane}$ (m^3 CH_4)	$C_{methane}$ (m^3 CH_4)
							0
Day 1	1,100	110	115.93	5.93	5.93	0.00	5.93
Day 2	1,150	115	115.93	0.93	0.93	0.00	6.86
Day 3	1,050	105	115.93	10.93	10.93	0.00	17.79
Day 4	1,150	115	115.93	0.93	0.93	0.00	18.71
Day 5	1,100	110	115.93	5.93	5.93	0.00	24.64
Day 6	1,275	127.5	115.93	-11.57	0.00	11.57	13.07
Day 7	1,290	129	115.93	-13.07	0.00	13.07	0.00

2.3 Determine the empirical formula of feedstock for a biomethane digester

The ultimate analyses of swine manure and rice straw were as listed in Table 2. In this study, the 27.4 of C/N ratio required for biomethane production was the average value obtained from several studies aforementioned in Section 1.

Table 2: Elements weight percentage for swine manure and rice straw (Li et al., 2013)

Organic waste	TS (%)	C (% TS)	H (% TS)	O (% TS)	N (% TS)	Others (% TS)	C/N	VS (%)
Swine manure	30.4	34.8	4.7	30.3	2.2	28	15.8	22
Rice straw	92.9	39.7	5.4	38.2	0.9	15.8	44.1	81.6

The theoretical production of CH_4 was determined via Bushwell's equation, Eq(4) by substituting the C, H, O, and N compositions of the biomethane digester feedstock (Li et al., 2013). To identify the mass flowrate ratio of swine manure to the rice straw required to satisfy the C/N ratio of the feedstock for biomethane digester, the previously established C/N ratio Pinch Analysis (Chee et al., 2021) methodology was adopted. In this study, a graph of cumulative carbon mass flowrate versus cumulative nitrogen mass flowrate for supply and demand sides was plotted. For demonstration purposes, a random mass demand of 20 kg biomethane digester feedstock that required C/N ratio of 27.4 was used.

$$C_cH_hO_oN_n + \left(c - \frac{h}{4} - \frac{o}{2} + \frac{3n}{4}\right) H_2O = \left(\frac{c}{2} - \frac{h}{8} + \frac{o}{4} + \frac{3n}{8}\right) CO_2 + \left(\frac{c}{2} + \frac{h}{8} - \frac{o}{4} - \frac{3n}{8}\right) CH_4 + nNH_3 \quad (4)$$

The final step for the C/N ratio Pinch Analysis for the biomethane feedstock mixing using swine manure and rice straw shown in Figure 3. The analysis results showed that the biomethane digester feedstock required 6.9968 kg of swine manure with C/N ratio of 15.82 mixed with 13.0032 kg of rice straw with C/N ratio of 44.11. The biomethane digester feedstock comprised 34.98 wt% of swine manure and 65.02 wt% of rice straw. The mixing of the swine manure and rice straw was assumed to form a homogeneous feedstock mixture.

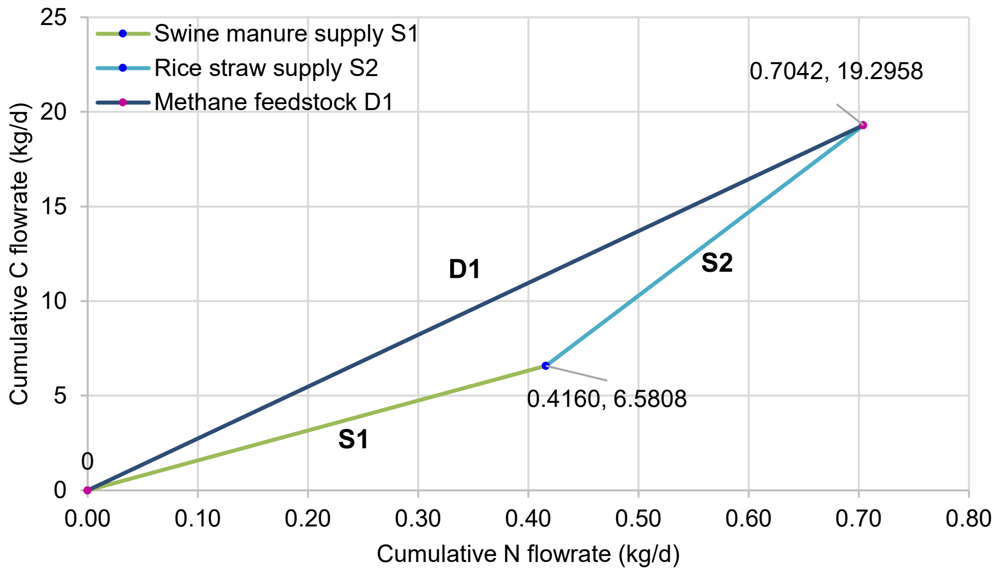

Figure 3 The mismatch of swine manure and rice straw to produce feedstock for a biomethane digester.

The individual wt% of the C, H, O and N elements for the biomethane feedstock mixture was obtained by substituting the respective elements wt% of swine manure and rice straw as the x symbol into Eq(5). The individual wt% of the C, H, O and N elements were 37.99, 5.16, 35.44 and 1.35.

$$x_{feedstock} = 0.3498(x_{swine\ manure}) + 0.6502(x_{rice\ straw}) \quad (5)$$

Then, the mole number of the elements was calculated by dividing the individual wt% of the elements by their molecular weight. The molecular formula for the biomethane feedstock was $C_{3.17}H_{5.16}O_{2.21}N_{0.097}$ and the normalized molecular formula was $C_{65}H_{107}O_{23}N$.

2.4 Determine the biomethane digester capacity

About 10 % of the organic matter does not degrade and another 10 % of the organic matter utilized for side reactions (Ayodele et al., 2019). A correction factor of 80 % was taken into account during theoretical biomethane production, TMP (mL CH_4/g VS) to indicate the fraction of organic matters involved Eq(6).

$$TMP = \frac{22.4 \times 1000 \times \left(\frac{c}{2} - \frac{h}{8} + \frac{o}{4} + \frac{3n}{8}\right)}{12c + h + 16o + 14n} \times 80\ \% \quad (6)$$

From Eq(6), the theoretical biomethane production, TMP in this study was 0.367 m^3 CH_4/kg VS. The production of CO_2 and NH_3 as side products were calculated as 0.343 m^3 CO_2/kg VS and 0.022 m^3 NH_3/kg VS via Eq(4). Based on the maximum cumulative of biomethane in Section 3.2, the CO_2 and NH_3 produced were 23.03 m^3 CO_2/kg VS and 1.34 m^3 NH_3/kg VS. By considering all the products produced from Eq(4), the biogas storage capacity for this case study was 49.01 m^3.

2.5 Cascade table analysis for feedstock storages

As the daily volatile solid supply, VSS (kg VS/d) of swine manure and rice straw were fluctuating, and another cascade table analysis was performed based on the volatile solid (VS) of the individual feedstock to determine the capacity of feedstock storages (Table 3). The cascade table analysis for feedstock storage was executed in terms of VS as the biomethane yield obtained from Bushwell's equation was in the unit of m^3 CH_4/kg VS. The total VS demand, TVSD (kg VS/d) was obtained by dividing the $P_{methane}$ with the TMP via Eq(7).

$$TVSD = \frac{P_{methane}}{TMP} \quad (7)$$

From the TVSD, the individual VS contributed by each substrate, IVSD (kg VS/d) was calculated via Eq(8) using the individual mass fraction of organic waste supply, y for each substrate as aforementioned in the Eq(5).

$$IVSD = y\,(TVSD) \quad (8)$$

The NVS, LVS, ULVS and CVS were the net volatile solid, volatile solid loading into and volatile solid unloading from the organic wastes supply storage tanks and cumulative volatile solid in the organic waste supply storage tank. The terms aforementioned have similar calculation steps as the $N_{methane}$, $L_{methane}$, $UL_{methane}$ and $C_{methane}$ elements in the cascade table analysis for biomethane storage. Degueurce et al. (2020) found 10% of organic composition loss in the storage over 10 d. The organic loss of 10 % was accounted during the process of unloading organic wastes from the storage tank. The organic waste supply storage, $OWSS_i$ (m^3) capacity was obtained via Eq(9) where the greatest value of CVS (denoted as $CVS_{max,\,i}$) was divided by individual volatile percentage, TS_i (VS%) and individual total solid percentage, TS_i (TS%) of the organic wastes. From the calculations, the OWSS for swine manure and rice straw were 2,695.17 and 416.17 m^3. The unutilized organic wastes accumulated in the storage tank during Day 7 will be disposed of to prevent overflow during the next cycle period. As daily biomethane production fixed at 115.93 m^3/d, biomethane storage helps regulate the surplus and deficit of biomethane required to satisfy the fluctuated daily energy demands. The organic waste supply storage helps regulate the feedstock entering the biomethane digester as the availability of the organic waste supply is inconsistent.

$$OWSS_i = \frac{CVS_{max,\,i}}{TS_i \times VS_i} \quad (9)$$

Table 3: Cascade table analysis for swine manure (SM) and rice straw (RS) storages

Time	TVSD (kg VS/d)	IVSD (kg VS/d)		VSS (kg VS/d)		NVS (kg VS/d)		LVS (kg VS/d)		ULVS (kg VS/d)		CVS (kg VS/d)	
		SM	RS	SM	RS	SM	RS	SM	RS	SM	RS	SM	RS
Day 1	316	179	137	270	195	91	58	91	58	0	0	91	58
Day 2	316	179	137	198	221	19	84	19	84	0	0	111	142
Day 3	316	179	137	186	182	7	45	7	45	0	0	118	187
Day 4	316	179	137	222	169	43	32	43	32	0	0	161	219
Day 5	316	179	137	198	234	19	97	19	97	0	0	180	315
Day 6	316	179	137	120	0	-59	-137	0	0	65	152	115	163
Day 7	316	179	137	90	0	-89	-137	0	0	99	152	16	11

3. Conclusion

The storage capacity for biomethane (49.01 m^3), swine manure (2,695.17 m^3) and rice straw (416.17 m^3) for organic wastes valorization system were determined. The C/N ratio, VS% and TS% were considered during the calculation of biomethane production via Bushwell's equation to make the analysis more reliable. This research work is flexible and applicable to other bioprocesses such as biohydrogen, bioethanol, and composting that requires different C/N ratios. Different combinations of organic wastes can be used as long as one organic waste has a higher C/N ratio and another organic waste has a lower C/N ratio than the demand side requires. In the future, biodigester operation constraints such as the organic loading rate, hydraulic retention time and working volume will be considered to make this study more feasible and realistic.

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