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Design and Process Simulation of a Small Scale Waste-To-Energy Bioreactor

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Abstract: Transformation of organic waste to energy is a complex process which involves hundreds of possible intermediate compounds and reactions. Simulation process can provide suitable assessment of a bioconversion system before its actual fabrication and commercialization. In addition, process simulation is a suitable tool for optimization of technical factors (e.g., bioreactor configuration and conversion units design) and economical factors (e.g., throughput, production cost, revenue and gross margin). In this study, biodegradation process of a small-scale anaerobic bioreactor was simulated using SuperPro Designer®. Process simulation flow sheet, materials registration and process reactions were conducted during model setup. Next, model validation was carried out by comparison between the outputs and actual data achieved during experimental phase. Results show the appreciable agreement between predicted and actual data due to appropriate process definition during simulation. Two different bioreactor configurations were investigated and efficiency and performance of each pattern was tested based on biogas production rate, methane content in biogas and biochemical and chemical oxygen demands (BOD and COD) removal efficiencies. Finally, economical analysis was performed in the model which indicates, biogas production from organic waste in a single small-scale bioreactor is a promising method for renewable energy generation.

Key words: Process simulation, biogas production, solid waste, energy

INTRODUCTION

For future world stability, investigations on alternative energy are significant. Renewable energy sources (mainly organic waste materials to energy) likely will become one of the most attractive substitutes in the near future (Kothari *et al*., 2010). Transformation of organic waste to energy is the product of anaerobic digestion. Anaerobic digestion is a biological process of converting separated biodegradable solid wastes into methane gas (Malakahmad *et al*., 2011). Methane is sourced from decomposition of organic material, such as cattle slurry, food scraps and sewage (Malakahmad *et al*., 2008). It has similar thermal characteristics to natural gas and, once the quality is upgraded it can be injected into the gas grid. Methane gas can be utilized as a renewable energy source to supply heat and electricity. In addition, waste-to-energy transformation is been recognized as an important and vital element in any Integrated Solid Waste Management (ISWM) plan (Malakahmad *et al*., 2010).

In general, anaerobic digestion is considered to occur in (1) liquefaction, (2) acid formation and (3) methane formation stages. Organic wastes consist of complex organic polymers such as proteins, fats, carbohydrates, cellulose, lignin, etc., some of which are in the form of insoluble solids. In liquefaction stage this organic polymers are broken down by extracellular enzymes produced by hydrolytic bacteria, and dissolves in water. The monomeric compounds released by the hydrolytic break down due to bacterial action in liquefaction stage are further converted to acetate, H_2 and CO_2 by the acetogenic bacteria in acid forming stage. The products of the acid forming stage are finally converted to energy in form of CH_4 and other end products in the methane formation stage. Numerous of possible intermediate compounds and reactions are existed in anaerobic digestion of organic materials. Therefore, process design and simulation can be applied to control the overall process conditions and to investigate the optimum level of important factors such as temperature, moisture content, pressure, Organic Loading Rate (OLR), pH, etc.

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The best range of these important factors can be found by running the simulated process several times to achieve the best efficiency of system before its actual design, fabrication and commercialization.

End products can be utilized by process improvement and renovating manufacturing operation. Process simulation is an important tool in this venture (Zeinali *et al*., 2009). The benefits of simulation for bioprocess improvement, assessment and expand have been realized previously (Evans and Field, 1986; Cooney *et al*., 1988; Petrides, 1994). Basically, process development is shortened by application of process models and simulators. They allow comparison of process alternatives on a consistent basis so that a large number of ideas can be synthesized and analyzed interactively in a short time. In addition, study of occurrence interaction between upstream and downstream processes will be possible through an integrated simulation (Petrides *et al*., 2002; Thomas, 2003). They provide some tasks such as; represent the entire process on the computer, perform material and energy balances, estimate the size of equipment, estimate the cycle time of the process and perform cost analysis. SuperPro Designer® is Windows-based software which can be used to design and analyze unit operations for water and wastewater treatment, air pollution control and industrial applications. By combination of manufacturing and environmental operations in the SuperPro Designer®, the user is able to design and assess manufacturing of the product and decide on treatment methods, pollution prevention and waste minimization approaches, at the same time. Application of SuperPro Designer® has been reported for process simulation in production of polyhydroxyalkanoates (Akiyama *et al*., 2003), monitoring of biopharmaceutical facility (Toumi *et al*., 2010; Pedrites *et al*., 2011), fuel ethanol production (Kwiatkowski *et al*., 2006) and biodiesel production costs analysis (Haas *et al*., 2006).

The aim of this study is to design, simulate and optimize production of renewable energy from biodegradable waste in a laboratory scale bioreactor using SuperPro Designer®.

MATERIALS AND METHODS

Process details: The first step in building a simulation model is collection of information about the process. In this study, a laboratory-scale anaerobic baffled bioreactor shown in Fig. 1 with a total working volume of 75 L was studied for process design and simulation. An influent tank was used for mixing and feeding of the materials into the bioreactor. An effluent tank was utilized for collection

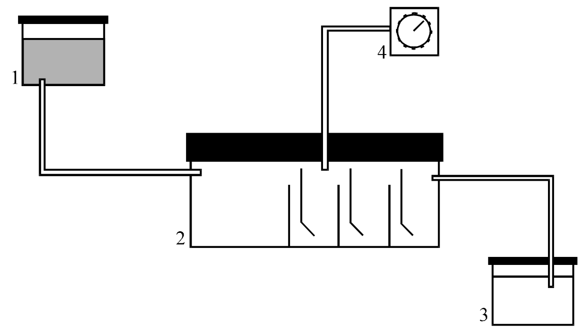

Fig. 1: Laboratory scale anaerobic bioreactor, 1: Influent tank, 2: Bioreactor, 3: Effluent tank, 4: Wet gas meter

of feedstock from the reactor. A gas collector was provided for collection, calculation and analysis on the amount of biogas. The dimension of the laboratory-scale treatment unit was 75, 42 cm height and 27 cm depth. The first compartment of a four-chamber unit was bigger while the three following compartments had identical volume.

Model setup: The model was built step-by-step and functionality of each part was checked. Then, registration of materials was carried out. Next, the flow diagram (Fig. 2) was developed by putting together the required unit procedures and joining them with material flow streams. Operations were then added to unit procedures and their operating conditions and performance parameters were specified. To enhance the best result from the software, the bioreactor, were divided into four anaerobic digesters in accordance to number of compartments is actual bioreactor. This is due to the fact that the bioreactor used in this study has four compartments and each of the compartments has a role as an anaerobic digester.

Registration of mixture and processes definition: Conceptual design of the bioconversion process was constructed using laboratory and technical data. Firstly, the raw materials which were kitchen waste, sewage sludge and water, were mixed in (P-1/MX-101) to achieve influent real characteristics.

Then, the influent proceeded into Anaerobic Digester (P-2/AD-101). The produced gas in each anaerobic digester was sent to a gas collector (P-6/MX-102) and the produced slurry in P-2/AD-101, P-3/AD-102 and P-4/AD-103 were used as influent for P-3/AD-102, P-4/AD-103 and, P-5/AD-104, respectively. Table 1 shows characteristics of the mixture.

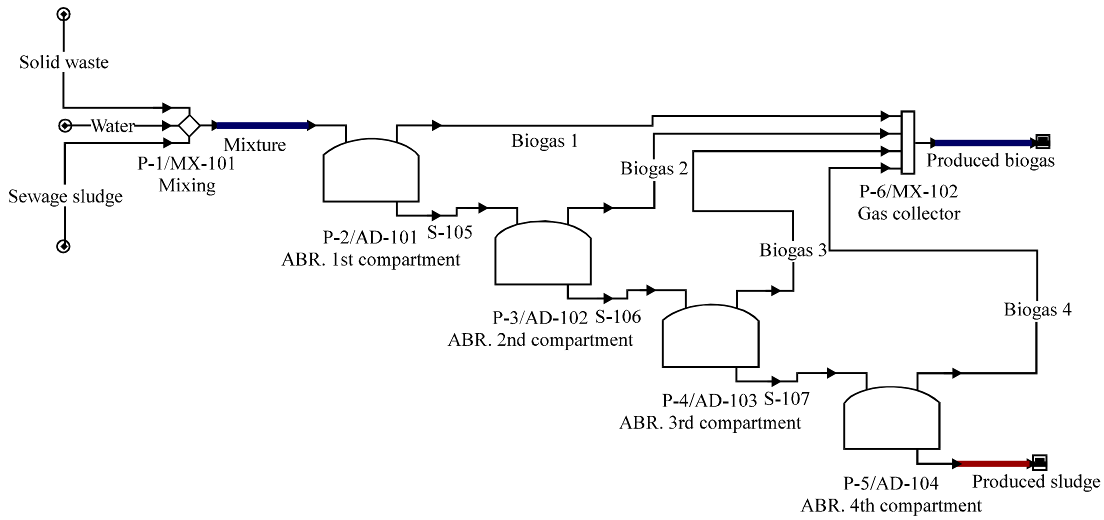

Fig. 2: Base case simulation flow sheet

Table 1: Characteristics of the mixture

Components	Concentration	Daily throughout
TOC	21357.9 mg C L^{-1}	8.4 g C/day
TP	253.1 mg P L^{-1}	0.1 g P/day
TKN	1442.8 mg N L^{-1}	0.6 g N/day
NH_3	1442.8 mg N L^{-1}	0.6 g N/day
COD	63502.8 mg O L^{-1}	25.0 g O/day
ThOD	63502.8 mg O L^{-1}	25.0 g O/day
BOD_u	52338.4 mg O L^{-1}	20.6 g O/day
BOD_5	32185.53 mg O L^{-1}	12.7 g O/day
TS	37967.3 mg solid L^{-1}	15.0 g solid/day
TSS	12655.8 mg solid L^{-1}	5.0 g solid/day
VSS	11390.2 mg solid L^{-1}	5.0 g solid/day
DVSS	11390.2 mg solid L^{-1}	10.0 g solid/day
TDS	25311.5 mg solid L^{-1}	10.0 g solid/day

The operation in P-2/AD-101 was about the degradation of organic polymers such as protein, fat, carbohydrate, cellulose and lignin by hydrolytic bacteria. The hydrolysis reaction in this stage was designed to convert fat into long-chain fatty acids, carbohydrate into simple sugars and protein into amino acids. The liquefaction of cellulose and other complex compounds to simple monomers can be the rate-limiting step in anaerobic digestion. Therefore, the unique modification of the bioreactor could solve this problem and hence, the digestion of these organic complexes was done in a short time. Thus, this reconfiguration was considered in simulations and volume of unit P-2/AD-101 was designed two times larger than other anaerobic digesters. Stream S-105 was included the simple soluble, organic components which were formed easily available to any acid producing bacteria.

The units P-3/AD-102 and P-4/AD-104 were responsible for degradation of monomeric components, which were produced in the first step (liquefaction). Volatile fatty acids which were produced as the end-products of liquefaction, transformed into short-chain alcohols (ethyl, propel and butyl alcohol) and short-chain acids (acetic, propionic and lactic acid). Carbon dioxide, ammonia, hydrogen sulfide and hydrogen gas which were also liberated during complex compounds catabolism, was included in the material that registered in units P-3/AD-102 and P-4/AD-104.

Finally, methane formation stage was designed in unit P-5/AD-105. The methanogenic bacteria use short-chain alcohols and acids and protein, carbon dioxide and hydrogen gas to produce methane. So, the balance between these materials happened in P-5/AD-105 and the produced methane was transferred to gas collector (P-6/MX-102) through gas collection lines. Figure 3 illustrates pathway leading to the production of methane and carbon dioxide from the anaerobic digestion of the organic fraction of organic waste (Tchobanoglous *et al*., 1993).

RESULTS AND DISCUSSION

Model validation: The computer model was designed and developed based on laboratory scale anaerobic bioreactor to estimate the biogas production rate, methane content in biogas and characteristics of effluent. Initially, Model outputs were compared with those achieved through experiments. After validation, users are able to change the model components and process parameters to evaluate the bioreactor performance. This will help to optimize all important conditions in bioreactor to attain best biogas production rate before fabrication and commercialization. The Operation Gantt Chart for the process is shown in Fig. 4.

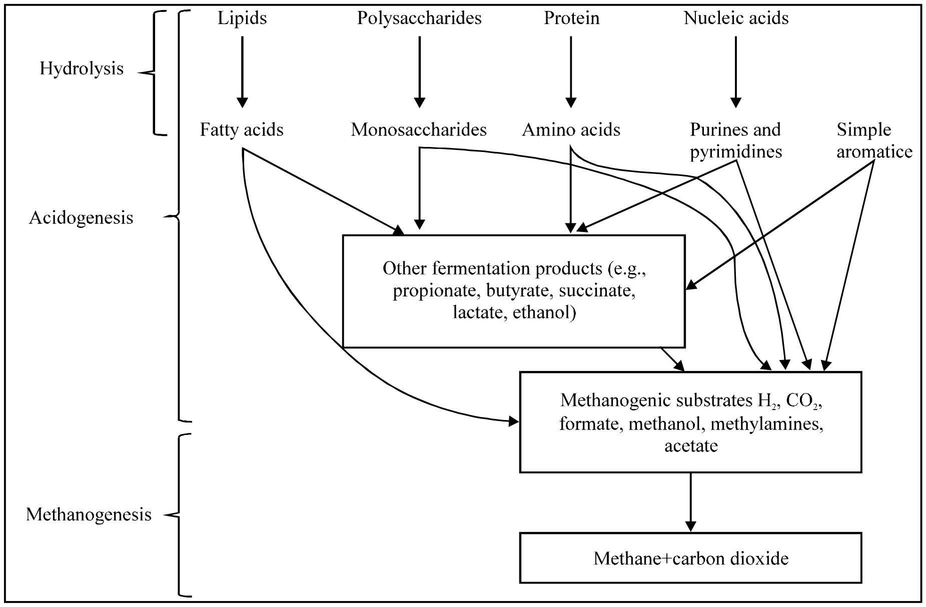

Fig. 3: Methane and carbon dioxide production path

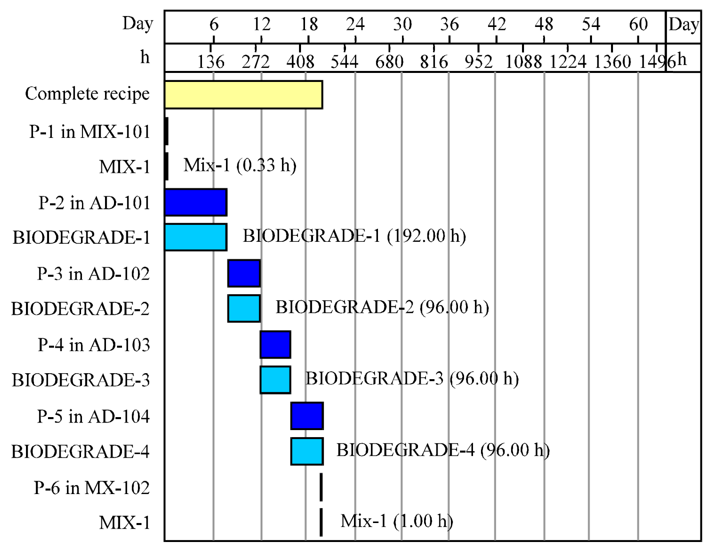

Fig. 4: Equipment occupancy chart in the zero-waste system

The process time for certain operations are dependent upon operations of other procedure. Hence, the duration of this slave operation is set to follow to the duration of the master operation using the Master-Slave Relationship function of Super Pro Designer.

Biogas production rate: The gas content of each digester was monitored in the model and the produced amounts were compared with experimental results achieved in the laboratory (Table 2).

Results indicate appreciable agreement between predicted and experimental values. Biogas production rate was increased toward the bioreactor last compartments. During preliminary stage at first digester, materials are gone through liquefaction stage. The liquefaction of polymers to simple monomers can be rate-limiting step in digestion as this bacterial action is much slower in stage one to compare to further two stages, which are acid formation and methane formation (Barber and Stuckey, 1999). Production of more methane in final

Table 2: The produced biogas characteristics in each compartment of bioreactor

		Predicted value			Experimental value		
Digester	Digester volume (L)	Biogas production (m^3 kg^{-1} VS)	CH_4 (%)	CO_2 (%)	Biogas production (m^3 kg^{-1} VS)	CH_4 (%)	CO_2 (%)
P-2/AD-101	37.5	0.017	nd	80	0.015	nd	77
P-3/AD-102	12.5	0.083	10	68	0.08	10	64
P-4/AD-103	12.5	0.194	35	50	0.187	32	51
P-5/AD-104	12.5	0.318	58	38	0.309	55	40

VS: Volatile solid, nd: Not detected

digesters is due to higher activity of methane bacteria. Methane bacteria can only use limited number of substrate for the formation of methane which are CO_2+H_2, formate, acetate, methanol, methylamines and carbon monoxide (Tchobanoglous *et al*., 1993). Higher production of methane in final digester is due to rector configuration and assigning methane formation reaction in last digester. The compliance between predicted and experimental values indicates appropriate allocation of each anaerobic reaction in the model.

Effect of configuration change on reactor performance: Performance of the bioreactor in biogas production and effluent removal efficiency was investigated by variation of compartments volume. Therefore, two configurations were simulated in the model which in the first configuration all four digesters had same volume while for second one, first digester volume was made double. Then, performance of both configurations was investigated in term of BOD and COD removal efficiencies as well as biogas production rate and content of methane in biogas. As shown in Table 3, more favorable results were obtained for second configuration as this physical modification provided longer solids retention time and superior performance compare to the reactor with similar size compartments. The larger compartment in the reactor acted as a natural filter and provided superior solids retention for the small particles.

Cost analysis: Cost analysis and project economic evaluation play an important role in any project installation and/or development. Interests on venture in biogas productions depend on profitability of investment. In bigger scale, building a new plant is a major capital expenditure and a lengthy process. To make a decision, management must have information on capital investment required and time to complete the facility (Petrides *et al*., 2010). To outsource the production, cost analysis is important and use as a basis for negotiation with contract manufacturers. Table 4 shows the economic evaluation results of the laboratory scale anaerobic bioreactor for production of biogas.

Fixed capital investment was estimated based on total equipment cost using various multipliers, some of which

Table 3: Effect of configuration change on bioreactor performance

Parameter	Configuration 1	Configuration 2
Number of compartments	4	4
Bioreactor volume (L)	75	75
First compartment volume (L)	18.75	37.5
Last three compartments volume (L)	18.75	12.5
BOD removal efficiency (%)	73	85
COD removal efficiency (%)	70	88
Biogas production rate (m^3 kg^{-1} VS)	0.295	0.318
Methane content in biogas(%)	56	58

Table 4: Key economic evaluation results

Parameter	Value
Total capital investment (RM)	2000
Bioreactor throughput (kg $year^{-1}$)	616
Production and treatment costs (RM $year^{-1}$)	300
Unit production cost (RM kg^{-1})	0.49
Market price (RM kg^{-1})	2
Revenues (RM $year^{-1}$)	930
Gross margin (%)	75.5

are equipment specific (e.g., installation cost, maintenance, microbes supply and gas purification) while others are plant specific (e.g., cost of piping). Key assumptions for the economic evaluations include: (1) a new bioreactor will be fabricated and dedicated to the client of this product; (2) total methane yield of bioreactor is 0.26 m^3 CH_4 kg^{-1} VS and (3) 860 m^3 (615 kg) methane will be produced per year. For a small-scale bioreactor, the total capital investment was assumed to be RM 2000. Based on the results, unit production cost is RM 0.49 kg^{-1} of product and market value of the product was estimated to be RM 2 kg^{-1} which results in revenue of RM 930 $year^{-1}$ and gross margin of 75.5%. This indicates biogas production from organic waste in a single small-scale bioreactor is a promising method for renewable energy generation.

CONCLUSION

Design and process simulation of a small-scale anaerobic bioreactor was done using SuperPro Designer®. The system was able to successfully simulate complex intermediate reactions of anaerobic digestion system for production of biogas as appreciable agreement between predicted and actual results was achieved. Results reveal the bioreactor with configuration of doubled-size first compartment is able to produce more biogas and methane which was 0.318 $m^3\ kg^{-1}$ VS and 58%, respectively compare to configuration with four same size compartments which produced 0.295 $m^3\ kg^{-1}$ VS of biogas contains 56% methane. Cost analysis results show revenue of RM 930 $year^{-1}$ and gross margin of 75.5%. Therefore, the results obtained from this study are useful in proposing waste-to-energy systems to enterprises which are dealing with organic feed stocks as waste.

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