MODELING AND SIMULATION OF SMALL-SCALE BIOGAS DIGESTER BASED ON KITCHEN WASTE

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ABSTRACT

Anaerobic digestion (AD) is a collection of biological processes where the organic material is converted by microorganisms to produce a mixture of mainly methane and carbon dioxide (biogas) in the absence of oxygen. Methane is a very powerful greenhouse gas. The combustion of methane releases energy, which can be used to generate heat and electricity. AD proves to be a beneficial technology in various spheres. Biogas technology has the potential to meet the energy requirements in many places, it can be designed to meet the electrical and/or heat demand in rural areas. On the other hand, kitchen waste can be used to produce biogas due to its high biodegradability which can reduce the dependency on fossil fuels. This paper presents a proposed design, modeling and simulation of small-scale biogas digester based on kitchen waste. The biological processes of the AD are mathematically modeled to give a complete representation of the physic-chemical reactions depending on several aspects such as microbial activity, substrate degradation, and temperature. A small-scale family size kitchen waste digester is designed to utilize the kitchen waste of an average Egyptian family and provides the required cooking heat of the house. The model is then simulated in Matlab/Simulink environment. The proposed model is simulated under different conditions to investigate the impacts of digester temperature, feed type, and reaction time on biogas production. The simulation results identify the best parameters for the operation of the proposed model. The study explains that the suitable size for a biogas digester based on the kitchen waste of an average Egyptian family is 0.06 m3, with a diameter of 0.4 m and a height of 0.5 m. The results show that there is a regular increase in methane

production at 30 ºC for about 18 days before it becomes constant, and best volume of methane equals to 0.05369 m3 /day.

Keywords: Organic wastes; Anaerobic digester; Kitchen waste, Biogas; Simulink modeling.

Nomenclature

b Retention time factor,
BVS Biodegradable Volatile Solids
F_{feed} Influent or feed flow (m^3/d),
F_{meth} Methane gas flow (m^3 CH_4/d),
k_1 Yield factor obtained from experimental data,
k_2 Yield factor obtained from experimental data,
k_3 Yield factor corresponding to the growth rate of methane,
k_5 A factor correlated to the methane flow and obtained from experimental data,
K_d Specific death rate of acidogens (d^{-1}),
K_{dc} Specific death rate of a methanogens (d^{-1}),
K_s A constant represents Monod half-velocity for acidogens (Kg BVS/ m^3),
K_{sc} A constant represents Monod half-velocity for methanogens (Kg BVS/ m^3),
Sbvs Concentration of BVS in the AD digester (Kg BVS/ m^3),
$Sbvs_{in}$ Concentration of BVS in the feed substrate (Kg BVS/ m^3),
Svfa Concentration of total VFA in the AD digester (Kg VFA/ m^3),
$Svfa_{in}$ Concentration of total VFA in the feed substrate (Kg VFA/ m^3),
T_{reac} Digester temperature (°C),
V Effective digester volume (m^3),
VFA Volatile Fatty Acids
X_{acid} Concentration of acidogens (Kg organism/ m^3),
X_{meth} Concentration of methanogens (Kg organism/ m^3),
μ Growth rate of acidogens (d^{-1}),
μ_c Growth rate of methanogens (d^{-1}),
$\mu_m(T_{reac})$ Maximum growth rate for acidogens (d^{-1}),
$\mu_{mc}(T_{reac})$ Maximum growth rate for methanogens (d^{-1}).

INTRODUCTION

Kitchen wastes (KW) is a typical municipal organic waste. They are characterized by high organic content, high relative humidity, and rich nutrition. If these wastes are properly treated, they may cause numerous environmental problems especially greenhouse gases emission. On other hand, KW can play an important role in renewable energy production (including biodiesel, and biogas) and in environmental sustainability. Nowadays, it is essential for scientific researchers to explore and design appropriate models for optimizing the fermentation process and accelerating renewable energy development from organic waste. From the microbiological point of view, Anaerobic Digestion (AD) is generally composed of four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Manjusha et al., 2016). During these steps, the hydrogen and acetic acid are converted to methane gas and carbon dioxide. This conversion is done by methanogens which are strict anaerobes bacteria. In the literature, several mathematical models are introduced to represent these phenomena but they are often very complex and cannot completely represent the physic-chemical reactions of the AD processes.

Until now, biogas digester based on kitchen waste is limited in developing countries due to the absence of appropriate treatment systems. Digester design and operational criteria selection depend on substrate characteristics and cost. However, each mode of operation always has its own advantages and disadvantages. The increased need of biogas digester based on kitchen waste has improved the technical efforts in reducing biogas plants cost and optimizing their process operation. This process can be done through well-organized mathematical modeling of the anaerobic process considering different factors affecting the AD processes (Manjusha *et al*., 2016).

The purpose of this study is to develop mathematical modeling of AD of kitchen waste and optimize the environmental conditions such as pH, Volatile Fatty Acid (VFA), temperature for increasing the biogas production in shorter retention time. The level of these factors must be in correct proportion in order to keep the production of biogas in a particular level.

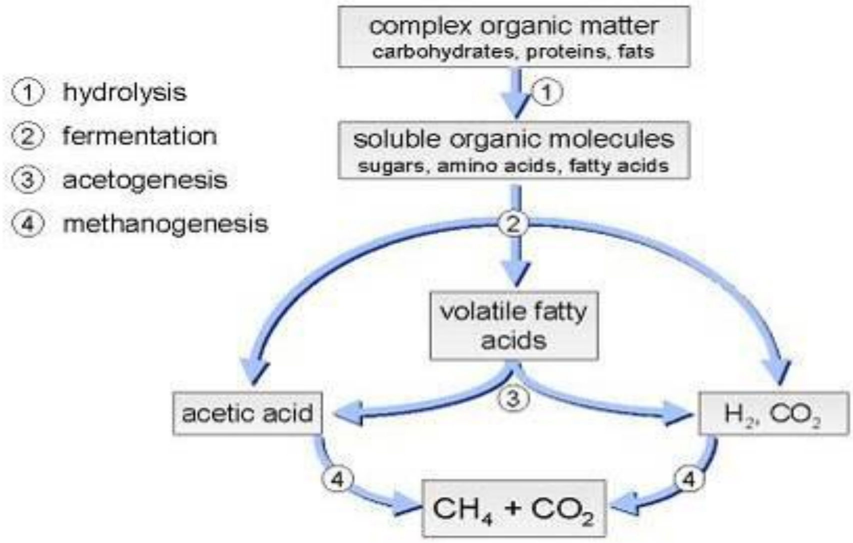
There are several varieties of researches undergoing in the field of waste treatment. The main aim of these researches is to analyze the parameters that will affect the production of biogas.

Many researches have been dedicated to discussing different aspects of modeling and simulation of small-scale biogas digester based on kitchen waste. Fedailaine *et al*., 2015 presented a mathematical model of biokinetics of AD based on mass balances on biomass, the organic substrate, and biogas. The model was simulated on Matlab using experimental data from the literature. The sensitivity of the model to the process parameters was studied by varying the initial concentration of the biomass and the amount of the organic substrate. Rathnasiri 2016 investigated the impact of recycling sludge and stability of pilot scale AD plant treating food waste. AD model No.1 (ADM1) was applied for modeling and simulation of continuous stirred tank anaerobic digester including recycling and was implemented in Aqua-Sim simulator. The paper proved that by increasing biomass recycling, the biogas production rate increases also. Whereas recycling of biomass not greatly affected by variations of pH inside the reactor. Gen, *et al*., 2015 presented a kinetic model of anaerobic hydrolysis of solid wastes, including disintegration processes. An ADM1-based anaerobic co-digestion model was presented and the kinetic parameters of the model were calibrated from batch digester experiments. The results proved the ability of the model to test the feasibility of different mixes of residues and to develop control strategies to optimize the blends in order to enhance the performance of the digesters. Manjusha *et al*., 2015 presented mathematical modeling and simulation of AD of solid waste. A modified version of ADM1 model was proposed to model and simulate AD of batch study. The model was implemented in Matlab and was used to find out how the factors such as pH and VFA affect the daily biogas production. Haugen *et al*., 2012 presented a dynamic model of an AD bioreactor using dairy manure is adapted to a real reactor using steady-state and dynamic operational data. The model for reactor temperature was adapted and used to find optimal operating conditions for an experimental reactor. Pathmasiri *et al*., 2013 proposed a simple dynamic model including four differential equations based on Hill's model for biogas production with a number of modifications. The model was used to simulate the production of methane gas in an anaerobic digester. The model was simulated using different simulators and the results were compared. Saeed *et al*., 2018 developed a proposed model for simulating a biogas fueled power plant to supply a rural farm with sufficient electricity considering both chemical and physical behaviors of the biogas production process. The reactor was fed with animal manure of the farm. The model was implemented using Matlab/Simulink program and tested under different operating conditions.

The rest of this paper is organized as follows. Section 2 describes the AD process including the four chemical stages; hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Section 3 presents the criteria and steps of designing a small-scale biogas digester. Section 4 presents the steps of Simulink modeling of an anaerobic digester, whereas section 5 illustrates and analyzes the simulation results. Finally, section 6 concludes the paper.

ANAEROBIC DIGESTION PROCESS

AD is a biochemical conversion process that converts organic materials by a consortium of microorganisms, typically in the absence of oxygen, to a mixture of methane and carbon dioxide. The conversion of organic material to CH4 involves a close relationship between four types of bacterial populations with the dynamic balance between the production and utilization of the intermediate products being critical to the overall success of the fermentation. While the VFAs are essential substrates for the reactions producing CH4, they are toxic to the bacteria when present at elevated levels. Toxicity results in reducing the methane productivity and eventually in digester failure. The actual methane content depends on the extent of CO2 dissolution in the digesting slurry (Manjusha *et al*., 2016). During these stages, microorganisms convert the hydrogen and acetic acid to methane gas and carbon dioxide. The anaerobic process microbiology consists of four steps as shown in Fig. 1. A brief description of each step will be presented in the following subsections.



Figure(1): Steps of the anaerobic process microbiology (Manjusha *et al*., 2016)

1) Hydrolysis: Hydrolysis is an enzyme-mediated conversion of complex organic compounds (carbohydrates, proteins, and lipids) to simple organics (sugar, amino acids, and peptides). This stage is very important because large organic molecules are simply too large to be directly absorbed and used by microorganisms as a substrate source. The biodegradation is accomplished by certain microorganisms which secrete different types of enzymes, called extracellular enzymes, Theses enzymes break the large, complex, and insoluble organics into small molecules that can be transported into microbial cells and metabolized and are used as a source of energy and nutrition (Adekunle *et al*., 2015). The rate of decomposition during this stage depends greatly on the nature of the substrate. The transformation of cellulose and hemicellulose generally takes place more slowly than the decomposition of proteins.

2) Acidogenesis: Acidogenesis is the process in which bacterial fermentation results in the formation of volatile acids. During this stage, the hydrogen-producing acetogens convert the volatile acids (longer than two carbons) to acetate and hydrogen. These microorganisms are related and can tolerate a wide range of environmental conditions. This process may be divided into two types: hydrogenation and dehydrogenation. The basic pathway of transformations passes through acetates, CO_2, and H_2, whereas other acidogenesis products play an insignificant role. Under standard conditions, the presence of hydrogen in solution inhibits oxidation, so that hydrogen bacteria are required to endure the conversion of all acids (Ali *et al.*, 2014).

3) Acetogenesis: The simple molecules from acidogenesis are further digested by bacteria called acetogens to produce CO2, hydrogen and acetic acid. Acid forming stage comprises two reactions, fermentation, and acetogenesis reactions. During the fermentation, the soluble organic products of the hydrolysis are transformed into simple organic compounds, mostly volatile (short chain) fatty acids such as propionic, formic, butyric, valericetc, ketones and alcohols. The acetogenesis is completed through carbohydrate fermentation and results in acetate, CO_2 and H_2, compounds that can be utilized by the methanogens. The presence of hydrogen is of critical importance in acetogenesis of compounds such as propionic & butyric acid. These reactions can only proceed if the concentration of H_2 is very low (Weinrich *et al.*, 2015). Thus, the presence of hydrogen scavenging bacteria is essential to ensure the thermodynamic feasibility of this reaction.

4) **Methanogenesis:** Finally, methanogens convert the acetate and hydrogen to methane and carbon dioxide, by bacteria called methanogens. The main route is the fermentation of the major product of the acid-forming phase, acetic acid, to methane and carbon dioxide. Two-thirds of the total produced methane is derived by converting the acetic acid or by fermentation of the alcohol formed. Whereas the other one third is a result of the reduction of carbon dioxide by hydrogen. The reaction that takes place in the process of CH_4 production is called Methanation and can be expressed by the following equations (Patsanza *et al*., 2015):

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (1)$$

$$\textit{Acetic acid} \rightarrow \textit{Methane} + \textit{Carbon dioxide}$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (2)$$

$$\textit{Ethanol} + \textit{Carbon dioxide} \rightarrow \textit{Methane} + \textit{Acetic acid}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H2O \quad (3)$$

$$\textit{Carbon dioxide} + \textit{hydrogen} \rightarrow \textit{Methane} + \textit{Water}$$

The above equations show that many products, by-products, and intermediate products are produced in the process of digestion of inputs in an anaerobic condition before the final product CH_4 is produced (Patsanza *et al*., 2015).

DESIGN of A SMALL-SCALE BIOGAS DIGESTER

The Procedure of the digester design and implementation can be summarized as:

1. Identify relevant criteria for designing an anaerobic digester.
2. Determine the feasibility of installing a digester with the intent to provide the required cooking heat of an Egyptian house
3. Develop designs for a bio-digester design based on the agreed criteria.

1) Design Criteria for Anaerobic Digester

- Select anaerobic sludge digestion for stabilization of organic solids. Single stage digestion is used as it has a simple design suitable for kitchens usage.
- Total volatile solids loading to the digester shall not exceed 2.5 VS kg. day/m3 under extreme high loading condition.
- The solids retention time at extreme high-flow condition shall not be less than 10 days (Shi *et al*., 2014).
- The digester mixing is achieved by internal gas mixing.
- The digester heating is achieved by recirculation of sludge through an external heat exchanger. The sludge recirculation system is designed to provide digester mixing.
- Floating digester cover is provided for gas collection.
- The digester design includes supernatant withdrawal system, sight glass, sampler, manhole, …. etc.
- The appropriate arrangement is provided to break the scum that may form on the sludge surface.

2) Digester Size: The small-scale family sized kitchen waste digester is designed on the assumption that the average Egyptian family is 5 individuals (Egypt Demographics Profile 2018), and the daily average of kitchen wastes (vegetables and fruits) per capita is 80 g/day (Al-Sadi 2010). This means that the waste produced by an average Egyptian house is about 0.4 kg/day or 12 kg/month.

The gas production rate (G) from AD can be computed as (Deublin *et al*., 2008):

$$\mathbf{G = W * \eta_y} \quad \mathbf{(4)}$$

Where, G is the gas production rate from the AD in m3, ηy is the biogas yield factor of the feed material in m3/kg, and W is the weight of the feed material in a kilogram.

For kitchen wastes, the biogas yield factor is taken as 0.3 m3/kg (Agrahari *et al*., 2016). So, for the average Egyptian house the gas production rate will be = 0.4 * 0.3 = 0.12 m3/day, which can be taken as a guide in designing the kitchen waste-based biogas digester.

A) Digester volume: A continuous feeding system is used, then it is essential to ensure that the digester is large enough to contain all the material that will be fed through in a whole digestion cycle.

The total digester volume (V_t) is a summation of the theoretical digester volume (V_m), inoculum feeding volume (V_{inc}) and storage and collection volume (V_g).

$$V_t = V_m + V_{inc} + V_g \qquad (5)$$

Each of these volumes can be computed as follow.

- **Theoretical digester volume:** The size of an anaerobic digester is a function of two main factors including both retention time (RT) and daily feedstock (FD). RT is the theoretical time that a particle or volume of liquid waste added to a digester would remain in the digester whereas FD is the amount of daily feedstock material added to the digester. The amount of feedstock material, in this case, is a combination of the kitchen waste collected mixed with water (Sendaaza 2018). A continuous flow digester is most ideal for the kitchen waste so as to minimize digester volume. This is because of the shorter (RTs) in continuous flow digesters compared to batch digesters and therefore relatively smaller digester volume requirements (Ogur *et al*., 2013).

In case that the feedstock material is mixed with water in a ratio of 1:2 (Sendaaza 2018), the total feedstock flow rate (FR) can be computed as:

$$FR = (1*0.4) + (2*0.4) = 1.2 \text{ kg/day} \approx 1.2 \text{ L/day} \approx 0.0012 \text{ m}^3\text{/day} \quad (6)$$

The volume of the digester (theoretical) can be calculated using the following equation:

$$V_m = \frac{FR * RT}{SF} \quad (7)$$

Where:

V_m : theoretical volume of the digester, m^3

RT: retention time, day

FR: total feedstock flow rate, m^3/day

SF: safety factor

Different researchers have established varying RT values for optimum methane and biogas yield from kitchen wastes (Ogur *et al*., 2013), Agrahari *et al*., 2016). For most dry feedstock (influent solids content), the RT ranges between 14 and 30 days and for wet (influent solids content) it can be as low as 3 days (Agrahari *et al*., 2016).

In this study, RT is taken as 30 days for the specified kitchen wastes and the safety factor is taken as 0.9, whereas the daily FR is taken as 0.0012 m3/day as computed in (6). Substituting at (7), the theoretical volume of digester will be 0.٠4 m3.

- **Inoculum feeding volume:** For enhancing the biogas production in the AD process, it is important to use some types of feed as starters which are called as inoculum feed. The inoculum feed is a substrate with a low concentration of biodegradable organic matter but with a wealth of various essential bacteria required for the AD process. Cow dung and output fertilizer from the digester can be used as Inoculum feeding (Pathmasiri *et al*., 2013). Usually, the inoculum feeding volume is taken as 25% of the theoretical digester volume.

Then summation of theoretical digester volume and inoculum feeding volume is called the active digester volume (V_{act}), i.e. $V_{act} = 0.05\ m^3$

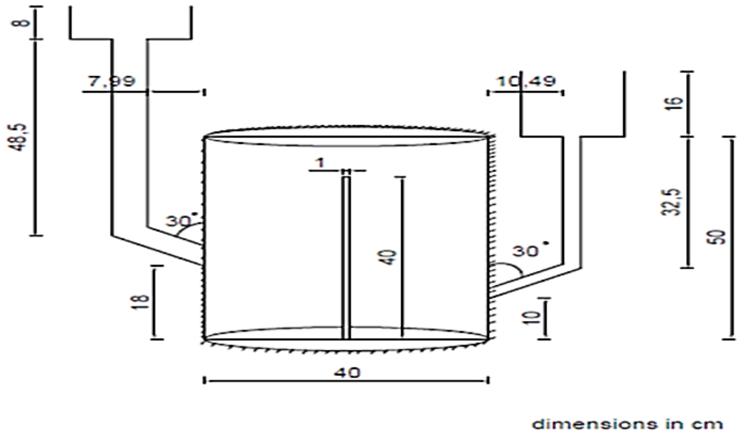
- **Storage and collection Volume :** It is important to let about 20-30% of the active digester volume as free space for the biogas extension (storage and collection) **(Ogur et al., 2013)**. In this study, this volume is taken as 20% of V_{act}, i.e. $V_g = 0.01\ m^3$.

Finally, the total digester unit volume, V_t is obtained by substituting at (4). Therefore, $V_t = 0.06\ m^3$ or 60 liters. This size will be used in sections 4 and 5 for modeling and the simulation analysis.

B) Digester dimensions: The most important dimensions of the digester are its height (H) and diameter (D). The ratio between H and D is usually taken as 1.25:1 (Pathmasiri *et al*., 2013). Therefore, H= 1.25 D. The height and diameter can be calculated by solving the mathematical formula of cylinder volume.

$$V_t = \frac{\pi\ H\ D^2}{4} = \frac{\pi\ (1.25\ D)\ D^2}{4} \quad (8)$$

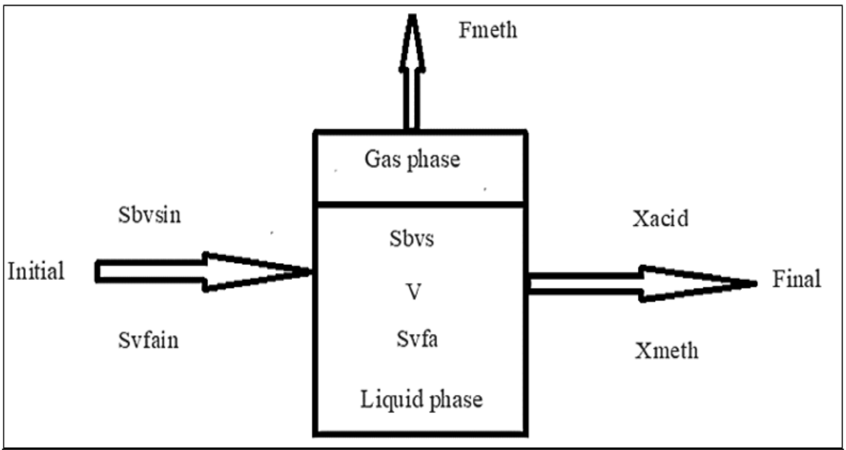
For Vt is 0.06 m3, the diameter and height are found as D= 0.4 m and H= 0.5 m. The length and breadth of partition aluminum in the half of cylinder (m) can be deduced for the proposed model as length = 40 cm, breadth = 40 cm, and thickness = 1 cm as explained by Fig. 2.



Figure(2): Sketch of the of digester proposed anaerobic digester

4. Modeling of an Anaerobic Digester: A simplified dynamic model is developed to completely represent the physic-chemical reactions of the AD processes and hence identify the best parameters for the operation of the AD.

Modeling of a bioprocess is a virtual representation of biological, physical and chemical processes taking place in the digester model. From that model and numerical calculation software, it is possible to simulate, quickly and cheaply, different treatments scenarios taking into account and evaluating the impact of input variations (quantities and qualities) and operation. The model is based on mass balances on the substrate, biomass and methane production in order to predict the observed behavior of anaerobic digestion and better understand the internal phenomena that occur within the digester. The model is described by three phenomena, substrate consumption growth and bacterial decay, methane production and inhibition of bacterial activity as explained by Fig. 3.



$Sbvs_{in}$: Concentration of biodegradable volatile solids (BVS) in the digester feed (gBVS/L),
$Svfa_{in}$: Concentration of total volatile fatty acids (VFA) in the digester feed (gVFA/L),
Sbvs: Concentration of biodegradable volatile solids (BVS) in the digester (gBVS/L),
Svfa: Concentration of total volatile fatty acids (VFA) in the digester (gVFA/L),
V: Effective digester volume (L),
X_{acid}: Concentration of acidogens (g organism/L),
X_{meth}: Concentration of methanogens (g organism/L),
F_{meth}: Methane gas flow (L CH_4/d)

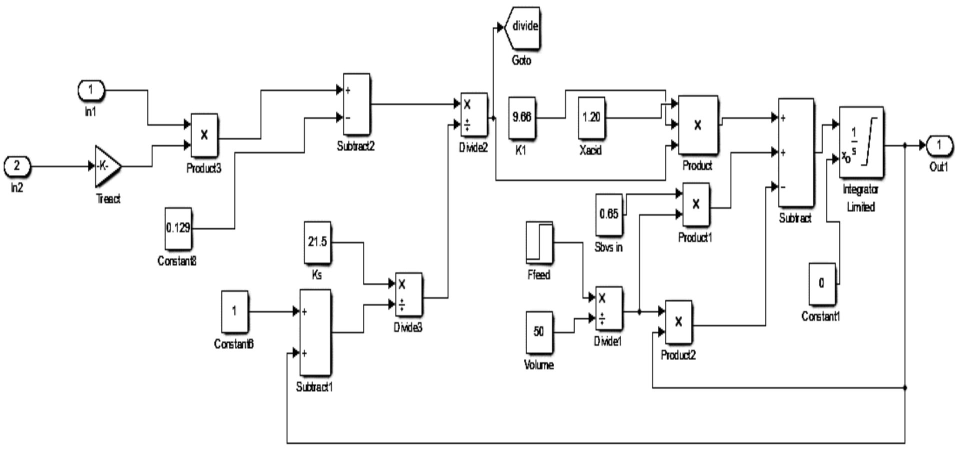
Figure(3): Operation of an anaerobic digester

Matlab/Simulink are widely used as simulation tool across various engineering and science disciplines. Matlab/Simulink enables to incorporate Matlab algorithms into models and export simulation results to Matlab for further analysis. The objective of this study is to simulate the behavior of AD using Matlab/Simulink to identify the best parameters for the operation of the proposed model. The dynamic behavior of the four aforementioned stages can be characterized by the following set of differential equations in a constant volume AD bioreactor (Gen *et al*., 2015).

- **<u>The hydrolysis process</u>** depends on the type of feed material, the feed flow rate, effective digester volume, and digester temperature. Mass balance of biodegradable volatile solids which is in terms of soluble can be represented by the following equation:

$$d(Sbvs)/dt = (Sbvs_{in} - Sbvs) \cdot (F_{feed}/V) + \mu \cdot k_1 \cdot X_{acid} \qquad (9)$$

The hydrolysis process is represented by a Simulink model shown in Fig.4.

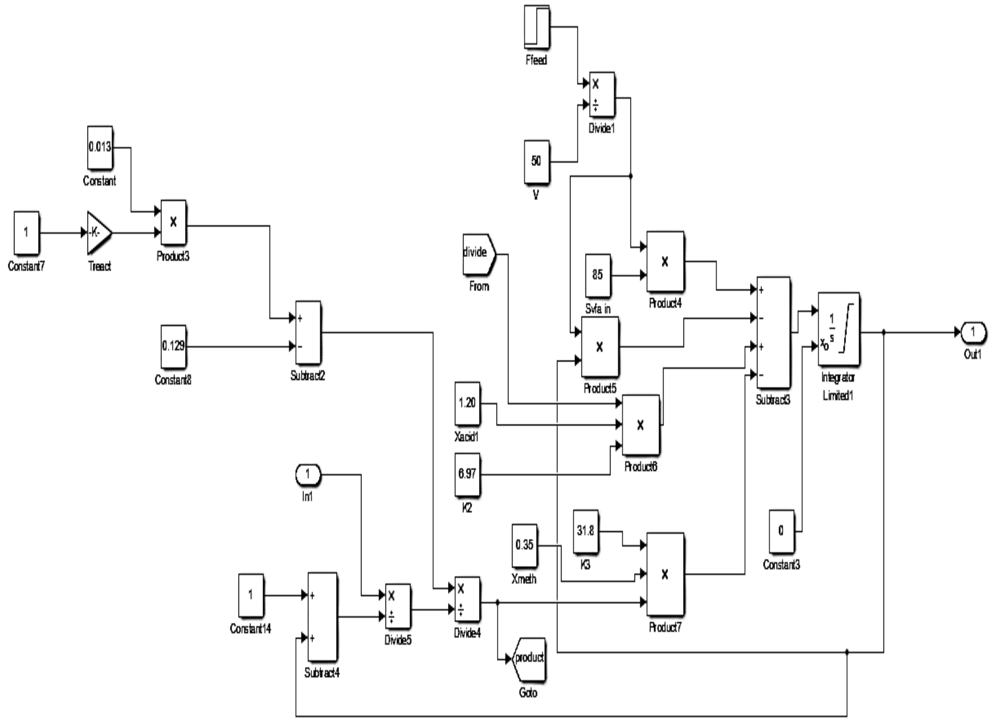


Figure(4): Simulink model of the hydrolysis process

- **<u>The acidogenesis process</u>** depends on the concentration of total VFAs in the digester (type of feed material), the feed flow rate, effective digester volume, and digester temperature. The mass balance of total VFA can be represented by the following equation (Gen *et al*., 2015):

$$d(Svfa)/dt = (Svfa_{in} - Svfa) \cdot (F_{feeed}/V) + \mu \cdot k_2 \cdot Xacid - \mu_c \cdot k_3 \cdot X_{meth} \quad (10)$$

The acidogenesis is represented by a Simulink model as shown in Fig. 5.



Figure(5): Simulink model of acidogenesis process

- **The acetogenesis process** depends on both concentrations of acidogens, type of feed material, feed flow rate, effective digester volume, and digester temperature. The mass balance of acidogens is represented as (Ernesto *et al*., 2015 , Haugen *et al*., 2012):

$$d(X_{acid})/dt = [\mu - K_d - (F_{feed}/b)/V] \cdot X_{acid} \quad (11)$$

Figure 6 expresses the Simulink model that represents the acetogenesis process.

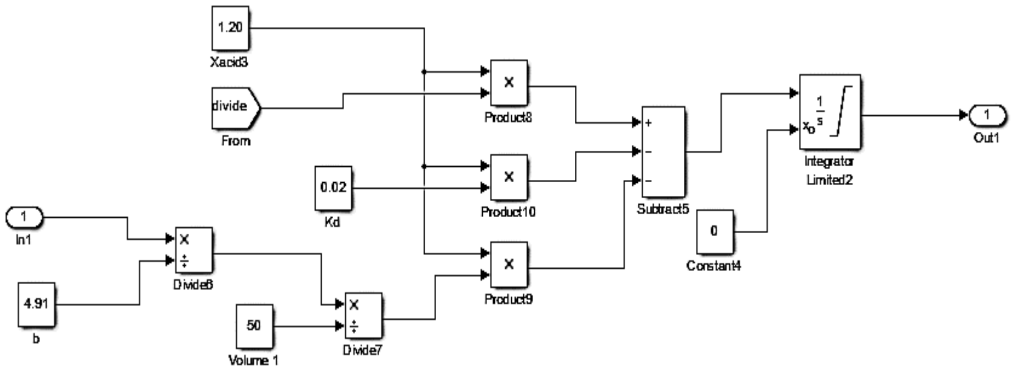


Figure (6): Simulink model of acetogenesis process

- **Finally, the methanogenesis process** depends on retention time, the feed flow rate, effective digester volume, and digester temperature. The Mass balance of methanogens is represented as (Ernesto *et al*., 2015 , Haugen *et al*., 2012):

$$d(X_{meth})/dt = [\mu_c - K_{dc} - (F_{feed}/b)/V] \cdot X_{meth} \qquad (12)$$

Figure 7 expresses the Simulink model that represents the methanogenesis process.

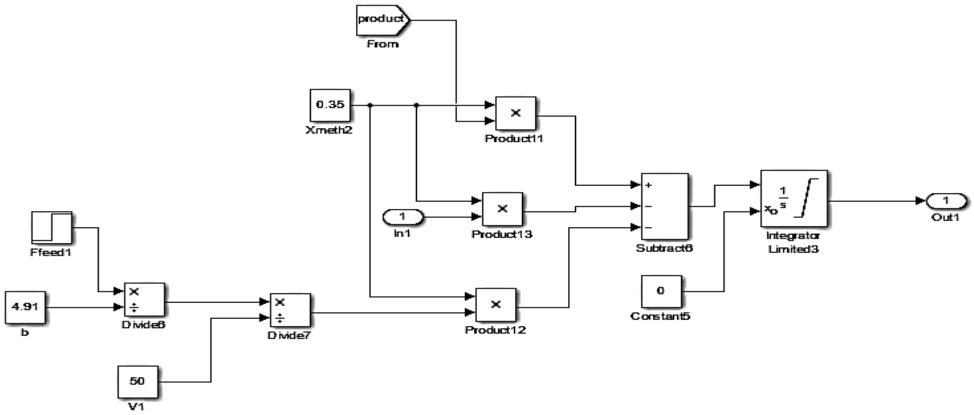


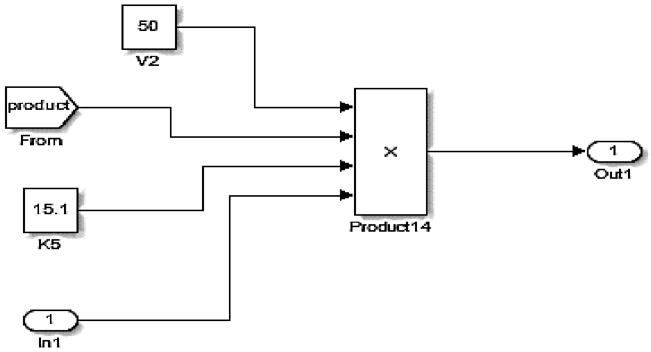
Figure (7): Simulink model of methanogenesis process

To completely represent the physic-chemical reactions of the AD processes the following equation are required:

Methane gas flow rate: The amount of methane output from the digester is determined from the following equation (Gen *et al.*, 2015).

$$F_{meth} = V \cdot \mu_c \cdot k_5 \cdot X_{meth} \qquad (13)$$

Figure 8 expresses the Simulink model that represents the methane gas flow rate process.



Figure(8): Simulink model of methane gas flow rate process

- **<u>Reaction rates with Monod kinetics:</u>** The growth rate of acidogens, μ and the growth rate of methanogens, μc can be defined as (Gen *et al.*, 2015):

$$\mu = \mu_m / (K_s/Sbvs + 1) \qquad (14)$$

$$\mu_c = \mu_{mc} / [(K_{sc}/Svfa) + 1] \qquad (15)$$

- **<u>Temperature dependency in reaction rates:</u>** The maximum growth rate for methanogens can be expressed as a function of the temperature dependence of reaction rates using the following empirical formula (Gen *et al.*, 2015):

For $20°C < T_{reac} < 60°C$:

$$\mu_m(T_{reac}) = \mu_{mc}\,(T_{reac}) = 0.013 \cdot T_{reac} - 0.129 \qquad (16)$$

The complete Simulink model represents the physic-chemical processes of an AD which are characterized by the aforementioned equations is explained by Fig. 9.

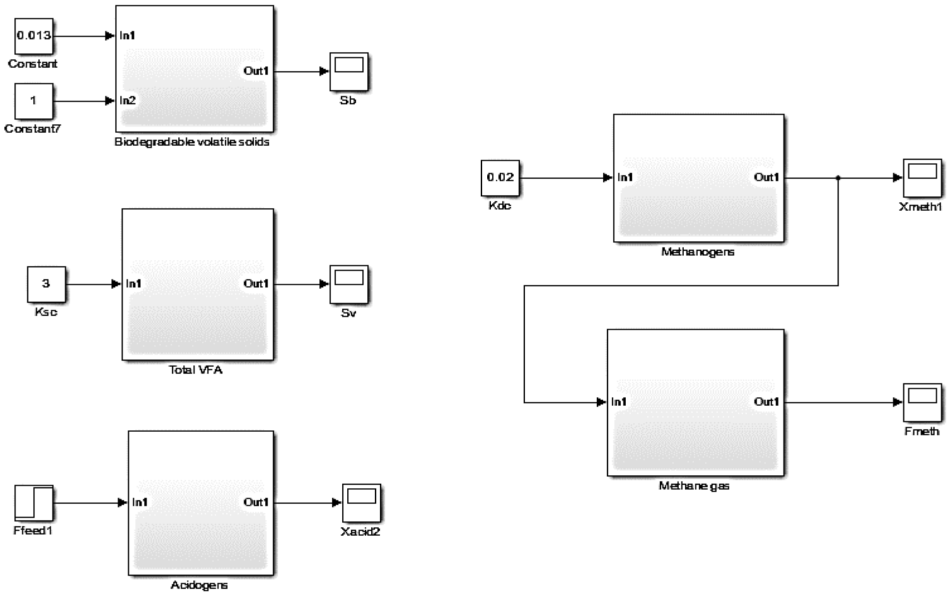


Figure (9): Simulink model of biogas digester

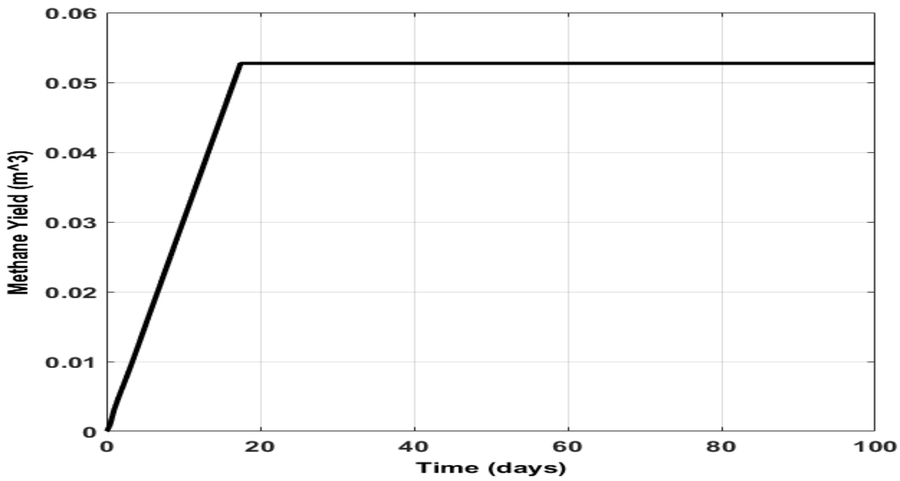
SIMULATION AND RESULTS

A simulation of a system is the operation of a model which represents the construction and the working of a system. Simulation of a system is done to both existing systems before any alterations are done or when a new system is set up to avoid any unforeseen effects, and to evaluate and optimize system performances over long periods of real-time (Husain 1998). A Simulink model for the proposed biogas digester is developed. The model consists of the previous stages of the AD process represented by the equations (8-15). In this model, different types of animal manures are fed to the AD as inputs. The proposed model is simulated to examine the impacts of different variables (the type of feed, temperature, digester size … etc.) on the output of the AD system. The parameters used for the simulation in this study are given in Table 1. The simulation is implemented under different conditions including the impact of anaerobic reaction time, the impact of digester temperature and the impact of feed type.

Table(1): Assumed known and estimated parameters of the proposed model (Husain 1998)

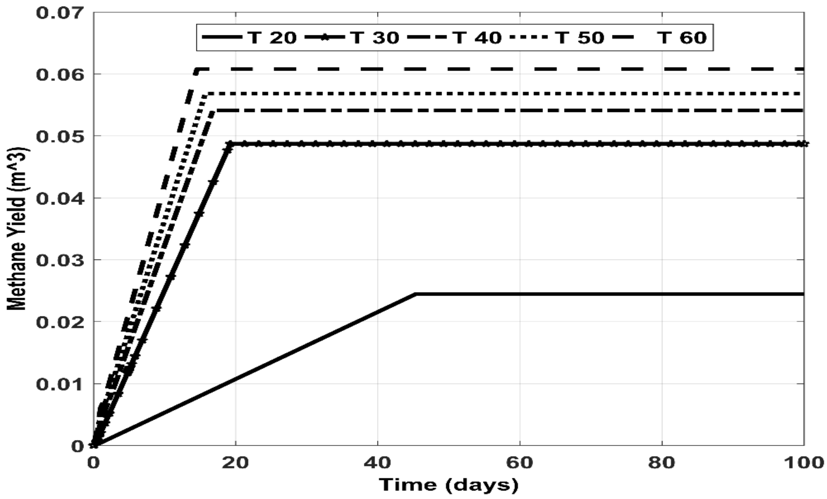
b = 4.91	(estimated)
Ks = 21.5	(estimated)
Ksc = 3	(assumed known)
Kd = 0.02	(assumed known)
Kdc = 0.02	(assumed known)
Yc = 0.0315	(assumed known)
Vact = ٥٠	(assumed known)
k1 = 9.66	(estimated)
k2 = 6.97	(estimated)
k3 = 31.8	(known/calculated)
k5 = 15.1	(estimated)
Xacid = 1.20	(estimated)
Xmeth = 0.35	(estimated)

1) **Impact of anaerobic reaction time:** In this case, the developed model is implemented to study the change of the cumulative methane production with the anaerobic reaction time. The digester is fed with diluted kitchen waste at a fed flow rate of 0.0015 m3/day. In this case, the digester temperature is maintained constant at 35º C as this is the best temperature of bacterial reaction in the AD process (Garcia-Gen *et al*., 2015). The results show that there is a gradual increase in methane production for about 18 days before it becomes constant as shown by Figure 10.



Figure(10): Change of cumulative methane production with anaerobic reaction time (digester temperature = 35º C)

2) Impact of digester temperature: According to (Garcia-Gen *et al*., 2015), the suitable temperatures for the fermentation process range from 20 ºC to 60 ºC. In case that digester temperature exceeds than 60 ºC, the fermentation process will not complete, because there will be severe reduction in methanogenesis (bacteria) concentration. The simulation is applied for a time of 100 days, daily feed step of 1.5 kg/day, and different temperature values (20, 30, 40, 50, 60). The graphs shown in Fig. 11, illustrate that increasing the digester temperature results in an increase in both volume and production period of methane production. For a digester temperature of 30 ºC the output methane becomes constant after 20 days.



Figure(11): Variation of methane production with digester temperature

The impact of digester temperature change on methane production is shown in Table 2. However, according to economic consideration, it may be better to produce the methane at the ambient temperature for a kitchen waste digester. A comparative analysis between the cost of the excess in the produced biogas and the costs required for raising the temperature of the digester is preferred.

Table(2): Impact of digester temperature change on methane production

Temperature, ºC	**20**	**30**	**40**	**50**	**60**
Time, day	45	19.26	16.81	15.74	14.56
Volume of methane, m3	0.0244	0.0487	0.0541	0.0568	0.0608

3) **Impact of input feed type:** There are several factors affecting the input feed type. The main factor affecting the feed type is the concentration of biodegradable, kitchen wastes (fruits and vegetable wastes) are the best substrate to produce biogas. This research is conducted to study about the best substrate composition that can be used in producing total solid biogas

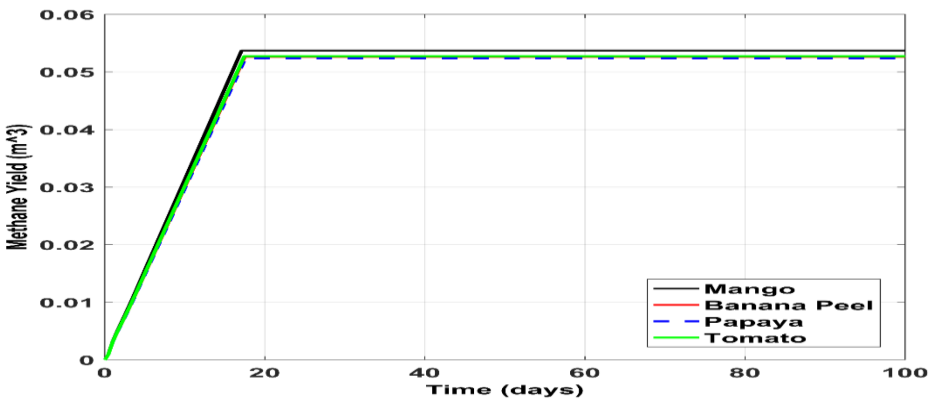
per gram every day, large amounts of solid wastes including fruits and vegetables discarded during selection, and those from processes such as peeling or coring. These typically have a high nutritional value. Biogas production from fruits and vegetable wastes like mango, banana peel, papaya, and tomato is starting from creating continuous digester instrument which will be used. Table 3 shows the concentration of biodegradable and VFA of kitchen wastes (kg/m3) for different feed types of kitchen wastes (Deressa *et al*., 2015).

Table(3): Concentration of biodegradable and VFA of kitchen wastes (kg/m3). (Budiyono *et al*., 2018, Deressa *et al*., 2015)

Types of feed waste	Concentration of biodegradable (kg/m3)	Concentration of VFA (kg/m3)
Mango	0.55	94.8
Banana peel	0.4	92.6
Papaya	0.4	92.12
Tomato	0.5	92.85

The proposed model is simulated using different types of feed such as mango, banana peel, papaya, and tomato, and the results are shown in Fig. 12. The results explain that there is a considerable change in both methane production period and volume for different feed types. For example, it takes a longer period for papaya and tomato to reach a constant volume compared to both mango and banana peel. The volume of produced methane is increased when using mango due to its higher biodegradable concentration. To simplify the simulations, the digester temperature is set to a time constant (100 days) with a daily feed step (1.5 kg/day) and a constant temperature of 35º C.

(Deressa *et al*., 2015). Table 4 shows the impact of input feed type change on methane production.



Figure(12): Change of simulated methane gas flow with different input feed type at (digester temperature = 35º C)

Table(4): Impact of input feed type change on methane production

Types of waste feed	Temperature, ºC	Time, day	Volume of methane, m3
Mango	35	18	0.05369
Banana peel	35	17	0.05261
Papaya	35	19	0.05237
Tomato	35	19	0.05273

CONCLUSIONS

Biogas from biodegradable waste technology readily accepts highly digestible organic kitchen wastes. It can be used in rural areas and its residues can be used as a fertilizer. This paper presents a proposed design, modeling and simulation of small-scale biogas digester based on kitchen waste (fruits and vegetables). A small-scale family size kitchen digester is designed to utilize the kitchen waste of an average Egyptian family to supply the family with its requirement of cooking heat. A mathematical model of a small-scale biogas digester based on kitchen waste was developed. The digester mathematical model was represented by a set of differential equations that characterize the dynamic behavior of the four chemical stages in the digester.

The model was built and simulated in Matlab/Simulink environment. The proposed model can be used for studying, monitoring, and optimizing a kitchen waste digester. The impact of time, feed type and digester temperature on the digester output were examined and the results were analyzed. The volume of methane delivered from this model depended on the digester volume, digester temperature, and the input feed type.

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نمذجة ومحاكاة لهاضم حيوي لمخلفات المطبخ على نطاق صغير

[٣]

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المستخلص

الهضم اللاهوائي هى تكنولوجيا لانتاج الغاز الحيوى من المخلفات العضوية ويمكن تمثيله بمجموعة من العمليات البيولوجية حيث يتم تحويل المخلفات العضوية عن طريق الكائنات الحية الدقيقة لإنتاج مزيج من الميثان وثاني أكسيد الكربون (الغاز الحيوي) في غياب الأكسجين. ويمكن استخدام الغاز الحيوي فى تلبية متطلبات الطاقة في العديد من الأماكن، فغاز الميثان هو أحد غازات الدفيئة القوية للغاية والتي يمكن استخدامها لتوليد الحرارة والكهرباء وبالأخص في المناطق الريفية. من ناحية أخرى يمكن استخدام مخلفات المطبخ لإنتاج الغاز الحيوي نظرًا لقدرتها العالية على التحلل الحيوي والتي يمكن أن تقلل من الاعتماد على الوقود الأحفوري.

تقدم هذه الورقة تصميمًا ومحاكاة لمنظومة الهضم اللاهوائي لمخلفات المطبخ. تم تصميم العمليات البيولوجية للهاضم المقترح بحيث تعطى تمثيلا كاملا للتفاعلات الفيزيائية والكيميائية إعتمادًا على جوانب عديدة مثل النشاط الميكروبي وتحلل المادة الأولية ودرجة الحرارة. وتم تصميم الهاضم المقترح لمخلفات المطبخ ذات الحجم الصغير للاستفادة من مخلفات المطبخ لعائلة مصرية متوسطة، حيث يُستخدم الغاز الحيوى الناتج لتوفير الحرارة المطلوبة للطهي في المنزل. تم محاكاة النموذج المقترح باستخدام برنامج الماتلاب/سيميولنك في ظل ظروف مختلفة لدراسة تأثير كل من مدة التفاعل ودرجة حرارة الهاضم ونوع التغذية على إنتاج الغاز الحيوي، وتحدد نتائج محاكاة النموذج أفضل القيم لتصميم و تشغيل هاضم حيوي لمخلفات المطبخ على نطاق صغير. وقد توصلت الدراسة إلى أن الحجم المناسب لهاضم حيوي لمخلفات مطبخ مصري لأسرة متوسطة هو ٠,٠٦ متر٣ ، وأبعاده هى 0.4 و 0.5 متر للقطر والارتفاع على الترتيب، وأن انتاج الميثان فى هذا الهاضم يتم من خلال زيادة تدريجية فى حجمه لنحو ١٨ يوم عند درجة حرارة 30 °C قبل أن يصبح الحجم ثابتا عند ٠,٠٥٣٦٩ متر٣ / يوم .