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APPENDIX A: CELLULAR KINETICS - TABLE 1

Biochemical rate coefficients ($v_{i,j}$) and kinetic rate equations (ρ_j) for particulate components (i= 1 – 12; j= 1 - 19)

Component → i		1	2	3	4	5	6	7	8	9	10	11	12	Kinetic Rates
j	Process ↓	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I	(ρ_j, kg COD·m^{-3}·d^{-1})
1	Disintegration										$-\sum_{i=1-9,11-24} C_i v_{i,1}$	$-\sum_{i=1-9,11-24} N_i v_{i,1}$	$f_{sI,xc}$	$k_{dis}\cdot X_c$
2	Hydrolysis of carbohydrates	1									$-\sum_{i=1-9,11-24} C_i v_{i,2}$			$K_{hyd,ch}\cdot X_{ch}$
3	Hydrolysis of proteins		1								$-\sum_{i=1-9,11-24} C_i v_{i,3}$			$K_{hyd,pr}\cdot X_{pr}$
4	Hydrolysis of lipids	$1-f_{fa,li}$		$f_{fa,li}$							$-\sum_{i=1-9,11-24} C_i v_{i,4}$			$K_{hyd,li}\cdot X_{li}$
5	Uptake of Sugars	-1				$(1-Y_{su})\cdot f_{bu,su}$	$(1-Y_{su})\cdot f_{pro,su}$	$(1-Y_{su})\cdot f_{ac,su}$	$(1-Y_{su})\cdot f_{h2,su}$		$-\sum_{i=1-9,11-24} C_i v_{i,5}$	$-(Y_{su})\cdot N_{biom}$		$k_{m,su}\frac{S_{su}}{K_{s,su}+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids		-1		$(1-Y_{aa})f_{va,aa}$	$(1-Y_{aa})\cdot f_{bu,aa}$	$(1-Y_{aa})\cdot f_{pro,aa}$	$(1-Y_{aa})\cdot f_{ac,aa}$	$(1-Y_{aa})\cdot f_{h2,aa}$		$-\sum_{i=1-9,11-24} C_i v_{i,6}$	$-\sum_{i=1-9,11-24} N_i v_{i,6}$		$k_{m,aa}\frac{S_{aa}}{K_{s,aa}+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA			-1				$(1-Y_{fa})\cdot 0.7$	$(1-Y_{fa})\cdot 0.3$		$-\sum_{i=1-9,11-24} C_i v_{i,7}$	$-(Y_{fa})\cdot N_{biom}$		$k_{m,fa}\frac{S_{fa}}{K_{s,fa}+S_{fa}}X_{fa}I_2$
8	Uptake of Valerate				-1		$(1-Y_{c4})\cdot 0.54$	$(1-Y_{c4})\cdot 0.31$	$(1-Y_{c4})\cdot 0.15$		$-\sum_{i=1-9,11-24} C_i v_{i,8}$	$-(Y_{c4})\cdot N_{biom}$		$k_{m,c4}\frac{S_{va}}{K_{s,c4}+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_3$
9	Uptake of Butyrate					-1		$(1-Y_{c4})\cdot 0.8$	$(1-Y_{c4})\cdot 0.2$		$-\sum_{i=1-9,11-24} C_i v_{i,9}$	$-(Y_{c4})\cdot N_{biom}$		$k_{m,c4}\frac{S_{bu}}{K_{s,c4}+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_3$
10	Uptake of Propionate						-1	$(1-Y_{pro})\cdot 0.57$	$(1-Y_{pro})\cdot 0.43$		$-\sum_{i=1-9,11-24} C_i v_{i,10}$	$-(Y_{pro})\cdot N_{biom}$		$k_{m,pro}\frac{S_{pro}}{K_{s,pro}+S_{pro}}X_{pro}I_4$
11	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-24} C_i v_{i,11}$	$-(Y_{ac})\cdot N_{biom}$		$k_{m,ac}\frac{S_{ac}}{K_{s,ac}+S_{ac}}X_{ac}I_5$
12	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-24} C_i v_{i,12}$	$-(Y_{h2})\cdot N_{biom}$		$k_{m,h2}\frac{S_{h2}}{K_{s,h2}+S_{h2}}X_{h2}I_6$
13	Decay of X_{su}										$-\sum_{i=1-9,11-24} C_i v_{i,13}$	$-\sum_{i=1-9,11-24} N_i v_{i,13}$		$k_{dec,Xsu}X_{su}$
14	Decay of X_{aa}										$-\sum_{i=1-9,11-24} C_i v_{i,14}$	$-\sum_{i=1-9,11-24} N_i v_{i,14}$		$k_{dec,Xaa}X_{aa}$
15	Decay of X_{fa}										$-\sum_{i=1-9,11-24} C_i v_{i,15}$	$-\sum_{i=1-9,11-24} N_i v_{i,15}$		$k_{dec,Xfa}X_{fa}$
16	Decay of X_{c4}										$-\sum_{i=1-9,11-24} C_i v_{i,16}$	$-\sum_{i=1-9,11-24} N_i v_{i,16}$		$k_{dec,Xc4}X_{c4}$
17	Decay of X_{pro}										$-\sum_{i=1-9,11-24} C_i v_{i,17}$	$-\sum_{i=1-9,11-24} N_i v_{i,17}$		$k_{dec,Xpro}X_{pro}$
18	Decay of X_{ac}										$-\sum_{i=1-9,11-24} C_i v_{i,18}$	$-\sum_{i=1-9,11-24} N_i v_{i,18}$		$k_{dec,Xac}X_{su}$
19	Decay of X_{h2}										$-\sum_{i=1-9,11-24} C_i v_{i,19}$	$-\sum_{i=1-9,11-24} N_i v_{i,19}$		$k_{dec,Xh2}X_{h2}$
		Sugar (kg COD/m^3)	Amino acids (kg COD/m^3)	LCFA (kg COD/m^3)	Total Valerate (kg COD/m^3)	Total butyrate (kg COD/m^3)	Total propionate (kg COD/m^3)	Total acetate (kg COD/m^3)	Hydrogen (kg COD/m^3)	Methane (kg COD/m^3)	Inorganic Carbon (kmole C/ m^3)	Inorganic Nitrogen (kmole N/m^3)	Soluble inerts (kg COD/m^3)	

APPENDIX B: CELLULAR KINETICS - TABLE 2

Biochemical rate coefficients ($v_{i,j}$) and kinetic rate equations (ρ_j) for particulate components (i= 13 - 24; j= 1 - 19)

Component → | i		13	14	15	16	17	18	19	20	21	22	23	24	25	26	Kinetic Rates
j	Process ↓	Xc	X_{ch}	X_{pr}	X_{li}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I	S_{cat}	S_{an}	(ρ_j, $kg\,COD \cdot m^{-3} \cdot d^{-1}$)
1	Disintegration	-1	$f_{ch,xc}$	$f_{pro,xc}$	$f_{li,xc}$								$f_{XI,xc}$			$k_{dis} \cdot X_c$
2	Hydrolysis of carbohydrates		-1													$K_{hyd,ch} \cdot X_{ch}$
3	Hydrolysis of proteins			-1												$K_{hyd,pr} \cdot X_{pr}$
4	Hydrolysis of lipids				-1											$K_{hyd,li} \cdot X_{li}$
5	Uptake of Sugars					Y_{su}										$k_{m,su} \frac{S_{su}}{K_{s,su} + S_{su}} X_{su} I_1$
6	Uptake of Amino Acids						Y_{aa}									$k_{m,aa} \frac{S_{aa}}{K_{s,aa} + S_{aa}} X_{aa} I_1$
7	Uptake of LCFA							Y_{fa}								$k_{m,fa} \frac{S_{fa}}{K_{s,fa} + S_{fa}} X_{fa} I_2$
8	Uptake of Valerate								Y_{c4}							$k_{m,c4} \frac{S_{va}}{K_{s,c4} + S_{va}} X_{c4} \frac{1}{1+S_{bu}/S_{va}} I_3$
9	Uptake of Butyrate								Y_{c4}							$k_{m,c4} \frac{S_{bu}}{K_{s,c4} + S_{bu}} X_{c4} \frac{1}{1+S_{va}/S_{bu}} I_3$
10	Uptake of Propionate									Y_{pro}						$k_{m,pro} \frac{S_{pro}}{K_{s,pro} + S_{pro}} X_{pro} I_4$
11	Uptake of Acetate										Y_{ac}					$k_{m,ac} \frac{S_{ac}}{K_{s,ac} + S_{ac}} X_{ac} I_5$
12	Uptake of Hydrogen											Y_{h2}				$k_{m,h2} \frac{S_{h2}}{K_{s,h2} + S_{h2}} X_{h2} I_6$
13	Decay of X_{su}	1				-1										$k_{dec,Xsu} X_{su}$
14	Decay of X_{aa}	1					-1									$k_{dec,Xaa} X_{aa}$
15	Decay of X_{fa}	1						-1								$k_{dec,Xfa} X_{fa}$
16	Decay of X_{c4}	1							-1							$k_{dec,Xc4} X_{c4}$
17	Decay of X_{pro}	1								-1						$k_{dec,Xpro} X_{pro}$
18	Decay of X_{ac}	1									-1					$k_{dec,Xac} X_{ac}$
19	Decay of X_{h2}	1										-1				$k_{dec,Xh2} X_{h2}$
		Composites (kg COD/m³)	Carbohydrates (kg COD/m³)	Proteins (kg COD/m³)	Lipids (kg COD/m³)	Sugars degraders (kg COD/m³)	Amino acids degraders (kg COD/m³)	LCFA degraders (kg COD/m³)	Vale- & Butyrate degraders (kg COD/m³)	Propionate degraders (kg COD/m³)	Acetate degraders (kg COD/m³)	Hydrogen degraders (kg COD/m³)	Particulate Inerts (kg COD/m³)	Cations (kmole/m³)	Anions (kmole/m³)	

APPENDIX C : PAPER 1

Life Cycle Analysis of Road Sector GHG Emission for a Three Wheeler Fueled with Biogas - Fifteenth International Forestry and Environment Symposium, 26th November 2010 – organized by University of Sri Jayewardenepura, Sri Lanka.

(Fernando K.C.A., Kularatna M.A.D.I.C., **Dilnayana K.W.N.**, Rathnasiri P.G., De Alwis A.A.P., University of Moratuwa, Sri Lanka)

Life cycle analysis of road sector GHG emission for a three wheeler fueled with biogas

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ABSTRACT

Climate change has been identified as the most burning issue in the world, which is mostly caused by GHG emissions. Road sector transport CO_2 contribution is more than 18%, out of the 12% global anthropogenic CO_2. Increasing usage of fossil fuels also result in faster degradation of fuel deposits. Waste derived vehicle fuel initiatives reduce fossil fuel dependence. A comprehensive Life Cycle Assessment (LCA) is the best methodology to assess the environmental consequences of transportation scenario. Due to data availability constraints the functional unit was selected as kgCO2e/km and the impacts category was selected as Global Warming Potential measured by GHG emissions. Research findings shown that both in fuel efficiency and specific GHG savings are higher in pilot scale biogas fuelled three wheeler. By further improving the biogas plant, these results will be further increased.

Keywords: life cycle analysis, biogas, road sector GHG emission

1. INTRODUCTION

Climate change has been identified as the most burning issue in the world, which is mostly caused by GHG emissions. A wide range of direct and indirect measurements confirm that the atmospheric mixing ratio of CO_2 has increased globally by about 100ppm (36%) over the last 250 years, from a range of 275 to 285ppm in the pre –industrial era (AD1000-1750) to 379ppm in 2005. (IPCC, 2007) Road sector transport CO_2 contribution is more than 18%, out of the 12% global anthropogenic CO_2 (WBSCD, 2005). Increasing usage of fossil fuels also result in faster degradation of fuel deposits.

1.1. VEHICLE AND FUEL COMPOSITION - SRI LANKAN CASE

Sri Lanka is a country fully depend on imported fossil fuels which shown the increasing utilization from total fossil fuel imports Units: Thousand tonnes of oil equivalent (ktoe) 1923 (year 1990) to 4,319 by year 2005. (World Resource Institute, 2007). The total vehicle population was increased and according to the statistics of the Department of Motor Traffic, Sri Lanka in 2008, three wheelers represent 12% of Sri Lankan vehicles on the road, which is the most common transport media of transit commuters which was taken as the reference vehicle in this study.

1.2. WASTE DERIVED BIOGAS AS A THREE-WHEELER FUEL

The Department of Chemical and Process Engineering of University of Moratuwa (UoM) developed a system to utilize Biomethane as a transport fuel with the collaboration of Alternative Energy Division of Ministry of Science and Technology. The main objective of this project is to design and construct a pilot scale biogas plant utilizing food waste obtained from university canteens for producing and upgrading biogas as a vehicle fuel and subsequent demonstration of the concept. The initial trials were conducted using a three-wheeler as the pilot vehicle.

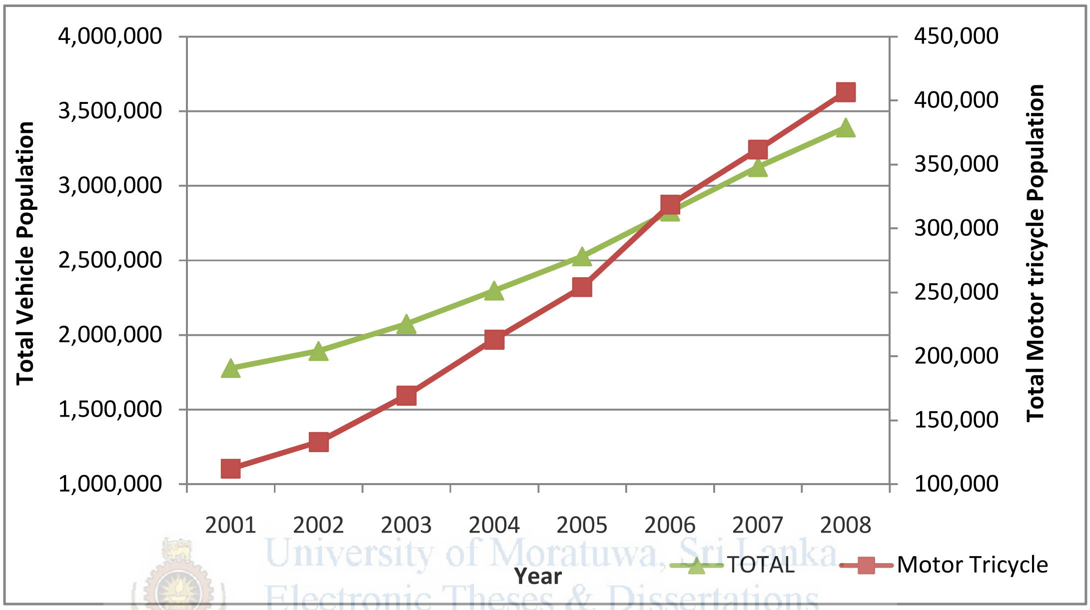

Figure 0-1: Growth of total active vehicle population in Sri Lanka

2. Research Objective

Waste derived vehicle fuel initiatives reduce fossil fuel dependence. Performing a Life cycle analysis for the derived biogas fuel from pilot biogas plant comparing traditional vehicle fuels as the baseline scenario was selected as the research objective. The research will provide a quantitative set of results on GHG aspects of the both fuel sources by selecting three-wheeler as the reference vehicle.

3. Research Methodology

A comprehensive Life Cycle Assessment (LCA) is the best methodology to assess the environmental consequences in between two scenarios, in this case two fuel scenarios. Throughout the study ISO 14040:2006 standard - Environmental management -- Life cycle assessment -- Principles and framework was selected as the LCA standard which also the research methodology. United Nations defined “Life Cycle Assessment (LCA) is an analytical tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. LCA provides an adequate instrument for environmental decision support. A reliable LCA performance is crucial for a life cycle economy.

3.1. LCA METHODOLOGY

The International Organization for Standardization (ISO) completed a whole series of Life Cycle Assessment standards in 2002, the 14040 series. (ATIS Exploratory Group on Green, 2010) This ISO 14040:2006 standard which is the most commonly accepted and practiced internationally, describes the principles and framework for life cycle assessment (LCA) which includes: defining of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements (ISO, 2006). However defining of a specific 'scope' is critical in these studies, due to the data availability present study scope was limited from fuel to emission. 'Global warming potential' measured by GHG emissions was selected as the impact category and the functional unit for the study was selected as $kgCO_2e/km$.

Two scenarios were studied by gathering information and collecting data for different fuel types which three wheelers use, petrol as the baseline scenario and biogas as the second scenario.

4. LCA SCENARIOS

In order to aligned with the research objective which is also the goal of the LCA, Data gathering was initiated for the two scenarios collecting the emission data for the selected reference vehicle three wheeler. Two fuel types used was petrol and pilot biogas generated at UoM.

4.1. BIOGAS

Biogas is the gas produced by the anaerobic digestion or fermentation of biodegradable organic matter under anaerobic (oxygen-free) conditions. Composition of biogas is varies depending on the feed types used for production. Typical composition of biogas as follows (Steinhauser, 2008).

Table 0-1: Typical biogas composition

Component	Content
CO_2	25 – 50% by vol.
H_2S	0 – 0.5% by vol.
Water vapour	1 – 5% by vol.
NH_3	0 – 0.05% by vol.
Dust	> 5 μ m
N_2	0 – 5% by vol.
Siloxane	0 – 50 mg m^{-3}

4.2. PILOT SCALE BIOGAS PLANT AT UOM

Biogas is produced at the pilot scale biogas plant at UoM utilizing food waste obtained from university canteens. The objective was to produce biogas from food waste & upgrade the gas to be used as a vehicle fuel. With the canteen food waste as the main substrate cow dung, water hyacinth and gliricidia leaves are also used for initiating the process.

Biogas reactor vessel was designed having the reaction capacity of 4.82m^3 and total volume (gas phase and liquid phase) of 5.40 m^3 according to the process calculations. It was designed to operate on 20 days residence time and at maximum pressure of 1.5 bars. There are 3 twisted paddle type impellers inside the vessel for uniform mixing. The slurry is prepared using a crusher adding food waste and water to achieve final solid content 10%. 200liters of prepared slurry is fed at a flow of 0.22 m^3/d to a continuously mixed reactor which having bulk volume of 4.82 m^3. Reactor is assuming to be operated at residence time of 20 days and expected biogas production is 2m^3/d according to experiment results.

Produced gas having average 60% of methane (CH_4) is then upgraded by removing Carbon Dioxide (CO_2) and Hydrogen Sulphide (H_2S).Scrubber is used to remove CO_2 and H_2S in the biogas and upgrade the quality. A water scrubber was designed to use for this purpose and planned to modify as required after testing the outcome later. The gas is entering the scrubber with 10 bar pressure from the bottom and water is sprayed from top of the column. By the counter current contact of the pressurized gas and water, carbon dioxide gets absorbs into the water and leaves the column from bottom. Plastic ring type packing has used initially as the packing medium inside of the column. Biogas coming out of reactor is then purified by removing CO_2 passing through water scrubbing packed column and water vapour is then collected using a moisture removal setup. Biogas having 85% CH_4 is then compressed up to the required pressure and stored in compressed form in gas cylinders to be used in vehicles. This value could be further improved with process optimization.

5. CALCULATION METHODOLOGY

Calculation was carried out in two steps process. Step 01 covers the data gathering for the pilot scale bio gas fuelled three wheeler, including efficiency and the specific CO_2 calculations. Step 02 is for the petrol fuelled three wheeler calculations mainly from literature reviews

5.1. STEP 01 : CALCULATIONS OF PILOT SCALE BIOGAS FUELLED CASE

According to experiment data, tuk tuk was being able to run for 5.3 km from 320 liter of biogas which had 85% methane by volume. Density (0.849 kg/m^3) of the biogas was obtained by using "Real and Ideal Gas Law Calculator" online program (Senese) according to theoretical density of the methane and carbon dioxide. According to the obtained density of the biogas, 320 liters of biogas is equal to 0.27168 kg in weight.

The efficiency was calculated as below Equation (1)

$$Fuel\ Consumption\ Efficiency = \frac{Weight\ of\ the\ fuel\ consumption\ in\ kg}{distance\ of\ the\ tuk\ tuk\ run} \quad (1)$$

Therefore efficiency of the biogas fuelled three wheeler was. $= \frac{0.27168}{5.3} = 0.0513$ kg of fuel/ km

In order to calculate the emissions from the bio gas fuelled three wheeler, the vehicle emission tests were carried out from CleanCo Lanka (Pvt) Limited – a the government approved testing body and the results are as follows.

Table 0-2: Emission Test for the biogas fuelled three wheeler

Items	Limits	High Idle	Low Idle
		Measured	
HC PPM VOL	9000	756	1621
CO % VOL	6.000	0.215	0.102
CO_2 % VOL		9.440	8.010
O_2 % VOL		7.320	9.060
Lambda		1.488	1.678
RPM		2523.00	1025.00
Estimated Fuel Wastage (Optional)			
High Idle Fuel Wastage (%)	5.51	Value (SLR per Litre)	6.34
High Idle Fuel Wastage (%)	11.38	Value (SLR per Litre)	13.09

It was assume that all methane inject into the engine of the tuk tuk was converted to CO_2 because of low amount of CO in the emission. Therefore it was assume that reaction in equation (2) was occurred inside the engine. Results show that the CO_2 content is higher than CO content. While comparing the two set of results, it is concluded that the CO emission is negligible and assumed as a total combustion of CH_4 inside the engine. Based on that assumption, the weight of CO_2 emission per kg of CH_4 fuel is calculated theoretically

$$CH_4 + 2O_2 \overset{\Delta}{\rightarrow} CO_2 + H_2O \qquad (2)$$

As per the above equation (2) one kilogram of fuel can produce 2.109 kilograms of CO_2. Therefore the CO_2 emission in kilograms per kilometre was calculated as below equation (3).

$$\left| \begin{matrix} CO_2\,emission \\ \left(\frac{kgCO_2}{km}\right) \end{matrix} \right| = \left| \begin{matrix} kg\,of\,CO_2\,emitted \\ for\,1kg\,of\,fuel \end{matrix} \right| \times \left| \begin{matrix} Fuel\,Consumption \\ Efficiency \end{matrix} \right| \qquad (3)$$

CO_2 emission for the biogas fuelled three wheeler $= (2.109) \times (0.0513) = 0.1081\ \mathrm{kgCO2e/km}$

5.2. *STEP 02 : CALCULATIONS OF PETROL FUELLED CASE*

Step 02 calculations were based on the literature survey results due to un-availability of national emission data to public. Emission factor of the petrol is 0.13 kg/ km (Preethika & Bandara, 2004), however the below calculation used to find the specific figures for the three wheeler fuel efficiency. It was found during literature review the mileage of tuk tuk (three wheeler) is 35 km/l

(Kondury, 2007) and the density of the petrol is 737.22 kg/ m^3 (Babel, Parkpian, & Sae-Ta, 2005).

The efficiency was calculated by dividing the density by mileage as shown in equation (4)

$$\boldsymbol{Efficiency} = \frac{\boldsymbol{Density}}{\boldsymbol{Mileage}} \tag{4}$$

Therefore efficiency of the petrol fuelled three wheeler = $\left(\frac{737.22}{35 \times 1000}\right) = 0.0211\ kg\ of\ fuel\ per\ km$

6. RESULTS AND CONCLUSION

Following results were obtained from the above calculation steps.

Table 0-3: Final results

Scenario / Fuel Type	Fuel Consumption Efficiency (kg of fuel / km)	$kgCO_2e/km$
01 - Petrol	0.0211	0.1300
02 – Biogas (UOM)	0.0513	0.1081

Research data shows, pilot scale biogas fuelled three wheeler is more fuel efficient and the GHG emission is lower than the petrol fuelled three wheeler. With the optimization of the biogas plant processes this achievement can be further increased. This LCA – GHG results can present as a quantitative indicator to develop the similar attempts in order to minimize the GHG emissions and conserve the fossil fuels. However the research can be further expanded to cover the other LCA impact categories like water pollution, smog formation and ozone depletion etc. Access to national vehicle emission testing database is a also identified as a critical constraint to continue further the same study. Considering the number of three-wheelers in Sri Lanka 44, 804 (in year 2008) and its usage, the absolute emission savings are high while the indirect savings by proper waste utilization for the biogas generation also makes an extra environmental advantages. Researching on scenario 3 LPG case is identified as future activities under this research.

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APPENDIX D : PAPER 2

Optimization of Anaerobic Co-digestion Process and use of Bio-methane as a transport fuel – VIDULKA – Sri Lankan National Energy Symposium, 06th August 2010 conducted by Sustainable Energy Authority of the Ministry of Power & Energy, Sri Lanka

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Optimization of an Anaerobic Co-digestion Process and use of Bio-methane as a transport fuel

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Abstract

Anaerobic co-digestion (ACD) is regarded as a key environmental technology in industrial, agricultural and domestic sectors for integrated solid and liquid waste treatment and renewable energy production. Bio-methane which is upgraded into compressed natural gas (CNG) quality is used as transport fuel in developed countries. In Sri Lankan context challenges are to produce bio methane with required quantity and quality using appropriate technology. Even though plenty of biodegradable substrates are locally available, lack of process fundamentals and poor monitoring of process parameters has been caused to failure of this technology.

Objectives of this study are to introduce efficient stable method to produce high quality methane, by co digestion of food (canteen) waste with different locally available substrates as gliricidia, water hyacinth and rice straw. In the first step, lab scale experiments were conducted by varying type of substrate under controlled conditions to find highest methanogenic potential. Optimum process parameters were determined using combined experimental and dynamic modeling approach. Anaerobic digestion model no. 1 (ADM1), was used to simulate the anaerobic co digestion process built in computer program called "AQUASIM 2.0." By this model it was confirmed that canteen food waste alone cannot be used in AD process because of high rate of hydrolysis, accumulation of Volatile Fatty Acid (VFA) and production of CO_2 in significant amount. Based on above findings, pilot plant was designed, fabricated and installed within University premises. When reactor was fed semi-continuously with food waste alone while cow dung was being used as inoculums, process was inhibited as confirmed by model. Pilot plant test run was conducted using gliricidia as co substrates. Gliricidia produced biogas with the highest methane potential of 60% methane. Biogas was upgraded removing CO_2 by water scrubbing and then passed through moisture trap. Final treated gas containing >80% CH_4 compressed and stored in gas cylinders. By using this upgraded bio-methane in three wheeler, successful test runs were conducted.

Key words: Anaerobic Digestion, Co-digestion, Transport fuel, Dynamic Modeling

Introduction

Biogas is the product of a biological process known as anaerobic digestion. In the absence of oxygen, anaerobic bacteria decompose organic matter and produce a gas mainly composed of methane and carbon dioxide and called biogas.

Biogas can be produced from raw materials such as sewage sludge, manure and energy-rich waste such as abattoir and vegetable waste. Degradation of mixture of these two or more components in an anaerobic digester is called as co-digestion. The advantage is a carbon-dioxide-neutral eco cycle. Two major environmental problem areas-over fertilizing and the greenhouse effect are reduced by using biogas. Sludge generated from anaerobic process is a valuable bio-fertilizer which supplies nutritive substances to the farms. Biogas can be used as vehicle fuel and combined heat and power generation (CHP) resulting less CO_2 emission.

Though this vital technology has been practicing in Sri Lanka nearly for three decades. It is not advancing as expected due to poor technology management and not properly monitoring and controlling of process parameters.

To optimize the co digestion process several studies have been conducted. One such study is a combined linear programming and experimental method developed using bio-kinetic potential and biodegradation potential [1]. Major limitation of this model is that it does not represent all consecutive steps of anaerobic digestion process. Another process optimization study based on Monod kinetics combining with experiments conducted to enhance higher methane productivity. In this experimental study volatile solids (VS) reduction was observed to find out microbial growth rate of anaerobic digestion process[2]. But microbial growth cannot be predicted based only on VS reduction. Therefore the Anaerobic Digestion Model No.1 (ADM1) developed by IWA anaerobic digestion modeling group and extended by [3], [4] was applied to optimize the anaerobic co-digestion process in these experiments. ADM1 comprises of 19 biochemical conversion processes and 24 dynamic state variables[5], and was built in AQUASIM 2.if dynamic simulator which is capable of conducting Linear Sensitivity Analysis and Parameter Estimation[6].

In this study, results of batch experiments were combined with dynamic mathematical modeling to optimize the co digestion process. The substrate which produced the highest methane potential with canteen waste was determined. The best substrates determined with these experiments were subsequently used as a feed stock to pilot plant reactor and biogas produced was purified to remove CO_2 by scrubbing with water. The treated biogas was compressed and used as a transport fuel.

Methodology

Batch experiments

Laboratory scale batch experiments were conducted to find out the best substrate for co-digestion process. Canteen food waste was the main substrate while water hyacinth and Gliricidia were co substrates. Inoculums obtained from the active anaerobic reactor operating at Ceylon cold stores PLC.

Experiment procedure – Batch 01

Samples were prepared according to the compositions given in Table 1 and transferred into 60ml syringes. Total sample weight was 50g and approximately equal to 50ml. In this experiment series, equal amount of co-substrate by 20% wt was used for Sample 1,2,3 and Sample 3 only consisted of food waste and inoculums. All experiments were conducted at room temperature. Total Solids (TS) content was control between 6-7% and pH, TS and COD were measured before (feed) and after (effluent) the digestion process. Cumulative gas production was measured for every 3 hr time interval for 5 days. Final accumulated CO_2 compositions were measured.

Table 0-1. Feed composition – batch 01

	1	2	3	4
Food Waste	70%	70%	70%	90%
Water Hyacinth	20%	-	-	-
Gliricidia	-	20%	-	-
Rice Straw	-	-	20%	-
Inoculums	10%	10%	10%	10%

Experiment procedure – Batch 02

In the 2nd batch experiments two or more co-substrates were mixed to make the C/N ratio equal to 15 [7] as shown in Table 2. Experiments were conducted at room temperature (30°C) and Total Solids (TS) content was controlled in between 6-7%. pH, TS and COD were measured before (feed) and after (effluent) the digestion process. Cumulative gas volume was measured for every 3 hr time interval for 3 days from the beginning of experiments. Final accumulated CO_2 compositions were measured. To confirm the validity of the results, all the experiments were repeated.

Table 0-2. Feed composition – batch 02

	1	2	3	4
Food Waste %	70	70	70	90
Water Hyacinth %	09	-	04	-
Gliricidia %	11	18	15	-
Rice Straw %	-	02	01	-
Activated Sludge %	10	10	10	10

Pilot Plant experiments

Bulk liquid volume of reactor is 4.9 m^3 and total volume including reactor head space is 5.2 m^3. Plant was operated at 20 days HRT [8] and at maximum pressure of 1.5 bars. There are 3 twisted paddle type impellers inside reactor vessel for uniform mixing which was performed for 30min per day. By water scrubbing, Carbon Dioxide (CO_2) and Hydrogen Sulfide (H_2S) in the biogas was removed and upgraded. By the countercurrent contact of the pressurized gas and water, carbon dioxide get absorbed into water and leave from the bottom of the column. Plastic ring type packing material is used in the column. Pilot plant reactor was fed for a period of two month at 20 days HRT [8]while controlling pH in 6-7 [7] of the feed by using soda lime. The feed mixture was prepared as shown in Table 3 and blended it for 15 minutes inside crusher. Then slurry was fed to reactor using submersible pump.

Table 0-3. Feed composition – Pilot plant

Canteen Food Waste	30 kg/d
Gliricidia	6 kg/d
Cow Dung (only for 10 days)	8 kg/d
Water	250 L/d

Pilot plant reactor was fed every weekday at same time of the day. The produced gas from the reactor, was sent through the scrubber and CO_2 was removed batch wise. Gas was collected to a barrel in water displacement method and then compressed in to LPG cylinder. This compressed gas was later used for conducting three wheeler test runs.

Procedure for modeling

The ADM No.1 was used as the model to simulate the biogas production rate, CH_4, CO_2 and H_2 composition by using simulator called AQUASIM 2.1f

Characterization of feed as dictated by ADM1

Composition of the feed was analyzed according to the ratio of mixed weight. Ratio of each components (carbohydrates, Proteins, Lipids and Inert) contain in the sample was calculated using theoretical data given in Table 4 .

$$\left(\begin{array}{c}\text{Carbohydrates}\\\text{composition}\\\text{of sample 01}\end{array}\right)=\left(\begin{array}{c}\text{Carbohydrates}\\\text{composition of}\\\text{Food waste}\end{array}\right)\times\left(\begin{array}{c}Carbohydrates\\Mixed\\ratio\end{array}\right)+\left(\begin{array}{c}\text{Carbohydrates}\\\text{composition of}\\\text{Water Hyacinth}\end{array}\right)\times\left(\begin{array}{c}Water\ Hyacinth\\Mixed\\ratio\end{array}\right)+\left(\begin{array}{c}\text{Carbohydrates}\\\text{composition of}\\\text{Inoculums}\end{array}\right)\times\left(\begin{array}{c}Inoculum\\Mixed\\ratio\end{array}\right)$$

In order to find out the COD value of each component (X_{ch}, X_{pr}, X_{li} and X_I), composition was multiplied with TCOD value of the corresponding sample.

$$\left(\begin{array}{c}Carbohydrats\\COD\\composition\\X_{ch}\end{array}\right)=\left(\begin{array}{c}Carbohydrates\\composition\\of\ the\ sample\end{array}\right)\times\left(\begin{array}{c}Total\ COD\\of\ the\ sample\end{array}\right)$$

Table 0-4. Characterization of substrates

	Water Hyacinth [9, 10]	Gliricidia[11, 12]	Rice Straw[13, 14]	Food Waste [15]	Activated Sludge[16-19]
Dry matter (DM), %	89.6	34.5	91.1	24.63	4.34
VS %	72.8	92.31	74.7	94.9	62.9
Ash, %	27.2	7.69	25.3	5.1	37.1
C %	-	-	45.2	52.47	-
TKN %	-	-	0.8	3.37	0.15
C/N ratio	23.5	13	60	15	10
Carbohydrates	34.9	21.89	36.6	47.73	12.5
Proteins	14.2	43.52	4.5	21.1	53.7
Lipids	3.3	23.9	7.4	4.87	5.8

50ml syringe was modeled as batch anaerobic reactor and calculated parameters (X_{ch}, X_{pr}, X_{li} and X_I) were set as initial values of the model which implemented in AQUASIM2.1f. Simulation process was carried out for five days in 0.001d of step size to find out gas production flow rate, CH_4, CO_2 and H_2 composition.

Results and Discussion

Experiment results - batch 01

For batch experiments No.1 results are shown in Fig.1. The highest cumulative gas production was observed from sample 02 and 03. But higher gas production rate was observed in sample 02. In sample 02 and sample 03,

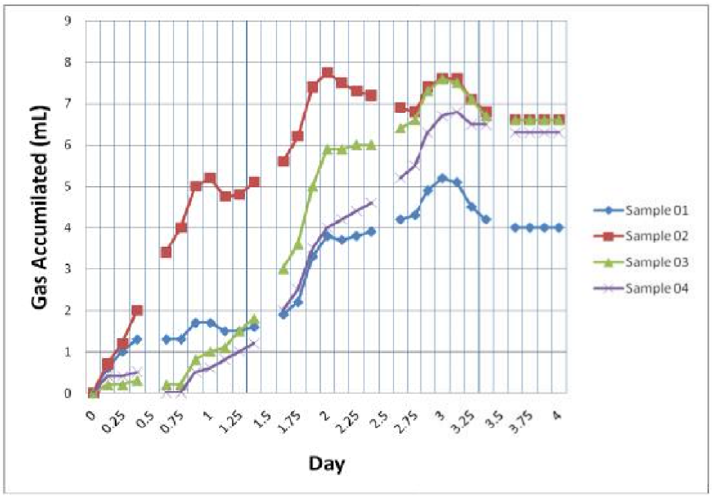

Figure 0-1. Accumulated gas production – batch experiment 01

Gliricidia and rice straw were the co-substrates. Rice straw contains higher amount of fiber and lignin compared in Gliricidia. This lignin and fiber content causes to reduce the hydrolysis rate which is the rate limiting step of anaerobic conversion. Therefore fast hydrolysis could lead to increase gas production in sample 02.

According to the theoretical composition data, Fig.2 shows that composition of samples doesn't vary in considerable amount. But C/N ratio of the sample 01 and 02 were 14.1 and 23.5 respectively. Therefore C/N ratio may affect the gas production rate of sample 02 & 3 as well as content of fiber and lignin.

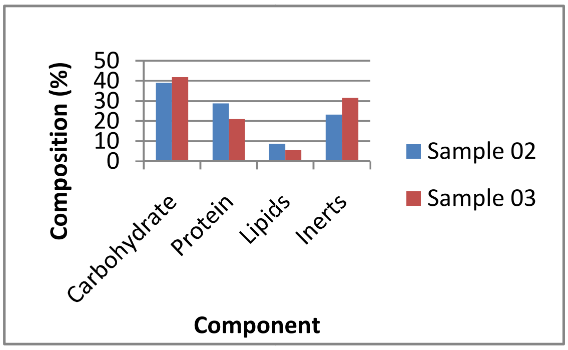

Figure 0-2. Composition of Sample 02 & 03

Experiments results – batch 02

In 2nd batch experiments, C/N ratio was controlled at 15 for all samples. But gas production could be observed only in sample 02 except controlling experiments. This observations shows that when water hyacinth and rice straw content is higher, biogas could not be produced even for same C/N ratio.

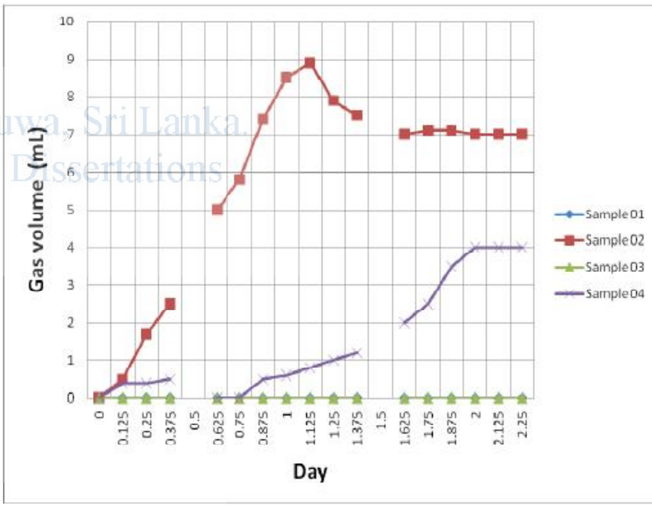

Figure 3 Accumulated gas volume – batch 02

Results from Modeling – Batch 01

According to the modeled results, all samples produces significant amount of CO_2 up to 2 days. This is due to fast fermentation of soluble substances and production of volatile fatty acids (VFA). Hydrogen produced during fermentation is consumed to produce methane and after 3 days no hydrogen can be found in reactor head space. Final CO_2 compositions of all samples are nearly 70%. When compared in Sample 2 and Sample 3, higher gas production rate was observed in sample 02. By volume (as well as weight) 70% of all samples contained food waste which has the highest composition of carbohydrates.

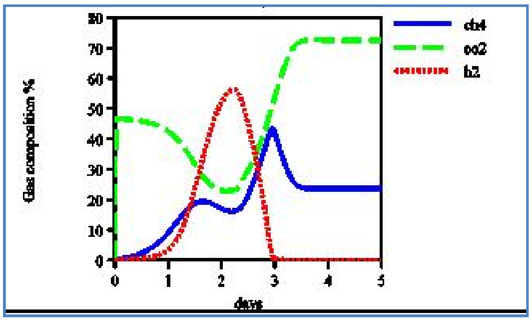

Figure 4. Gas composition for Sample 1

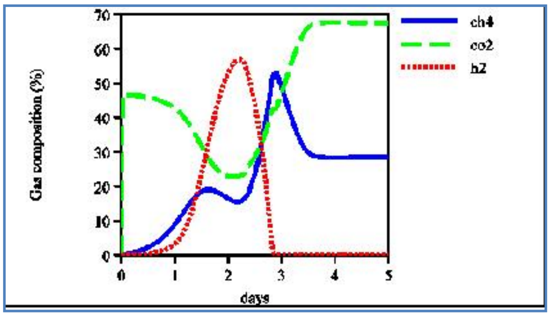

Figure 5. Gas composition for Sample 2

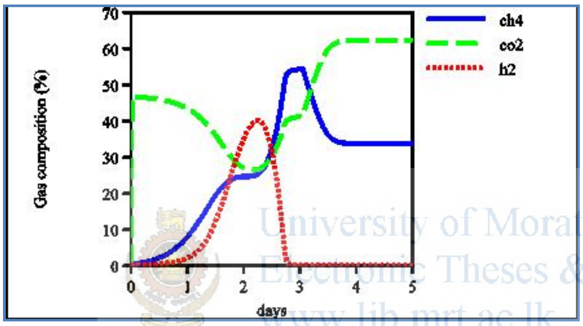

Figure 6. Gas composition for Sample 3

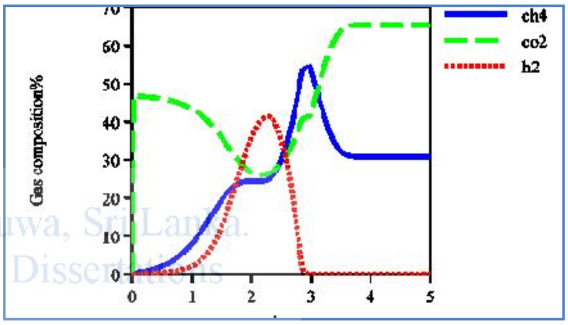

Figure 7 Gas composition for Sample 4

Results from pilot plant

When methane composition is low in biogas, it couldn't generate a flame. During first month of the pilot plant experiment, produced gas could not be burnt because of high amount of CO_2 presence. But after a month of processing, biogas produced was burned and contained average of 60%CH_4. Generally it takes 10 – 20 days to stabilize methanogenic reactions in anaerobic digestion process [8]. In the scrubbing process, methane composition of the feed was 60% and output was improved to 85% of methane. Scrubbing process conducted 15 minutes to treat a 100 L of biogas from reactor.

Upgraded biogas following scrubbing was compressed into fuel tank of three wheeler and test runs were conducted. Biogas was compressed using four stroke overhead valve type compressor at 20 bars. Using volume of 320 liter biogas at 1 atm ambient temperature of 30^0C, distance of 5.3 km travelled. To compress this gas into the fuel tank it took 8 min. Petrol consumption by compressor for this compression task was 0.25L.

Conclusions

Based on batch experiments and dynamic modeling results, it can be concluded that when the feedstock contains 70% food waste, effect of co substrate is minimal and biogas produce mostly contains CO_2 with low methane composition. This is due to the presence of large amount of carbohydrates in the food wastes and resultant fast hydrolysis. Gas production rate is higher when the Gliricidia was used in feed stock as co substrate**.**

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APPENDIX E : PAPER 3

Optimization of an Anaerobic Co-digestion Process – South Asia Regional Workshop on Biogas Technology & Application – 08th July 2010, organized by Energy Forum and Lanka Biogas Association, Sri Lanka.

(**Dilnayana K.W.N.** and Rathnasiri P.G.)

Optimization of an Anaerobic Co-digestion Process

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Abstract

Anaerobic digestion is one of the oldest biological process used for the stabilization of solids and bio solids which is a sustainable technology for waste minimization with renewable energy production. Co-digestion refers to the feeding of two or more substrates to anaerobic reactor for stable operation. In Sri Lankan context, even though plenty of candidate substrates are locally available for co-digestion, lack of technical knowhow, process fundamentals and poor monitoring of process parameters have been caused to failure and less dissemination of this technology.

Objectives of this study are to develop combined experimental and dynamic modeling approach for optimization of co-digestion process to produce high quality methane. Co- digestion of food (canteen) waste with different locally available substrates as gliricidia, water hyacinth and rice straw are used in this analysis. In the first step, lab scale batch experiments were conducted by varying type of substrate under controlled conditions to find highest methanogenic potential. For the same co-digestion mixtures, semi continuously fed lab experiments was also conducted. Optimum process parameters were determined using combined experimental and dynamic modeling approach. Anaerobic digestion model no. 1 (ADM1), was used to simulate the anaerobic co digestion process built in computer program called "AQUASIM 2.1f." By this model it was confirmed that canteen food waste alone cannot be used in AD process because of high rate of hydrolysis and accumulation of Volatile Fatty Acid (VFA). A sensitivity analysis in order to analyze the effects of input waste composition was also performed; revealing that the gas composition changes were particularly sensitive to the carbohydrate content. According to batch experiment results, all samples produced CO_2 at initial phase of anaerobic digestion. Gas production was higher when Gliricidia was used as co-substrate. Dynamic modeling also confirmed that when the co-digested mixture contains 70% food waste, effect of co-substrate is minimal and biogas mostly produces CO_2 with low methane content.

Key words: Anaerobic Digestion, Co-digestion, ADM1, Dynamic Modeling

APPENDIX F : PAPER 4

<u>Development of a New Pilot Scale Co-Digestion Anaerobic Process for Solid Waste Treatment and Bio Methane as a Transport Fuel</u> - Annual Symposium, 4th December 2009, organized by the General Sir John Kotelawala Defense University, Sri Lanka. (**Dilnayana K.W.N**, Kularatne M.A.D.I.C., Rathnasiri P.G., De Alwis A.A.P)

Development of New Pilot Scale Co-digestion Anaerobic Process for Solid Waste Treatment and Biomethane as Transport Fuel

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Abstract

Anaerobic digestion (AD) process has been accepted as a sustainable technology in terms of waste management, renewable energy production and reduction of green house gas emissions. This AD technology has still not been able to solve national solid waste problem because of the lack of technological knowledge on how and reluctance to accept by the public because of failures of these installed reactors. Objectives of this study are two folds: viz. to introduce a new technique for anaerobic solid waste treatment and use upgraded biomethane as transport fuel. The treatment of mixture of two or more substrates such as kitchen waste, sewage slurry, agricultural residues, municipal solid wastes, animal manure in an anaerobic digester is referred to as co-digestion. Before development of the new process, micro-scale and lab-scale experiments were conducted to find methenogenic potential of different substrates readily available in local conditions. Process parameters were identified using combined experimental and computer simulation approach. A Dynamic model called the Anaerobic Digestion Model No.l was used to simulate the anaerobic process which enabled identification of different options for co-digestion. It was concluded that canteen waste which is mainly constitute of carbohydrates alone cannot be used in AD process because of fast hydrolysis and subsequent production and accumulation of volatile fatty acids (VFA). With the aid of experimental and mathematical modeling findings, the pilot-scale plant was designed, fabricated locally and constructed within University of Moratuwa premises to treat canteen waste generated by students. The first trial run was conducted by semi-continuously feeding canteen waste alone with cow dung as the inoculum and as expected the process was inhibited accumulating VFA and reduction of mixed liquid pH. To overcome this problem, waste was co-digested with salvenia, which is readily available in Bolgoda Lake in order to increase nitrogen content of mixture of waste and subsequently the process was recovered. Biogas is upgraded using water scrubbing and brought to > 95 % CH_4 composition, compressed and stored in gas cylinders for tests to be carried out using three wheelers.

Keywords: Anaerobic Digestion, Co-digestion, Dynamic Modeling