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Healthy-Smart Concept as Standard Design of Kitchen Waste Biogas Digester for Urban Households

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Abstract

This paper aims to analyse the healthy-smart concept as a standard design of kitchen waste biogas for urban people. The anaerobic digester (AD) is designed for family size. The planned vertical digester is a one-stage- semi-continuous type because this AD type is easy to operate in urban areas. Kitchen waste or food waste can be generalized as all bio-materials produced from kitchen activities (including vegetables, fruits, bread, rice, coffee ground, tea leaves, etc). The biggest problem with household waste is the non-uniformity of feedstock entering the digester biogas. Five steps will be carried out: to establish technical standards in designing kitchen waste; to calculate the biogas potential from kitchen waste; to simulate the methane demand and generation profile; to calculate the geometry of the biogas digester; and to analyse the operation parameter for gas production into the healthy-smart concept. With a simple simulation of two people in the household for 1 d, the results show that biogas produced from kitchen waste is sufficient for cooking purposes. For the healthy-smart concept of biogas production, some operation parameters must be considered, such as; pH, alkalinity, temperature, volatile fatty acid concentration, volatile solids, and C/N ratio. The results can be used in overcoming the urban household waste and also as a reference in sustainable urban planning.

Keywords: Biodegradation, Circulair economy, Eco-friendly technology, Green energy, Methane capture, Municipal solid waste, Waste management, Welfare improvement

1. Introduction

The demand for renewable energy is increasing along with emission reduction campaigns by the use of fossil energy (Nizami *et al.*, 2020; Owusu and Asumadu-Sarkodie, 2016). Every alternative deserves to be explored regardless of scale so long as source availability exists. Countries like China, India, Indonesia, Pakistan, which have a big population, produce biomass energy sources from inhabitant activities (Abbasi and Abbasi, 2010; Helwani *et al*., 2020; Khan and Khan, 2020). Humans produce organic waste daily. In this case, organic waste is waste that can be converted into energy, such as agricultural waste, household kitchen waste, human waste (excreta disposal from septic tanks), animal waste, and so on (Adinurani *et al*., 2018; Herry, *et al*., 2020; Heryadi *et al*., 2018; Heryadi *et al*., 2019a; Heryadi *et al*., 2019b, Leela *et al*., 2018; Prabowo *et al*., 2017; Syaifudin *et al*., 2018a; Syaifudin *et al*., 2018b; Setyobudi *et al*, 2012a; Setyobudi *et al*, 2012b; Setyobudi *et al*., 2018; Setyobudi *et al*., 2019). The term household kitchen waste is not limited to civilian household kitchen waste but includes food waste generated by hotel kitchens, restaurants, and

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also the waste food from supermarkets (Ramadhita *et al*., 2021). Kitchen waste or food waste can be generalized as all bio-materials produced from kitchen activities (which include: vegetables, fruits, remains of food such as gravy, oils, bones, fish remains, bread, rice, coffee filters, coffee ground, tea bags, and tea leaves, etc. The Ministry of National Development Planning (Indonesian: *Kementerian Perencanaan Pembangunan Nasional Republik Indonesia*) (abbreviated Bappenas) states that food waste in Indonesia is 112×10^6 t yr^{-1} (Hidayat, 2021).

Anaerobic digester (AD) is one technology used to digest organic waste and produce energy as renewable energy (Adinurani *et al*., 2017; Yusuf *et al*., 2020). AD can be developed from small to large sizes for cooking or energy generation purpose. AD for cooking purposes is very popular for the rural people in China, Bangladesh, India, Indonesia, and Nepal. Mostly, the digester is supplied with animal dung, such as cow manure, chicken manure, and pig manure. On the contrary, AD is not so popular for urban people. Urban people may think of AD as dirty, impractical, and low technology for rural people.

AD can also be fed with organic waste that is generated greatly in an urban household. In other words, to supply the energy for cooking in an urban household, AD can be applied to produce biogas. One of the major components of organic waste in municipal solid waste (MSW) is household kitchen waste. But, this waste is non-uniformity that allows process instability in AD (Adinurani *et al*, 2017; Setyobudi, *et al*, 2015).

Based on studies from Shenzhen, family size and household income levels are the main factors affecting the production of household kitchen waste (Zhang *et al*., 2018). Compared to wind and solar energy (Hendroko *et al*., 2013; Slorach *et al*., 2019), the electrical energy produced from AD requires lower energy. AD also has the potential to reduce toxicity, heavy metals, and pathogen. Unfortunately, AD has a higher global warming potential, mainly for methane capture. Biodegradation in AD is eco-friendly technology for welfare improvement through a circular economy because AD produces solid and liquid organic fertilizers (Setyobudi *et al*, 2012a; Setyobudi *et al*, 2012b).

For urban households, we focus on the healthy-smart concept as the standard design of kitchen waste. That means that it has to meet several criteria such as: being odorless or non-pollutive to the air; the effluent liquid waste is non-pollutive to the surrounding water-source and soil; the gas can be used safely for cooking without leaking; no remaining waste in the process (all must be processed); modular systems for ease of installation, operation, and maintenance. We determined the digester was a one-stage- semi-continuous type with multiple feedstocks (household kitchen waste mixed with excreta disposal from septic tanks). However, this design can be changed to two stages if there are processing difficulties due to the diversity of feedstocks.

The process of methane with AD is explained in Figure 1. While acting on biodegradable materials in an anaerobic condition, the bacteria methanogenic can produce a mixture of gas, called biogas. The composition of biogas contains 50 % to 60 % CH_4, 38 % to 48 % CO_2, and the rest 2 % (H_2, H_2S, etc.). To facilitate the conversion process, there are two key groups of bacteria (Khalid *et al.*, 2011; Setyobudi *et al.*, 2015). Group 1 acts as the fermenting bacteria. It uses extracellular enzymes. It works as successive fermentation of the hydrolyzed products. Through hydrolysis, it transforms the organic material into short-chain fatty acids. Alcohol, CO_2, and H_2 are the other products of the fermentation process. The organic materials are transformed into advantageous ingredients for the bacteria during the process of hydrolysis. Group 2 acts as the acidogenic bacteria. It burns the short-chain fatty acids under the forming of H_2, formic acid, acetic acid, and CO_2. During the transformation processes, there are two additional groups of bacterias. Group 3 acts as the methanogen bacteria. It transforms the CH_3COOH, H_2, and CO_2 into CH_4. From the metabolism, it benefits more energy at high hydrogen concentrations. Group 4 acts as the homoacetogens bacteria. Under the production of CH_3COOH, it agitates a wide range of ingredients. Group 5 acts as the acetic acid oxidizers bacteria. If the H_2 is detached at the same time by other processes, it will oxidize the CH_3COOH to H_2 and CO_2. The hydrolysing process becomes gradual when the biomaterial accommodates a high quantity of cellulose. The intensification of acetic acid plays a meaningful role in AD to produce CH_4 and CO_2 (Setyobudi *et al.*, 2013).

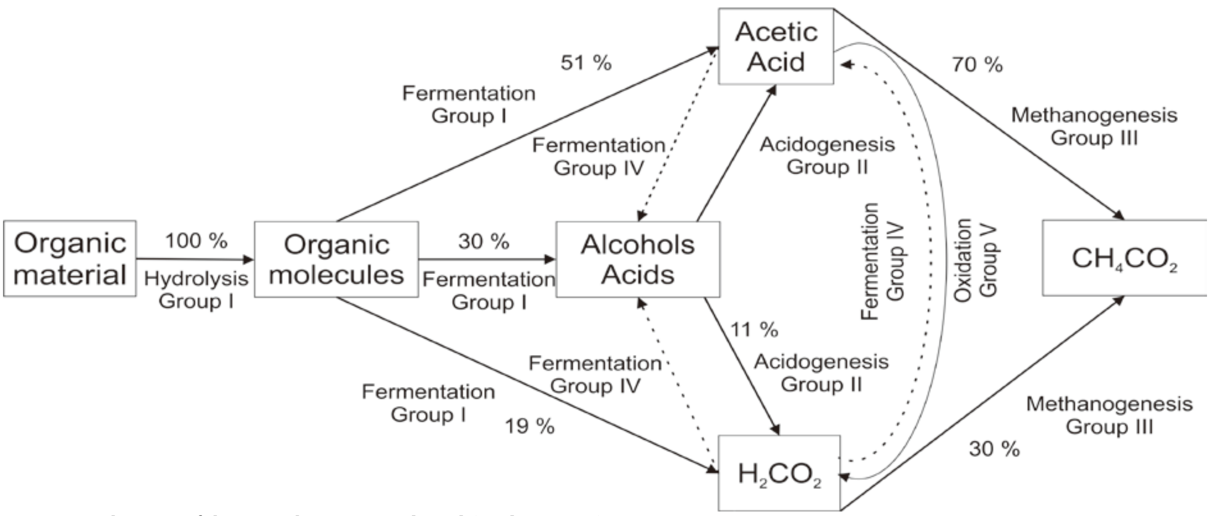

Figure 1. Schematic of the anaerobic process adopted (Poulsen, 2003)

A feasibility study of kitchen waste for biogas plants as an alternative energy source contributing around 50 % of total solid waste in urban areas has been carried out by Hanafi *et al*., in 2016. As a feasible solution for low organic load and a decentralized strategy to improve MSW management, Muñoz (2019) suggested anaerobic digester food waste at psychrophilic temperatures. Alexander *et al*. (2019) analysed the domestic urban biogas digester to accomplish the brine decarbonisation of the system of energy. Tasnim *et al*. (2017) suggested combining cow manure with kitchen waste and other waste materials such as sewage. Rianawati *et al*. (2018) suggested the household scale biogas digester as the most feasible to be implemented due to the small amount of waste needed. Oguntoke *et al*. (2019) classified the positive proportions of bio-digestible waste based on the family size and income level of households in a city in Nigeria. Nwaigwe *et al*. (2018) estimated the potential of 0.7 kg household wastes per person per day generated in Johannesburg, South Africa. Gandhi *et al*. (2019) reported a lot of food waste from the different classes of hotels in Jaipur, India. Gaballah *et al*. (2020) reported that solar energy can be integrated with biogas digester to accomplish the ideal temperature for biogas production. Amir *et al*. (2016) studied some technical failures of AD to produce biogas due to the compliance of people. Curry and Pillay (2012) investigated the analysis of production with molecular formula and computer simulation for the AD model. Gebreegziabher *et al*. (2014) reviewed the potential, opportunities, challenges, and demanding conditions for the success of biogas in urban applications. Kjerstadius *et al*. (2015) studied how biogas production can increase more than 70 % compared with a conventional system with the source control systems. Igoni *et al*. (2008) synthesised the key issues design of a high-performance AD. Apte *et al*. (2013) identified the potential of biogas production based on the kitchen waste survey from several cities. Kayhanian and Hardy (1994) investigated the methane production rate as the contrary comparable to the moderate size of feedstock, the ratio of C/N organic, and the retention times. Clercq *et al*. (2016) reported the previous project of urban AD with food waste facing similar operational issues in China. Setyobudi *et al* (2012a), Setyobudi *et al*. (2012b), and Herry *et al*. (2020) showed impacts one-stage, and two-stage AD in the circular economy on household scale biorefinery. Akkoli *et al*. (2015) created a more cost-effective, eco-friendly organic processing facility to generate biogas.

Based on the literature review above, there have been many studies with various topics related to biogas in urban areas. However, it seems that there is no clear healthy-smart concept for the standard design of kitchen waste biogas digesters for urban households. The purpose of this study is to analyse the healthy-smart concept as the standard design of kitchen waste biogas digesters for urban households. The digester is designed as family size, as one of the efforts in realizing national energy security, (Yandri *et al*., 2017; Yandri *et al*., 2020). Other goals to be achieved with AD are suppressing global warning, welfare improvement with a circular economy, and improving human health in urban areas (Herry *et al*., 2020; Setyobudi *et al*., 2012a; Setyobudi *et al*., 2012b).

2. Materials and Methods

To achieve the objectives of this study, five steps were carried out, as follows; *First,* establishing the technical standards in designing kitchen waste biogas digesters for urban households. The standard becomes a reference in subsequent calculations. *Second*, calculating the biogas potential from kitchen waste with AD. The composition of typical waste organic matter is

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3 \quad (1)$$

Under standard conditions (0 °C, 1 atm), the specific theoretical methane yield (B_{th}), Nm^3 CH_4 per ton volatile solids (VS), defined as agitation loss at 55 °C);

$$B_{th} = 22.4\frac{\left(\frac{4a+b-2c-3d}{8}\right)}{12a+b+16c+14d} \quad (2)$$

Under anaerobic conditions, Lignin is formed from parts of organic material that cannot be broken down. The estimation of Biodegradable fraction (*BF*) for lignin content LC;

$$BF = 0.83 - 0.028LC \quad (3)$$

The formulation as a function of design for methane yield (B) per mass of COP or VS input;

$$B = \frac{B_0S_0}{HRT}\left(1-\frac{K}{HRT\mu_m - 1 + K}\right) \quad (4)$$

where: B_0 *is* the ultimate methane yield can be found by plotting the steady-state methane production against *1/HRT* for different levels of *HRT* (hydraulic retention time) for a given constant temperature and extend the plot to infinity (*1/HRT = 0*). The input biodegradable substrate concentration, S_0, in terms of chemical oxygen demand (COD):

$$S_0 = \frac{Dry\ Matter \times (1 - Inert\ solids)}{Vol_{input}} \times BF \quad (5)$$

where; S_e = input biodegradable effluent substrate concentration S_e has relation with S_o

$$S_e = (1 - VS_{design}) \times S_0 \quad (6)$$

where; μ_m is the optimum growth rate of the bacteria in the biogas digester, can be estimated;

$$\mu_m = 0.013T - 0.129 \quad (7)$$

where; *T and K are* the temperature [°C] and the dimensionless kinetic parameter, respectively. The degree of digestion is controlled by HRT, as the reactor volume V_f is divided by input volumetric flow rate Q.

$$HRT = \frac{V_d}{Q} \quad (8)$$

Third, simulating the methane demand and generation profile for a household. The aim was to determine the potential kitchen waste generated and gas requirements in an urban household with several family members. *Fourth,* calculating the geometry of the biogas digester which be used to estimate the exact area requirement and appropriate location for the biogas digester. *Fifth*, analysing the operation parameter for gas production into a healthy-smart concept, included site location, operational parameters, construction, effluent treatment, utilization: single/hybrid.

For analysis, there were some estimations and assumptions. The purposes were to know how much biogas demand and also how much kitchen waste will be generated for this family. The digestion processes determined the control of temperature. The mesophilic processes (30 ^{o}C to 40 ^{o}C) were operated by the experienced AD. Recently, thermophilic processes (50 ^{o}C to 60 ^{o}C) have become more common to use. Table 1 was used to estimate the chemical composition of input organic matter.

Table 1. Standard design for biogas digester

	Parameter	Unit	Value
Kitchen Waste	Estimate inert solid of dry weight	[%]	1
	The estimated water content of input weight	[%]	80
	The design water content of input weight	[%]	90
	Design dry matter weight	[%]	10
	Design biodegradable VS reduction eff.	[%]	80
Household	Biogas consumption for cooking	[Nm^3/person d^{-1}]	1
	Design cooking behaviour	[times d^{-1}]	80
	Person supplied per unit digester	[persons/digester]	90
	Number of person per household	[person]	4
	Kitchen waste generation per person (wet)	[kg/person d^{-1}]	1

3. Results

To know how much biogas can be produced from kitchen waste, some calculations were done to find several parameters. Using Table 1, the other parameters were calculated. Methane potential from kitchen waste was calculated using some steps. There were specified references to explain the chemical composition of the food waste. In this case, its chemical composition was considered so close to kitchen waste.

Table 2 used the weight percentage of organic atoms data for food waste. The chemical composition of kitchen waste was calculated by assuming it as food waste. The CH_4 yield kg^{-1} of biodegradable VS degraded in the digester was calculated from Equation (1) and Equation (2).

Table 2. Design biogas potential from kitchen waste

Description	Unit	Calculation	Equation
Total Solid (TS) of actual input weight	kg d^{-1}	0.8	
Water Content (WC) of actual input weight	kg d^{-1}	3.2	
Water Content (WC)	kg d^{-1}	7.2	
Volume input after dilution	m^3 d^{-1}	0.008	
Constant mass flow rate, m (kg s^{-1}) during 24 h	kg s^{-1}	9.26×10^{-5}	
Biodegradable Factor *(BF)*	kg m^{-3}	0.819	Eq.(3)
Input biodegradable substrate concentration S_o	kg m^{-3}	81.061	Eq.(5)
Input biodegradable effluent substrate concentration S_e	kg m^{-3}	16.212	Eq.(6)
Hydraulic Retention Time (HRT)	D	16	Eq.(8)
Methane yield kg^{-1} of biodegradable vol. solids B_{th}	Nm^3 kg^{-1} × VS	0.507	Eq.(2)
	Nm^3 d^{-1}	0.329	
	Nm^3 h^{-1}	0.014	
	Nm^3	0.4113	

Methane content in biogas was approximately 60 % of the total biogas volume. For initial estimation, the digester was designed for two persons. The needs of biogas for two persons must be supplied by the digester. Two persons also can produce 4 kg of kitchen waste (wet) to supply to the digester. This was the reason to make the digester small, easy to maintain, less space, and modular system. member of the family has also increased. Methane demand for a household that must be produced per digester was calculated as;

$$B_{design} = 0.25\ Nm^3 / person / d \times 60\ \% \times 2\ person = 0.3\ Nm^3 / d \quad (9)$$

So, for one-time cooking, methane consumed by one person ($B_{con,\ person}$) was described in Equation (10).

$$B_{cons.person} = \frac{0.25\ Nm^3/d}{3\ cooking/d} \times 60\ \% = 0.05\ Nm^3/d \quad (10)$$

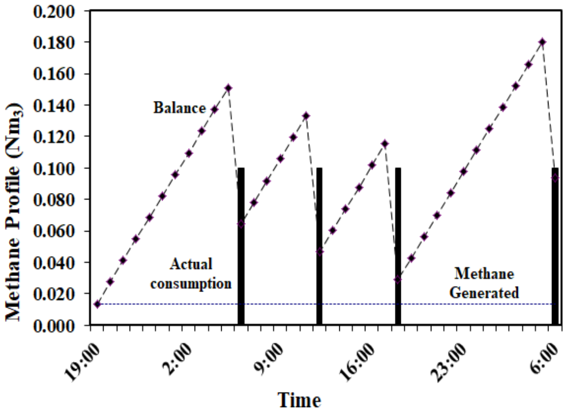

Figure 2. Methane generation and consumption profile vs time

Methane demand and generation profile was plotted by using data from the previous calculation as shown in Figure 2. The standard methane demand for cooking per person per day was 0.05 Nm^3 [3], which means 0.10 Nm^3 for two persons. Methane generated per hour by digester from the previous calculation was 0.014 Nm^3. The total volume of the digester geometry:

$$V_{tot} = V_f + V_s + V_g \tag{11}$$

where: V_{tot} is the total digester volume, V_f is the fermentation chamber volume, V_s is the sludge chamber volume (assumed 5 % of V_f), V_g is the gas chamber volume (6 h to stored hourly biogas production from 18.00 to 06.00). The digester height was calculated as a cylinder. The design radius geometry of the cylinder was 0.25 m. Then, the digester height was also calculated, as shown in Table 3.

Table 3. Geometrical summary of the digester

Item	Volume (m^3)		Height (m)	
Fermentation chamber	V_f	0.128	H_f	0.620
Gas chamber	V_g	0.140	H_g	0.033
Sludge chamber	V_s	0.006	H_s	0.699
Digester chamber	V_{tot}	0.274	H_{tot}	1.352

For the healthy-smart concept biogas production, some operation parameters must be considered, such as pH, temperature, alkalinity, volatile fatty acid (VFA) concentration, volatile solids, C/N ratio. Table 4 shows a summary of operational control for gas production. All parameters must be controlled by a computer-based instrument in real-time to produce optimal biogas with safe operation. For this reason, the control value of these parameters must be known by reference to existing standards, which must be ensured during the initial biogas digester testing.

Table 4. Summary of operational for gas production

Parameters	Controlled items	Optimum values
pH	Acid concentration vs buffer materials	refer to standard and testing
Temperature	Medium or high temperature	refer to standard and testing
Alkalinity	Acid concentration vs bicarbonate & fatty acid	refer to standard and testing
VFA	degradation of organic material into acetate and hydrogen	refer to standard and testing
VS	The degradation efficiency of output to input	refer to standard and testing
C/N	The amount of carbon and nitrogen	refer to standard and testing

4. Discussion

Based on what has been analysed so far, two things need to be discussed. The first issue concerns the design and operational parameters, which were very important to be understood and anticipated from the beginning. This means that, from the initial design stage, the cost, performance, and failure of biogas can be anticipated. The organic material will not be fully degraded if the HRT is too short, resulting in low gas yields and possible inhibition of the process. If the HRT is shorter than their rate of multiplication, this results in a washout of the methanogenic bacteria. The main contribution failures of biogas digester were caused by some factors, such as the unrealistic assumptions on bio-waste quantity quality, unsuitable AD designs and overestimation of economic returns from biogas, underestimation of the complex bio-waste supply chain (Breitenmoser *et al*., 2019). The second issue concerns the layout area of urban households. Households in large cities are generally located in densely populated areas with small layouts. For this reason, the location of the biogas digester must be determined using certain analysis to minimize the environmental and social impact (Akther *et al*., 2019). Both points must strongly adopt the defined healthy-smart concept.

This research discussed the concept of healthy-smart kitchen waste biogas digesters ideas for urban households. Our results are very useful in overcoming the problem of urban household waste that is used as a source of biogas energy. The results can also be contributed as a reference in sustainable urban planning, as well as the hi-tech cookstove concept (Yandri *et al*., 2021). This concept can also be applied in other urban buildings, such as offices or campuses as a complement to green buildings and industries with energy efficiency (Purba *et al*., 2021; Yandri *et al*., 2020). For future research directions, the healthy-smart concept design of the kitchen biogas digester needs to be developed. It has to be complemented with the other studies, such as: how to analyse in detail the potential of biogas from a variety of kitchen waste materials in different cities, how to design an appropriate electronic or mechanical control system so that biogas digester operates with healthy and optimal conditions, and also how to get greener by utilizing renewable energy as energy mix from solar energy such as photovoltaic (PV) module (Faturachman *et al*., 2021; Suherman and Astuty, 2020), or hybrid photovoltaic-thermal (PVT) collector to produce electricity and heat (Yandri, 2019). The initial target of implementation should be focused on established urban households, or hotel management that is considered more adaptable to the operating/technical system as required by advanced biogas technology.

However, the authors plan further studies on possible process instability in AD due to feedstock non-uniformity. Therefore, this follow-up study will expand the AD design by implementing a two-stage modification as has been carried out by Adinurani *et al.* (2017) and Setyobudi *et al*. (2015).

5. Conclusion

Kitchen waste as a source of urban waste can be processed by every household into biogas with biogas digester technology with a healthy-smart design concept. This design is very important in controlling the material to produce optimal biogas without causing effects on the environment, such as air and water pollution. Based on a simple simulation for two people in the household, the biogas produced from kitchen waste biogas digester is sufficient for a day's cooking purposes. With a vertical design, the total volume and height of a digester unit are 0.274 m^3 and 1.352 m, respectively. If the need for biogas increases as the number of families increases, then the next units can be connected in parallel. For the healthy-smart concept biogas production, some operation parameters must be controlled properly, such as pH, alkalinity, temperature, volatile fatty acid (VFA) concentration, volatile solids, and C/N ratio. The results can be used in overcoming the problem of urban household waste that is used as a source of biogas energy, can also be contributed as a reference in sustainable urban planning.

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