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Analysis of Biogas from Agricultural Biomass Wastes fueled in an Internal Combustion Engine Unit

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Abstract

Objectives: Performance and emissions of internal combustion (spark ignition) engine generator is investigated using the representative biogas composition from an anaerobic co-digestion mixture of various agricultural biomass wastes present in Mindanao, Philippines such as rice hull, coconut shell, cow manure as feedstock. **Methods:** The gases from the representative biogas composition are then fed to the 30kW engine generator and investigated the power generated, and its exhaust emissions. **Findings**: Results indicated that the variation of energy generated can be related to the electrical power produced from the engine unit to power the electrical appliances used at the same flow rate and pressure. At 1.4 kW electrical load and heating value of the purified biogas as 50 MJ kg-1, the consumption of biogas was observed to be the same. The engine also showed comparable efficiency ranging from 6.26% to 7.00% at 1.4 kW load. Further, the CO_2 emission is observed to be 5.40% and amount of other emission pollutants are extremely few (nearly zero) using the representative biogas fuel in the engine. Thus, biogas fuel can be used directly as fuel in the spark ignition engine. **Application:** The biogas fuel can be used to other engines, but it requires some minor engine modifications in order to correct the compression ratio, spark ignition timing due to the slower flame speed of biogas fuel.

Keywords: Biofuels, Biogas, Biomass, Engine Emissions, Engine Performance

1. Introduction

Biogas from anaerobic digestion is a potential source of renewable energy. It can be used for the production of process heat and electricity in engines, turbines and fuel cells. Biogas can be cleaned/upgraded to bio-methane and can also be transformed by desulfurization and upgrading. This can be used as a direct substitute for natural gas in power generation, process heating, operating the commercial or industrial gas equipment, cogeneration plants, and in the transportation sector. The components of biogas can be divided as combustible components and non-combustible components. This combustible component comprises mainly CH_4, CO, and H_2 and the non-combustible components as CO_2 and N_2. The combustion characteristics such as flame propagation speed, adiabatic combustion temperature, and chemical reaction process differ from CO, CH_4, and H_2 components. In addition, CO_2 and N_2, differs in heat capacity and their influences on combustion that gives impact on the overall performance of biogas. Moreover, some factors such as the preparation technique and sources of raw material lead to the change of components of the biogas, which is a restriction to the extensive and efficient use of gaseous fuels in internal combustion (IC) engines. With this, many researchers have attempted to utilize bio-methane (biogas) with various gas components in an internal combustion engine.

Biogas is a type of high-octane fuel that can be easily used in the Spark Ignition (SI) engine. Compare to other gases (LPG and natural gas), biogas has much lower flame speed and heating value. Moreover, the ignition temperature of the biogas is higher than that of other gases. These could contribute to the influences of physical and chemi-

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cal characteristics on the application of bio-methane (biogas) in spark-ignition engines.

Most of the recent researches focus on the effects of combustion and emission attributes of utilizing biogas fuel in the engine. There was a reported[1] difference on the efficiency and NO_x emissions of spark ignition engines under different equivalence ratios and compression ratios with CH_4/CO_2 using biogas as fuel. It was found out that increased CO_2 concentrations in biogas fuel, the effect on NO_x emissions can be prevented, and a high-volume fraction of CO_2 can help to inhibit engine knocking.

In addition, another study tried to directly study biogas under laboratory conditions. One of the studies[2] shows that the emissions of biogas as fuel in SI engines and showed that the molecular structure of biogas made it a low emission fuel. CO emissions can be neglected, and HC and NO_x emissions are significantly reduced. However, carbon dioxide emissions will increase, especially without the removal of impurities from the biogas. Moreover, another study[3] conducted using a philosophical model to replicate the effects of compression ratio and ignition timing on the combustion and emissions in an SI engine using syngas as fuel.

To further test the use of biogas in SI engines, some scholars com-pared the combustion and emission of biogas with those of commercial fuels. This study[4] compared with conventional petrol, Compressed Bio-Gas (CBG), Swedish summer (E85) and winter ethanol fuels (E85W) in a CNG/petrol car and an ethanol/petrol passenger car. They found that for the CNG/petrol vehicle, the compressed biogas led to the decrease in energy consumption and NOx, PM and PN emissions, but the CH_4 emissions increased compared to petrol.

The same study[2] compared the effects of gasoline, purified biogas and biogas on the performance of the SI engine by increasing the compression ratio and optimizing the ignition timing. It was found out that higher proportions of CO_2 and other non-combustible gases in the biogas reduced the engine gas efficiency as the maximum power of engine decreased and the fuel consumption increased.

Currently, there is no biogas-operated engine designed four stroke SI combustion system for the locomotive application. Typically, a four-stroke SI engine has been chosen for biogas conversion since it is convenient to modify the engine to use biogas as they can continue to use as conventional fuel. Likewise, conversion of petrol engines to use biogas as fuel, for higher energy output requires some component design. As the biogas fuel concentration is less than 100%, it requires some modification on the supply lines and for optimal running using biogas fuel. The biogas can be introduced to the carburetor via the inlet pipe, fitted between it and the air cleaner, regulator. Even when the conversion is made correctly, there is likely to be some loss of power when the engines run biogas instead of petrol, because of the compromise required adapting the engine to use both fuels interchangeably. This can be compensated for by increased compression ratio of the engine in order to increase the engine efficiency. Altering the spark ignition engine for biogas fuel requires some modifications in the carburetor with mixing chamber attached. This can evaluate the use of biogas on the performance, emissions of a four-stroke SI engine generator.

The goal of this current research is to determine the effect of biogas fuel from agricultural biomass wastes and also to determine the engine generator performance as well as its exhaust emissions and comparing the performance of the biogas-fueled engine with a standard gasoline engine.

2. Materials and Methods

2.1 Biogas Production from Agricultural Biomass Waste

The biogas utilization experiments were conducted using chemically pure (99.99%) methane gas; and a mixture of methane gas and carbon dioxide (65% CH_4 and 35% CO_2), prepared by Airgas (Airgas Southwest, Woodlands TX). This gas mixture is a good representation of the product biogas from the Anaerobic Digestion of Agricultural Biomass Waste and product gas of the Pressure Swing Adsorption processes. The feedstock used for biogas production was a mixture of cow manure with rice straw, coconut shell, and sewage sludge. The biogas samples were collected into a 1 L Tedlar bags (Restek, Bellefonte, PA) throughout the study and analyzed using SRI gas chromatograph (SRI Instruments, Torrance, CA) with TCD and HID detector to validate the H_2, CO, CO_2, and hydrocarbon composition. Shincarbon ST, 100/120 mesh and Molecular sieve 13X packed columns were used to separate the gas components

2.2 Characterization of the Test (Biogas) Fuel

The energy content of the fuels was also determined and reported as the gross heating value in Table 1. It is basically the amount of energy released by the combustion processes. The compositional analysis of the used fuel, which is the methane-enriched gas and biogas were analyzed using SRI Gas Chromatograph. The reference data for gasoline and compressed natural gas are given by[5-6].

2.3 Biogas Engine Test (Natural Gas Engine)

Figure 1 shows the 30-kW natural gas engine-generator used for the biogas utilization system for power generation using purified biogas as a fuel. The experiment will test the performances of the engines at a certain electrical load such as two glycol chillers using the biogas test fuels that were determined in accordance to SAE J1349 Power test code procedures[7]. A randomized complete block experimental design was used to determine the effects of the type of fuel and electrical load on the generator on the overall engine generator efficiency, exhaust temperature, and emissions, particularly the NO_x, Hydro-Carbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2) concentrations. Standard gasoline and biogas, at different electrical power loads – no load, and 5% load (1.4 kW) were used throughout the experiments. Electric heaters were utilized to provide the different electrical load to the generator. The fuel energy input to the generator for each electrical power load was measured as the product of flow rate and the net heating value of the respective fuels.

The Brake Specific Fuel Consumption (BSFC) is a measure of fuel efficiency within the crankshaft of an internal combustion engine[8]. As an indicator of the performance of fuels in engines, it denotes fuel consumption to the power produced. Moreover, efficiency is generally the same when using gasoline or biogas (bio-methane) fuel[9].

Efficiency various fuel efficiency as this describes fuel consumption in an engine. The range of operating speeds is generally operated at consistent, intermediate loads. However, this range does not completely represent the moveable off-road engines units, which may be operated at maximum engine speed.

2.4 Biogas Emission Testing

The engine performance and exhaust emissions testing were conducted at the Texas A&M University, Bio-Energy, and Analysis Laboratory (BETA Lab) engine testing facility. Instrumentation needed to measure some of the EPA regulated emissions, such as CO, CO_2, NO_x, THC, and SO_2 was in place. Exhaust emissions such as CO, NO_x, and SO_2 were measured with electrochemical SEM sensors, while CO_2 and Total Hydro-Carbons (THC) were collected and analyzed using an ENERAC Model 3000E emissions analyzer (Enerac Inc., Holbrook, NY) during each test that lasted for 15 min. The emissions analyzer was designed to meet all the performance specifications of US Environmental Protection Agency's Test Method for the Determination of Nitric Oxide, Nitrogen Dioxide and NO_x emissions from stationary combustion sources by an electrochemical analyzer. Non-Dispersive Infra-Red (NDIR) detectors were used to measure the hydrocarbons, carbon monoxide and carbon dioxide concentrations of the exhaust gas. Stack temperature was measured with a thermocouple placed at the inlet of the gas sample probe.

Table 1. Table of selected fuels and their properties

Properties	Gasoline	Compressed Natural Gas	Methane enriched biogas	Biogas
Composition (%v/v)		CH_4 - 86% C_2H_6 - 7 % C_3H_8 - 2% N_2 - 1% CO_2 - 5%	CH_4 – 99 % Other gases – 1%	CH_4 – 61.75% CO_2 – 35.98% N_2 – 0.75% Other gases – 1.1%
Lower Heating value (MJ/kg)	42.50	48	50.03	19.25
Relative Density	827-840	0.78	0.657	-
Flame speed (cm/s)	-	34	-	-
Stoichiometric A/F (kg of air/kg of fuel)	-	14.5	-	-
Auto-ignition Temperature (°C)	250	540	-	-
Reference	[5]	[6]	This Study	This Study

Figure 1. Experimental set-up for biogas utilization in natural gas engine.

The emissions analyzer has a capability of measuring NO_X concentrations; CO and SO_2 concentrations; THC concentrations; and CO_2 concentrations shown in Table 2. In addition, it also measures the ambient temperature, stack temperature, stack velocity, and test cell O_2 concentrations. Air and relative humidity are carefully monitored. Fuel temperature is controlled as outlined in the test procedure. Tests were conducted in a block design to prove that the fuel is not significant to the results of the study. Fuel consumption (L/h), NO_x concentrations (ppm), unburned hydrocarbon concentrations (ppm), CO concentrations (ppm), and CO_2 concentrations (%) are the results of the said experiments.

Table 2. Enerac 3000E integrated emission system technical data

Measured Parameters	Measured Range	Resolution
Ambient Temperature	0 - 150 °C	1 °C
Exhaust Temperature	0 - 1,100 °C	1 °C
Oxygen (O_2)	0 - 25% vol.	0.10% vol.
Nitrogen Oxide (NO)	0 - 3,500 PPM	1 PPM
Nitrogen Dioxide (NO_2)	0 - 500 PPM	1 PPM
Carbon Monoxide(CO)	0 - 20,000 PPM	1 PPM
Carbon Dioxide (CO_2)	0 - 20% vol.	0.10% vol.
Sulfur Dioxide (SO_2)	0 - 7,000 PPM	1 PPM
Hydrocarbon	0 - 10,000 PPM	1 PPM

2.5 Biogas Engine and Emission Tests Experimental Procedure

In the engine testing and emission analysis experiment shown in Figure 2 is conducted using the natural gas engine unit with purified biogas (99% CH_4) as a fuel. The purified biogas was used to ignite the engine by feeding the purified biogas to the engine unit with a gas flow rate of 73 sLPM and pressure at 65 psi (450 kPa). After the engine warmed up enough, the generator turned and the electrical loads (2 glycol chillers) are also turned on simultaneously. During the experimental runs, electrical

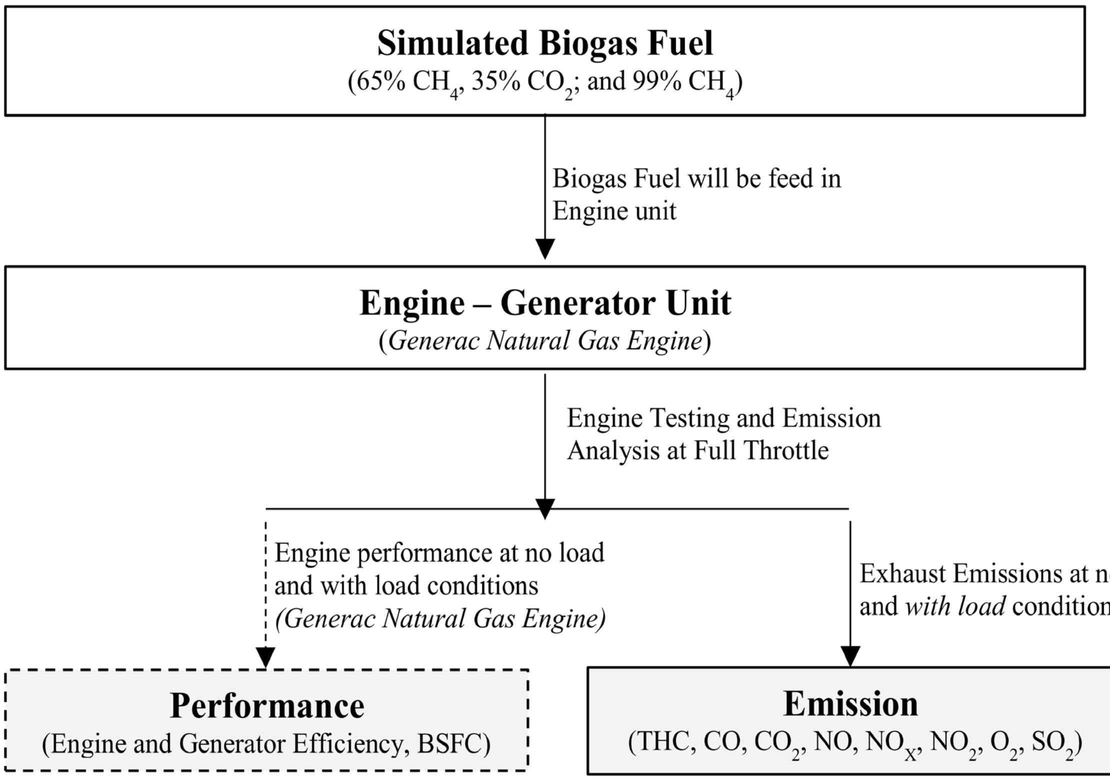

Figure 2. Schematic diagram of the biogas utilization and engine testing experimental procedure conducted in this study.

power, energy generated, flow rate, pressure, and emissions are being recorded periodically for the analysis.

3. Results and Discussion

3.1 Performance Analysis of Natural Gas Engine using Biogas as a Fuel

The comparative variation of energy generated and combustion efficiency with respect to the fuel rate (54 LPM) and pressure (65 psi) are represented in Figure 3. Based on the observations, it shows that there is no significant difference in combustion efficiency while using purified biogas (99% CH_4), at a fixed electrical load of 1.4 kW. Moreover, the variation of energy generated can be related to the electrical power load (Figure 4), produced from the natural gas engine unit to power the electrical load, provided that has the same flow rate and pressure. The energy generated is dependent on the electrical power consumption. However, the energy generated has little fluctuation considering the electrical load used was a glycol chiller which has a compressor that causes the fluctuations.

In addition, the comparative variation of energy generated with exhaust temperature and time are shown in Figure 5. As observed, the exhaust temperature increases with increasing energy generated. Also, exhaust temperature was maintained during the engine testing operation using purified biogas as a fuel.

3.2 Analysis of the Exhaust Emissions of Biogas Fueled in a Natural Gas Engine Unit

The emission concentrations of NO_x, hydrocarbons, carbon monoxide, and carbon dioxide are shown in Figure 6 and 7. The NO_x emissions for the biogas fueled were relatively the same and within the error limit at 1.4 kW electrical loads. The lower NO_x emissions for the purified biogas operation without load might be due to the lower temperatures in the engine cylinder because of the lower LHV of biogas and the less favorable condition for the reaction between nitrogen and oxygen to occur. NO_x is formed from the reaction between oxygen and nitrogen at high temperatures in a reaction separate from combustion by[10].

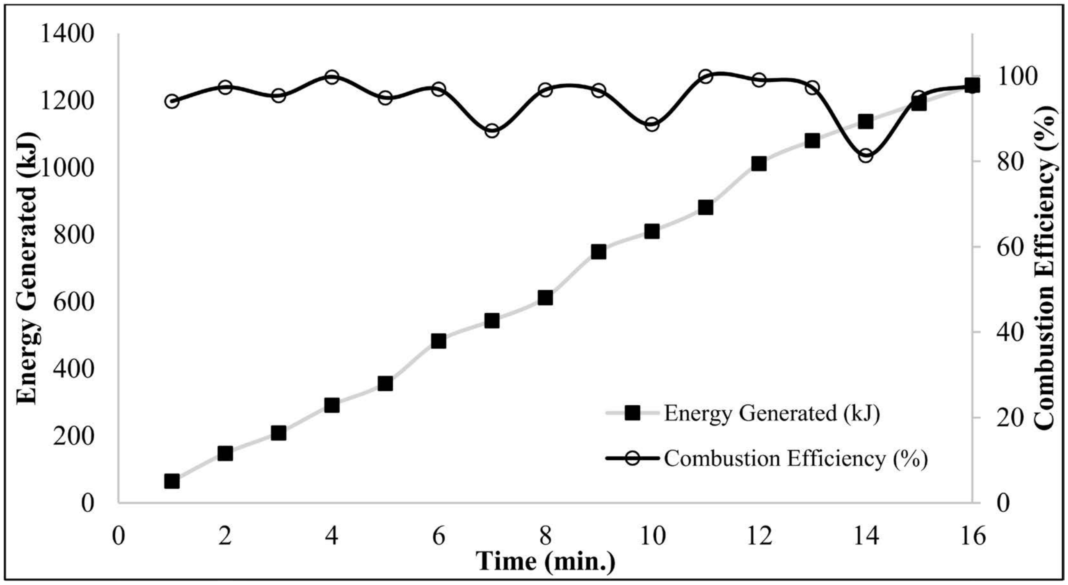

Figure 3. Variation of power generation and combustion efficiency with time.

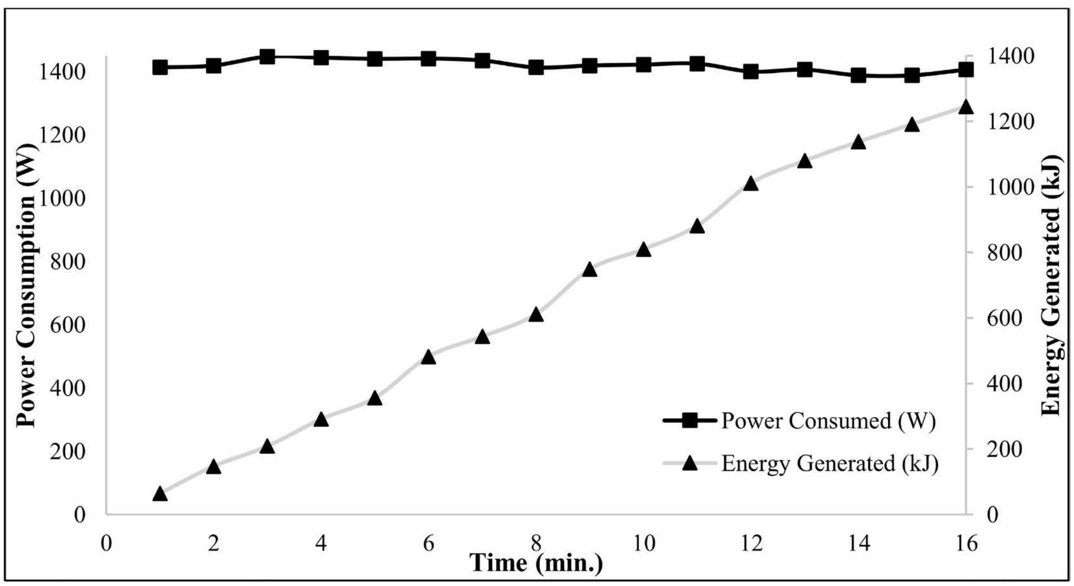

Figure 4. Variation of power consumption with energy generated.

This signifies the dependence of NO_x emissions on temperature. For gasoline fuels, the higher NO_x emissions were expected as the temperature is expected to increase as the electrical power load was increased. The temperature generated within the engine cylinder would be higher with higher electrical power output from the generator. The significantly lower NO_x emissions of biogas as engine fuel as compared to gasoline add to the potential use of biogas to run engines. NO_x causes lung irritation, impairment of functions of the lungs, tissue damage and irritation of mucous membranes and increases the risk of nitric acid formation[11].

With an average of 43 ppm, the total HC concentrations of the exhaust gas from the gasoline operation did not show any significant difference at different electrical loads. The HC concentration for biogas fuel was highest (46.60 ppm) at 0 electrical loads and lowest (33.73 ppm) at 1.4 kW electrical loads.

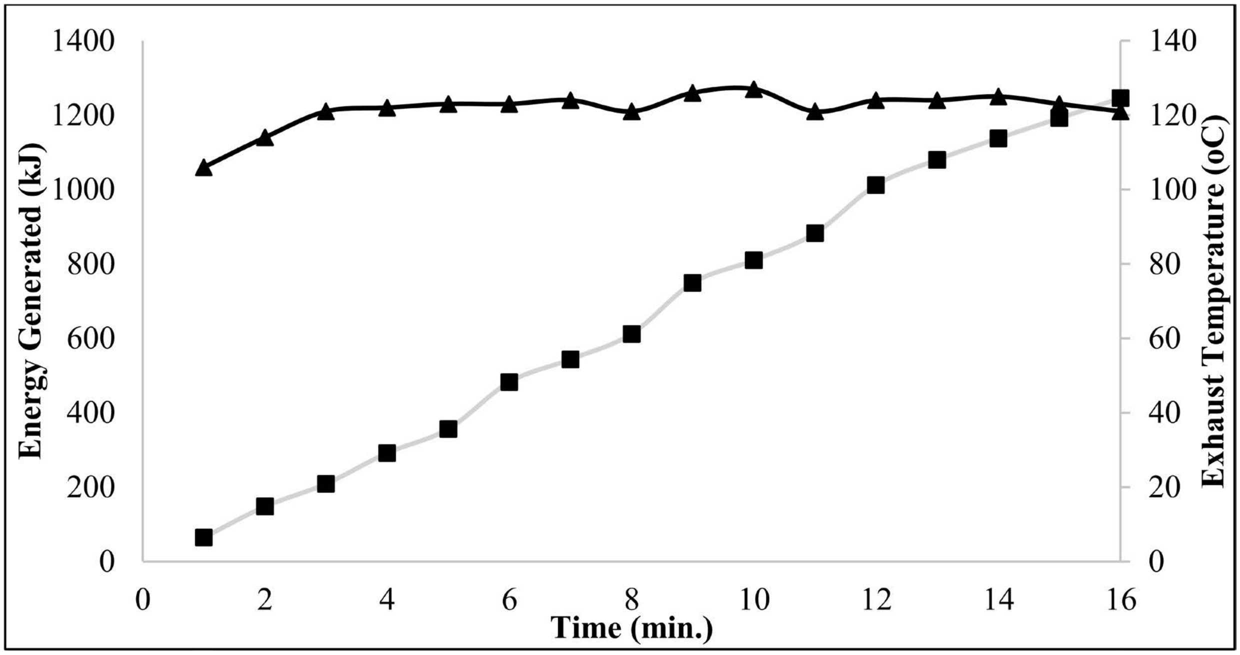

Figure 5. Variation of exhaust temperature with energy generated of power consumption with energy generated.

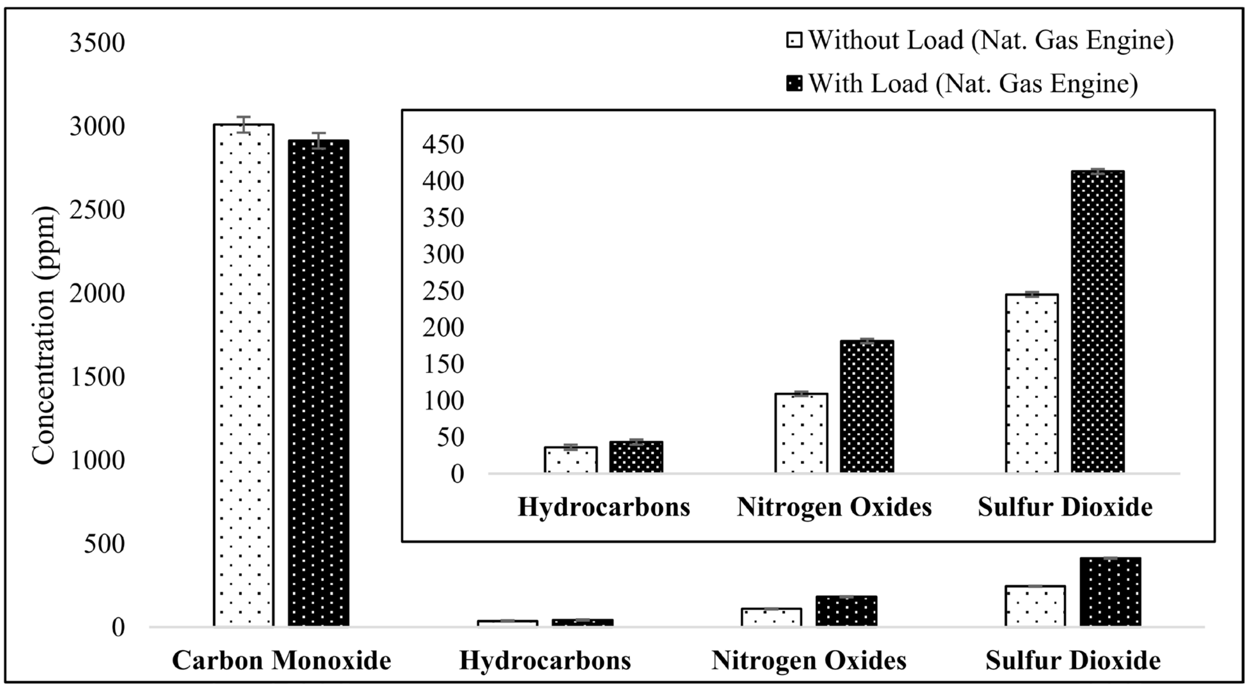

Figure 6. Exhaust emissions data for CO, HC, NO_X and SO_2.

Hydrocarbons in the exhaust gas are the unburned fuel that has been left because of incomplete combustion. A rich mixture, lack of oxygen or excess fuel results in high amounts of HC. Another cause is an excessively weak mixture that does not support complete combustion within the combustion chamber. HCs are also formed when fuel vaporizes and escapes into the atmosphere from the fuel system[12]. High HC level would result in the reduction in combustion efficiency. A rich mixture could be the reason why HCs are high in gasoline operation since the engine is at the wide-open throttle. Low HCs on biogas operation at higher loads were directly related to the higher overall efficiency.

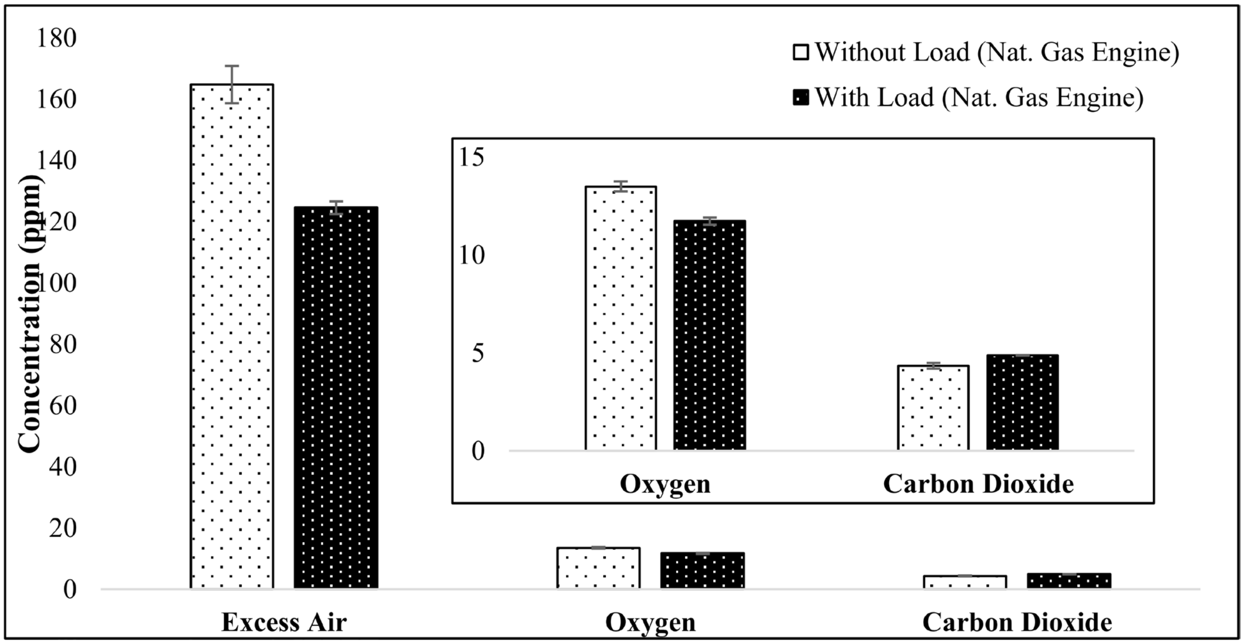

Figure 7. Exhaust emissions data for oxygen, carbon dioxide and excess air.

CO is formed during partial combustion of fuel. The combination of a carbon atom from hydrocarbon fuel with an oxygen atom from the inducted air forms CO. It is produced under a rich condition or poor mixing of fuel and air resulting in pocket[12]. CO emission was significantly lower for biogas fuel compared to gasoline fuel, perhaps because of the lower carbon content in biogas when compared to gasoline.

The substantial decrease in CO emission with the use of biogas engine fuel reinforces its importance as low concentrations of CO would decrease the risk of suffocation caused by the strong adherence of CO to hemoglobin[11].

Carbon dioxide CO_2 emissions in the biogas operation were significantly lowers since it is a product of complete combustion. The more efficient the combustion is the higher the CO_2 content in the exhaust gas. However, this experiment shows that the CO_2 emissions in the biogas were lowered due to the CO_2 component present in the biogas are already removed thru Pressure Swing Adsorption (PSA) process. The experiment shows a decreasing trend in CO_2 emissions as the electrical power load is fixed at 1.4 kW. The trends of the results for the different emissions obtained in this study were similar to those obtained from previous studies conducted[2,13].

The amount of sulfur dioxide present in the exhaust emission can be expected due to varying engine speed and impurities of engine-cylinder oil or lubricant. Moreover, it is reported that SO_2 from diesel exhaust deteriorates NO_x catalyst[14]. Moreover, tar is possibly formed in the piston-cylinder assembly during the testing of syngas fuel, which is prior to the biogas fuel testing. In addition, the sulfur dioxide on the emissions can be accounted for the residual sulfur in the engine and also the sulfur compounds present in the environment.

3.3 Parametric Evaluation on Exhaust Emissions in a Natural Gas Engine Unit

The A 30-kW natural gas engine-generator was connected to a gas tank which contains methane (represented as purified biogas). The emission test is conducted for 15 minutes and it was repeated three times, and the results are shown in Figure 8-11.

Carbon monoxide produced by the partial reduction of carbon dioxide will depend on the gaseous fuel mixture temperature[13]. The effect of carbon monoxide emissions on energy generated under normal biogas operation at an electrical load of 1.4 kW, a flow rate of 54 LPM is shown in Figure 8. From observation, carbon monoxide emissions show relatively the same with increasing operation time and energy generated. At maximum energy generated, the CO emissions are observed to be 2,832 PPM. This represents that corresponding reduction of CO.

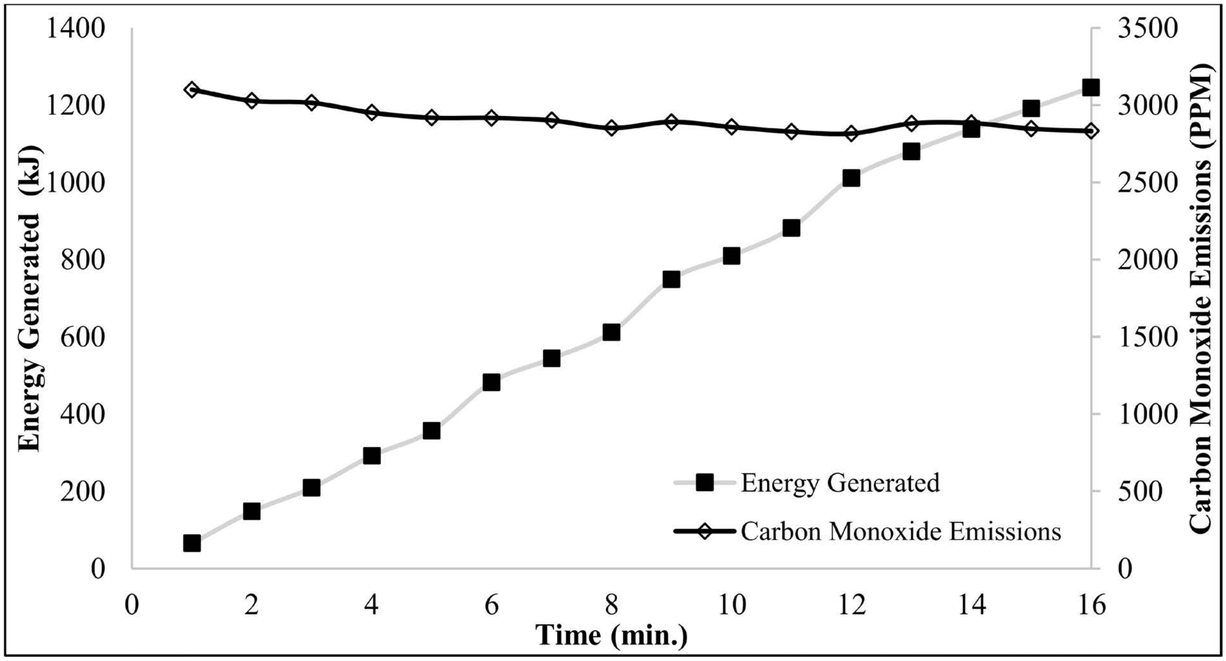

Figure 8. Effect of power generation on CO emission.

The emission of carbon dioxide emission at the generator exhaust unit using the chemically pure biogas fuel at a fuel flow rate of 54 LPM and a pressure of 65 psi (≈450 kPa) is shown in Figure 9.

From the observations, % CO_2 increases with increase in energy generated for the purified biogas fuel (99% CH_4) considered. At maximum energy generated (1,137.6 kJ), the CO_2 emission is observed to be 5.40%. As per emission analyzer technical data from Table 2, CO_2 emissions for more than 20,000 PPM (2% vol.) are not measured. The effect of energy generated on the natural gas engine generator using purified biogas was shown in Figure 10. The concentration of unburned hydrocarbons will depend mainly on the combustion quality of the engine.

However, 90% of the total unburned hydrocarbons emissions typically consisted of unburned methane and non-methane hydro-carbon emissions[5].

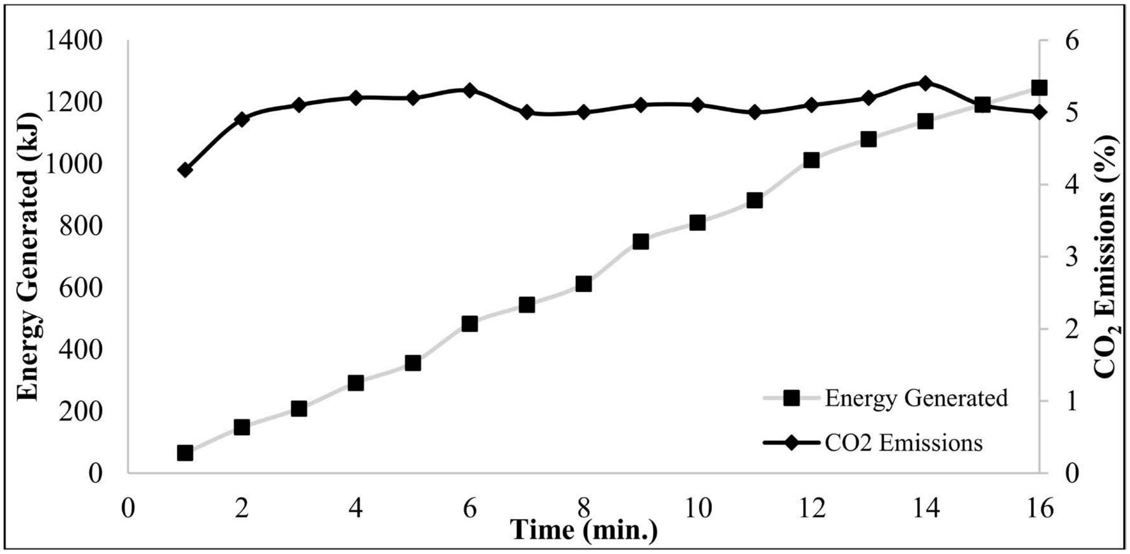

Figure 9. Effect of power generation on carbon dioxide (CO_2) emission.

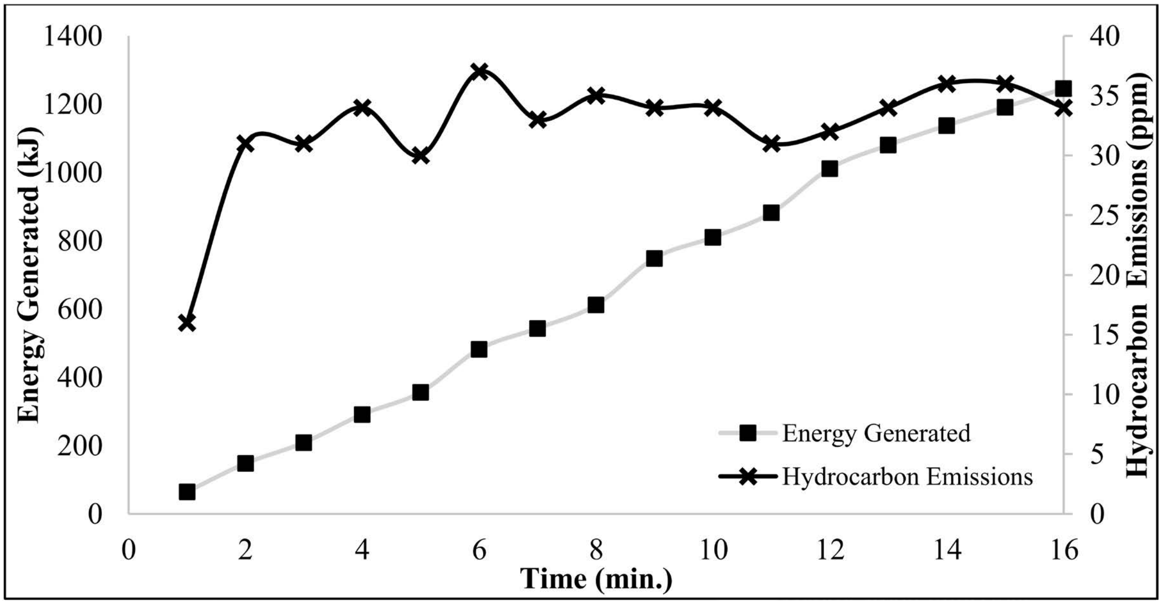

Figure 10. Effect of power generation on HC emission.

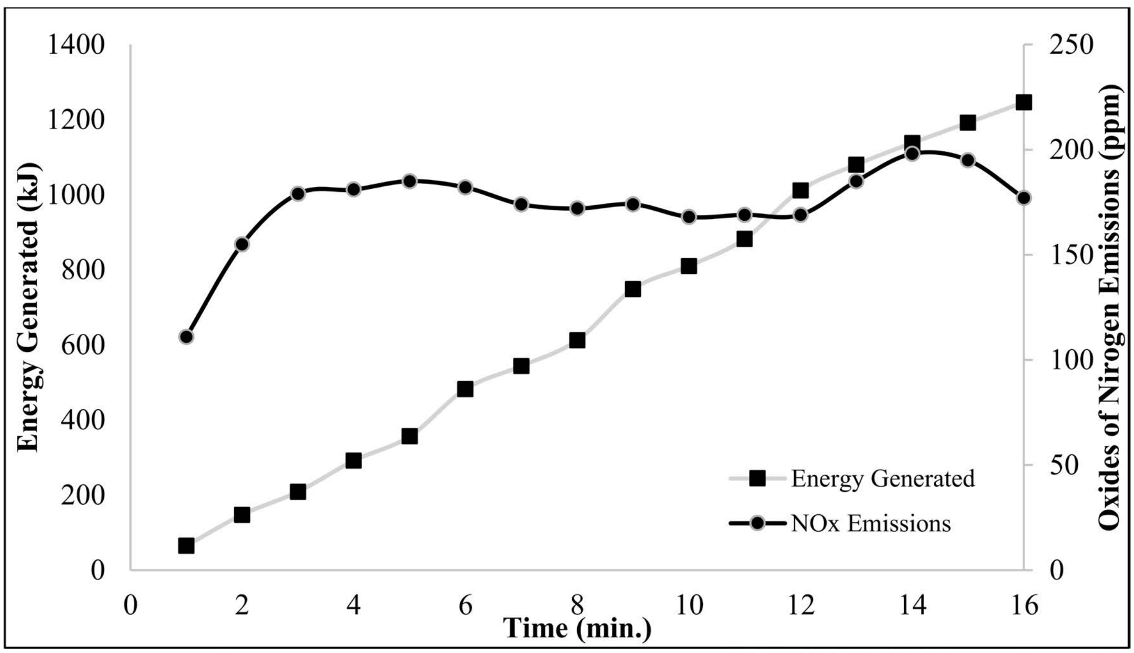

Figure 11. Effect of power generation on oxides of nitrogen (NOx) emission.

As observed, the HC emissions will remain the same (within the error limits) through the electrical load is constant under purified biogas operation. HC results on these experiments conform to the results of[13] that variation of hydrocarbons will decrease significantly with an increase in electrical load. Other studies of[5] contradict the present study since the unburned hydrocarbon emissions increase with electrical load due to incomplete combustion of biogas.

This also supported by[15] that significantly drop levels of unburned hydrocarbon emissions lead to complete combustion of the engine using biogas as a fuel. The HC emissions data confirms the argument of improved and complete combustion and also to confirm the effect of using purified biogas fuel as opposed to non-purified biogas shown in Figure 10.

As shown in Figure 11, the lean fuel-air ratio mixture in natural gas engines using purified biogas as the fuel produces lower NO_X emissions as a result of lower combustion temperature as compared with a stoichiometric operation. In the same manner, NO_X concentration relatively the same even after the energy generated increases with time at the maximum NO_X concentration observed at 195 and 198 PPM.

In addition, there are no reported values of nitrogen dioxide (NO_2) observed in the experiments and established that most of the NO_X emissions are contains only with nitrogen oxide (NO) gases. As reported to other literature studies, the formation of NO emissions takes place at higher temperatures and it depends on the oxygen concentration and gaseous fuel temperature[13].

3.4 Comparison Exhaust Gas Emissions Values

The contents of exhaust gas components measured by Enercon 3000E Emission analyzer are shown in Table 3. The number of emission pollutants is extremely few (nearly zero) in using purified biogas as a fuel in a natural gas engine. It was observed that oxygen content is higher (13.50, 11.73%) in reference to the published data of[16]. This implies that the air to fuel mixture is lean, have more oxygen required in order to have complete combustion. In the same manner, the amount of sulfur dioxide is also higher than the reported values, and it simply implied that sulfur components from the emission test were coming from the engine oil[17], that cause the emissions although the purified biogas contains purely methane gas molecules since the Hydrogen Sulfide (H_2S) is already removed through the dry desulfurization systems.

4. Conclusion

The performance of a natural gas engine generator using biogas from agricultural biomass waste was evaluated based on its efficiency and exhaust emissions. A 30 kW Natural Gas Engine was tested in order to determine the effects of the purified biogas fuel and electrical power loads on the generator exhaust temperature, and emissions.

At 1.4 kW electrical load and heating value of the purified biogas 50 MJ kg-1, consumption of biogas was observed to be the same. The natural gas engine also showed comparable efficiency ranging from 6.26% to 7.00%. Thus, biogas fuel can be used directly as fuel in the Spark Ignition Engine. However, it needs some engine modifications in order to correct the Compression Ratio (CR), spark ignition timing due to the slower flame speed of Biogas fuel.

Further refinement and optimization of engines and emissions of an engine under variable conditions need to be analyzed in detail. Also, extensive research on the engine exhaust and non-methane hydrocarbon emissions can be analyzed since the process is dealing with agricultural biomass wastes.

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Table 3. Gas emission values for Enercon 3000E emission analyzer

Gas Emissions	Test Value		Reference value		
	Without load	**With load**	**Biogas**	**Gasoline**	**Diesel**
O_2 (%)	13.50	11.73	6.24	0.3 - 0.8	2.0 - 18.0
CO_2 (%)	4.34	4.87	8.36	5.0 - 12.0	1.0 - 10.0
NO_x (%)	0.01	0.02	0.19	0.1 - 0.05	0.001 - 0.4
SO_2 (%)	0.02	0.04	0.00	0 - 0.0002	0 - 0.03
AFR	17.37	10.88	42.28	no data	no data

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