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Biogas from anaerobic co-digestion of food waste and primary sludge for cogeneration of power and heat

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Abstract

The anaerobic digestion (AD) process is being increasingly recognised as a technology for clean energy generation. However, in Ecuador, there is a little application of this technology due to lack of adequate research, economic incentives and the current relatively low price of electricity. This study examined the feasibility of biogas production using anaerobic co-digestion of food waste (FW) and primary sludge (PS) under thermophilic (55 ºC) and mesophilic (35 ºC) conditions. The biogas is then used for power and heat generation. Using case study approach, data were collected from Riobamba vegetable market and Penipe waste treatment plant in Ecuador. Three different mixing ratios of FW: PS were used (1:2, 1:1 and 2:1) with volatile solids (VS) content of 84.53%, 86.99%, and 89.6% respectively. Furthermore, the organic loading rates (OLR) used were 2.08, 2.49 and 3.34 $g_{VS}\ l^{-1}\ day^{-1}$ for the above mixing ratios with a hydraulic retention time (HRT) of 21 days.

Computational models of biogas production and a combined heat and power (CHP) system were developed using Aspen Plus software. Results indicated that a mixing ratio of 1:2 and mass flow of 132.42 tonnes/day, the maximum specific methane production obtained was 270 and 205 ml $CH_4/\ g_{VS}$ at thermophilic and mesophilic conditions respectively. The power production with the aforementioned values were 188.42 and 137.79 kW for both thermal conditions. Finally, an economic analysis for both scenarios was carried out using Ecuadorian renewable energy tariffs. A positive NPV values of £147,580 and £186,307 with a discounted payback period of 20.97 and 17.33 years were obtained for both scenarios respectively, assuming that the interest rate was 4.89% and a lifetime of 25 years.

Keywords: Anaerobic co-digestion, CHP simulation system, biogas simulation;

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1. Introduction

The increasing threat of global warming, price instability and energy security have necessitated decoupling of global economy from fossil fuel which still accounts for over 67% of the world total energy consumption in 2015 [1]. Ecuador an upper middle-income country is a fossil fuel energy-based economy [2] but with public policies that encourage the use of renewable energy. In 2014, Ecuador reached an energy access index of 97.04% of which, the electricity generation was 51% from thermoelectric, 47% from hydro and only 2% from non-conventional renewable energy including the wind, solar and biomass source [3]. Although the Ecuadorian government is encouraging the use of renewable resources, the use of wastes to produce energy can be considered negligible compared to other renewable energy sources.

Furthermore, in the country, the final waste disposal is handled by the local municipalities and it represents a serious environmental and social issue. According to the Department of Statistics and Censuses, 39% of the solid waste collected is disposed of in landfills, 26% in controlled dumps, 23% in open dumps and 12% in emergent cells [4]. Similarly, about 88% of wastewater is disposed of in rivers and only 12% is treated before its final disposal [5]. This has, in the past, led to serious environmental and social concerns. Biosolid composting and anaerobic digestion (AD) are the frequently used matured mechanisms to recover useful energy from bio-waste. However, the implementation of AD technology in Ecuador has been limited to pilot or empirical projects [6]. Hence, there is a need for further studies on how this technology can be technically and profitably utilised to solve challenges of the Ecuadorian waste management as well as the generation of useful energy.

Anaerobic Digestion Model No. 1 (ADM1) is being more frequently used because of its complexity and its kinetic values related with temperature and pH influence in all the steps of AD process. Nevertheless, ADM1 does not include all the mechanisms in AD, but the results obtained have a satisfactory accuracy [7]. Based on ADM1, some authors have developed software simulations which are able to forecast real scenarios of AD system with accurate results at low resources compared to experiments carried out in labs [8-10]. However, these studies mainly focused on biogas generation and do not include power generation and heat recovery. Thus, the main objective of this study was to investigate the feasibility of producing power and heat from anaerobic co-digestion of food waste (FW) and primary sludge (PS) under thermophilic and mesophilic conditions, in one assembled model simulation for biogas production and a combined heat and power (CHP) system using Aspen Plus. Furthermore, an economic analysis is also included.

2. Materials and methods

2.1. Case Study

Food waste was collected from the biggest local market in Riobamba where vegetables, fruits, and other food products are mainly sold directly by farmers. Riobamba is the capital city of Chimborazo province (1°40′27.65″S 78°38′53.86″W). Its population at 2010 was 225,741; land mass 59.05 km^2 and elevation 2,754 m above the sea. The temperatures averaging between 23 °C and 14 °C. Moreover, the primary sludge required in the process was collected from Penipe treatment plant located 30 km north-east far from the market.

2.2. Characterization of wastes and energy consumption of the market.

The average daily waste production of 6,598 kg/day is assumed constant all the year. This is because there is a constant influx of fruits and vegetables amongst the regions which experience seasonal variations at different times of the year. The daily production of PS in the treatment plant is 4,854 kg/day. More PS would be required to meet the set VS of the AD process. This is expected to be collected from small wastewater treatment plants around the city. The proximate analysis of FW and PS were evaluated separately with the standardised ISO methods. Subsequently, characterization of the mixtures is determined following references [11-13] and presented in Table 1.

Table 1. Characterization of food waste, primary sludge, and mixing ratios

Parameters			MIXTURE (FW: PS ratios)		
	FW	PS	1:2	1:1	2:1
Moisture (%)	67.99	96	94.6	93.34	91.14
Total solids (TS)	32.01	4	5.4	6.66	8.86
Volatile solids (VS)	95.32	80	84.53	86.99	89.6
Ash (% of TS)	4.68	20	15.47	13.01	10.4
Fat (% of VS)	8.79	5.3	6.46	7.05	7.63
Proteins (% of VS)	17.17	78	57.72	47.59	37.45
Carbohydrates (% of VS)	74.04	16.7	35.81	45.37	54.93

The energy consumption of the market was carried out using data available in the web portal of the local municipality during one year [14]. It is assumed for the following calculations, an average energy monthly consumption of 12,076 kWh and a paid bill of 877 £/month.

2.3. Simulation of Biogas production and CHP system

Using Aspen Plus, a simulation model was developed following the earlier work by [8, 9]. The model was evaluated and validated using data from other researchers' results. The validated model was then used to simulate the biogas production under thermophilic conditions and also modified to predict the biogas production under mesophilic conditions using equations and kinetic coefficients from ADM1 [8]. The model has two reactors: one for the hydrolysis stage and a second one where Acidogenesis, Acetogenesis, and Methanogenesis steps take place. The digester is modelled as a cylindrical vessel using polyurethane foam as an insulation material, with a thermal conductivity of 0.026 W m^{-1} $^{0}K^{-1}$ and a thickness of 0.2 m. Table 2 summarises the simulated results obtained for validation under mesophilic and thermophilic conditions.

Table 2. Model validation under thermophilic and mesophilic conditions

Substrate: Cow manure					
	Volume of the reactor [l]	HRT [days]	Experimental results [15] and [16]	Simulation results	Difference [%]
Thermophilic	5	15	353.5 [l/kg_{VS} day]	356.7 [l/ kg_{VS} day]	0.9
Mesophilic	16	20	155.2 [l CH4/ kg_{VS}]	142 [l CH4/ kg_{VS}]	8.5

Considering the available biogas, a four stroke internal combustion engine was selected and simulated. The model is developed following the earlier work reported by [17]. The air required is taken from the surroundings through the intake stage and divided into two streams which compress it in a ratio of 2.5:1 (turbocharger). Then, the compressed hot air is cooled using two heat exchangers (heat rejection aftercooler). A mixer is used to merge the two streams and a second compression stage is carried out until the compression ratio 10.3:1 is reached. In the working stroke, the compressed air and fuel are mixed inside of a reactor where the stoichiometric combustion reactions take. Table 3 shows the validation of the engine model.

Table 3. Gas engine validation.

Parameter	**Manufacturer's specifications [18]**	**Simulation values**	**Deviation (%)**
Power (kW)	224	229.68	2.54
Heat rejection to intercooler (kW)	12.203	12.203	0
Heat rejection to Jacket water and lube oil (kW)	235.93	235.93	0
Input air volume flow (kg/hr)	968.71	968.71	0
Exhaust gas flowrate (kg/hr)	1,018.59	1,017.51	-0.11
Exhaust temperature (^{0}C)	525	543	3.43

The complete model implemented in Aspen Plus is presented in Figure 1 below which include the biogas production and the CHP system. The outer shape of the model is the same for both thermal conditions, however, internally they have a different configuration and kinetic constants.

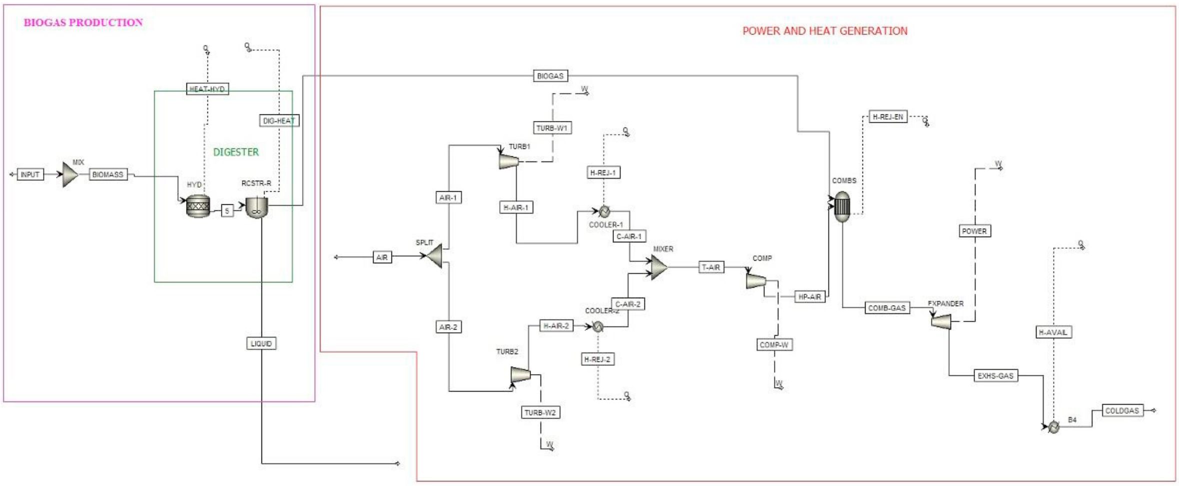

Fig. 1 Assembled model simulation of biogas production and CHP system

2.4. Economic analysis.

The economic analysis was performed for two scenarios based on the best results obtained in the power and heat production. The following parameters were used in both analysis: a) lifetime for the plant is 25 years b) all the money will be obtained from a bank credit c) the capital cost was calculated using the study report "Review of Renewable Electricity Generation Cost and Technical Assumptions" presented by the UK Department of Energy and Climate change, d) the load factor or availability factor for the plant is 84% [19] e) The discount rate is 4.89% [20].

The offsite cost (OSBL) used is 40% of inside battery limits investment (ISBL), the engineering cost is 30% of ISBL plus the OSBL, contingency charges are 10% of ISBL plus the OSBL cost. The total investment is the sum of ISBL cost, OSBL cost, engineering, and contingency cost [21]. In order to calculate the payback time of the plant, the market power consumption will be cover first and the remaining electricity produced will be sold. Furthermore, the digestate from the anaerobic process is sold as fertiliser. In Ecuador, the price of electricity generated from renewable sources is 0.1105 US$/kWh (0.09 £/kWh) [22]. The depreciation and federal income taxes are not considered in the calculation.

3. Results and discussion

3.1. Biogas production results

Based on the waste availability, six scenarios were simulated using the mixing ratios described in Table 1. The simulation results obtained are presented in Table 4 for both conditions.

Table 4. Simulation results of biogas production at both thermal conditions.

				Thermophilic results			Mesophilic results		
	RATIO (FW:PS)	Input mass flow [kg/day]	Organic loading rate OLR [g_{VS}/l day]	Methane % (Vol fraction)	Biogas production in [l/kg_{VS} day]	Specific methane production [l CH4/kg_{VS}]	Methane % (Vol fraction)	Biogas production in [l/kg_{VS} day]	Specific methane production [l CH4/kg_{VS}]
CASE 1	01:02	132,421.58	2.08	0.50	546	270	0.76	271	205
CASE 2	01:02	5,111.02	2.08	0.50	546	270	0.75	272	205

CASE 3	01:01	69,509.79	2.49	0.48	503	242	0.73	237	173
CASE 4	01:01	5,365.68	2.49	0.48	504	242	0.73	237	173
CASE 5	02:01	38,053.89	3.34	0.47	464	217	0.69	221	152
CASE6	02:01	5,875.00	3.34	0.47	464	217	0.69	221	152

For both simulations, 21 days were used as hydraulic retention time (HRT) and three different organic loading rates (OLR) as is shown in the Table 4. The final difference of specific biogas production between mesophilic and thermophilic conditions differ in 65 litres of CH_4/ g_{VS} add (around 32% more in thermophilic conditions) which is similar to the experimental results reported by Kim *et al.* [12]. Interestingly, the methane content of mesophilic condition is 25% higher than that produced by the thermophilic process. This is obtained at FW: PS ratio of 1:2 for the two conditions. More so, from the result, it is observed that mass flow rates 132,421kg/day and 5,111 kg/day with the same OLR produced the similar specific methane production. For further analysis, only the highest flow is evaluated.

3.2. Power and heat production results

The power production is calculated by Aspen engine simulation using the local conditions of the study area (18 °C and 0.7 atm). Those variations influence the final power production. Hence, an aftercooler heat rejection factor of 1.39 established in the technical data is included in the simulation. The power consumed by the compression and turbocharger stages must be subtracted from the final result and a 4.2 % is assumed as local consumption of the CHP system. The results are presented in Table 5. Aspen Plus models are not able to calculate the heat lost by the reactor to the surrounding. Hence, it is evaluated following reference [23] and includes: a) the heat required by the process to warm up the substrate b) the heat lost by radiation c) heat consumed and release by the biochemical reactions inside of the digester.

Table 5. Power available and heat balance.

Units: kW	Thermophilic	Mesophilic
Power produced (Electricity)	188.42	137.79
Substrate warming-up (Q_W)	-205.34	-77.00
Radiation losses with insulation (Q_L)	-5.43	-2.33
Biochemical reactions (Q_m)	-78.85	-78.85
Total heat required	-289.62	-173.15
Heat produced (exhaust gases)	80.28	43.00
Heat produced (rejected to jacket)	210.10	210.10
Heat available (surplus).	0.76	79.85

From Table 5, it can be seen that there is a small surplus of 0.76 kW of heat in thermophilic conditions and a higher surplus of 79.85 kW at the mesophilic scenario. The efficiency of power production is also analysed based on the biogas flow entering to the CHP system, and the lower heating value (LHV) of the biogas calculated by Aspen. The electrical efficiencies are 29.71 and 27.6% for the thermophilic and mesophilic conditions respectively. The use of the CHP system rise the system efficiencies to 75.25 and 78.43% respectively.

3.3. Economic analysis

The total cost of the plants is £1.45 and £1.06 million for both scenarios respectively. The ISBL, OSBL, engineering cost and contingency cost are presented in Table 6 with the percentages previously mentioned. Furthermore, in order to calculate the discounted payback period (DPP), the profits and revenues were calculated. The direct and indirect operating costs including the cost of raw materials, the personal cost of employees, maintenance, consumables reserve, insurance, corporate directions, and transport were included in the revenues of the project. The total operating cost calculated for both scenarios were £/year 124,896 and 113,017; the profits obtained from selling electricity and fertiliser were £ 231,056/year and £205,134/year. The final taxable incomes and the net present values (NPV) are also included in Table 6.

Table 6. Capital and total investment cost, NPVs

	Thermophilic (188.42 kW)	Mesophilic (137.79 kW)
Total Capital cost [£] ISBL	858,442	627,270
Offsite cost [£] OSBL	257,532	188,181
Engineering cost [£]	223,195	163,090
Contingency cost [£]	111,597	81,545
Total investment cost [£]	1’450,766	1’060,086
Taxable income [£/year]	112,160	92,117
NPV [£]	147,580	252,644

The DPPs using the aforementioned conditions are 20.97 and 17.33 years for both scenarios respectively. The Levelized cost of energy for this project was calculated as 81.15 £ MW^{-1} which is slightly less than normal the cost of the electricity in the country (90 £ MW^{-1}). The analysis does not include any grants from the government, however, nowadays it is possible to find governmental financial support for this kind of projects.

4. Conclusion

An assembled model for biogas production and CHP system has been developed, validated and used with Ecuadorian data. The system efficiency using the heat generated increase to 75.25 % and 78.43% for thermophilic and mesophilic conditions respectively. However, despite the biogas production is higher at thermophilic conditions (137.4 m^3 hr^{-1}) compared to mesophilic scenario (67.74 m^3 hr^{-1}), the results of heat balance and power generation suggest that the use of mesophilic condition is more suitable for this waste treatment. Furthermore, the mesophilic conditions have a heat surplus of 79.85 kW that can be used in other process required by the market (tri-generation). The economic analysis showed that the lowest investment cost and DPP were at the mesophilic scenario with £ 1.06 million and 17.33 years. It is suggested that further research includes the governmental financial support. Finally, the use of primary sludge will help to reduce the pollution in one of the biggest local rivers reported as one of the most polluted rivers in the country and used by the farmers to irrigate their crops. Importantly, the co-digestion process will reduce GHG emissions at least in 3116 metric tonnes of CO_2 equivalent every year.

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