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Performance of Various Fuels: Gasoline, Liquefied Petroleum Gas and Biogas from Agricultural Biomass Waste in a Two-Stroke Internal Combustion Engine

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Abstract

The Philippines is an agricultural country with massive agricultural waste. The Biofuels Law (Republic Act 9367) aims to minimize the dependence on fossil fuels and encouraged the use of bio-based fuel sources as an alternative fuel in rural areas where farming is the only source of income, and energy is scarce. Biogas is a renewable energy carrier consisting of methane and carbon dioxide mixture. Because of its improved mixing ability with air, clean-burning nature and high-octane number that resists knocking, biogas is an excellent alternative source of energy for internal combustion engines. The single-cylinder two-stroke spark-ignition (43 cm^3) was designed to be fed with a variety of fuel in order to assess engine performance parameters such as brake power, brake speed, brake-specific fuel consumption (BSFC) and thermal efficiency at different throttling positions (low- and high-load throttle). This study evaluated the engine performance of biogas (cow, swine and cow-swine manure), liquefied petroleum gas (LPG) and gasoline with two-stroke engine oil (2T) in a dynamometer without modifying the compression ratio. To optimize its use as a fuel for power generation, biogas was purified using hydrogen sulfide adsorption and carbon dioxide absorption. The results showed that biogas fuel from swine manure generated the highest electrical power load of 761 W with a methane concentration of 51% and a BSFC of 1.4 kg/kW-h. The LPG achieved the highest engine speed at 14,700 rpm with 549 W. In conclusion, the purified biogas fuel can be used in a small-scale internal combustion engine.

Keywords*:* biogas fuels, gasoline with 2T engine oil, liquefied petroleum gas, spark-ignition engine, two-stroke engine

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1. Introduction

Biogas is a flammable mixture of different gases produced by the decomposition of biodegradable organic matter in the absence of air (no oxygen) and the presence of anaerobic microorganisms. It consists of a mixture of 55-65% methane (CH_4) and 35-45% carbon dioxide (CO_2) with small traces of nitrogen, oxygen, water vapor, and hydrogen sulfide, which are produced naturally (Kaparaju and Rintala, 2013). Among these components, only methane is essential in the combustion process; other components are not flammable at normal conditions but can significantly reduce the calorific value of the fuel. Biogas, being a clean fuel, has great potential to be applied in internal combustion engines because of its better mixing ability with air and cleaner burning nature which leads to lower costs and lower emissions compared with other secondary fuels. Moreover, purified biogas has higher auto-ignition temperature, lower emission and higher knocking resistance because of its high-octane number and allows spark-ignition engines (SI) to run at higher compression ratios, which increase the brake thermal efficiency (BTE) of the engine (Simsek and Uslu, 2020). Like conventional petroleum-based fuel, gaseous fuels are desirable in SI engines because of their wide ignition limits and capability to form homogeneous mixtures with a high hydrogen-to-carbon ratio. Maintenance of the engine's original compression ratios, air-fuel and ignition timing for the biogas-fueled engine is also highly recommended to achieve low emission and high fuel conversion efficiency when operated in an SI engine (Porpatham *et al.*, 2013). Also, it is much easier to modify an SI engine to run on biogas than a diesel engine. Compared with liquefied petroleum gas (LPG), syngas and compressed natural gas (CNG), biogas has a lower flame speed, energy density and heating value if used in compressed form in cylinders. Due to its high ignition temperature, biogas cannot be used to power a compression ignition (CI) engine, but it may be used in a CI dual-fuel system (Barik and Sivalingam, 2013).

As an alternative fuel to gasoline engines, LPG is widely used in SI engines because of its efficient combustion characteristics and low emissions with high octane rating (Sim et al., 2005). Although propane is the most abundant component of LPG, it also contains butane, propene, iso-butane and n-butane in different portions at high pressures. Liquefied petroleum gas has a higher latent heat of vaporization, low carbon content and clean burning fuel; it is less expensive than gasoline and can be used in SI engines. The calorific value and octane number of LPG are higher compared with other gaseous fuels making it suitable for SI engines although it has a lower cetane number (Ravi et al., 2017). However, the advantages of LPG cannot be fully exploited when it is used in gasoline engines with well-known techniques of conversion application (Porpatham *et al*., 2013). The use of gasoline with 2T engine oil as an alternative fuel for gasoline engines is increasing because of its simple design, ability to provide high power output, quick starts at low temperatures, and low cost. The 2T engine oil of the two-stroke internal combustion engine serves as the lubricant because of the absence of a built-in lubrication system with the presence of air. The use of gasoline fuel in SI engines produces several gaseous impurities that lower the octane number and oxidizes unsaturated hydrocarbons, which decrease the lubricating quality and tend to form sludge on piston and rings. Gasoline fuel also has a lower efficiency and higher cost than other fuels (Ray *et al*., 2013).

Some studies on the use of biogas as a fuel in SI engines have been conducted in recent years. Hotta *et al.* (2019) performed tests at several engine speeds to investigate biogas in a 10-compression ratio gasoline engine, and the results showed that the brake-specific fuel consumption (BSFC) increased by 66% while BTE decreased by 12%. The result also indicated that CO and NO_x emissions decreased by 40 and 81.5%, and HC and CO_2 increased by 6.8 and 40%. Moreover, the cylinder pressure obtained by the utilization of biogas was found to be lower than gasoline. Simek *et al*. (2020) investigated emissions, performance and combustion of LPG, gasoline and biogas fuels in a single-cylinder, four-stroke, SI engine. Biogas and LPG resulted in a 75 and 34% increase in the BSFC values, respectively, relative to gasoline in the full-throttle operative conditions; however, they had a decreasing effect on cylinder gas pressure. Reddy *et al*. (2016) used biogas in SI engines under different loading conditions at different fuel flow rates, and the results showed that the thermal efficiency was reduced by 4%. The engine was also tested using biogas and LPG, with biogas emitting less carbon monoxide. Nayak *et al*. (2016) examined the effects of different gasoline and LPG mixtures (25, 50, 75 and 100% LPG) on the SI engine at different engine speeds. The experiment results suggested that the pressure increased as the LPG ratio in the test fuel increased. Porpatham *et al.* (2013) examined the effect of the concentration of methane in biogas used as a fuel in an SI engine. They observed that the increase in methane concentration in biogas significantly enhanced the performance and reduced the emissions of the hydrocarbons. Moreover, the elimination of CO_2 from biogas resulted in higher methane and oxygen concentrations in the charge leading to faster combustion and higher power outputs at a given equivalence ratio. In the study by Chandra *et al.* (2011) on an internal combustion engine, it was found that the thermal efficiency, specific gas consumption and brake power of methane-enriched biogas were comparable with compressed natural gas. As a result, methane-enriched biogas showed an increase of up to 1.6 times of power output over raw biogas when used in an SI engine. It was concluded that the methane-enriched biogas had excellent fuel properties similar to natural gas. Çinar *et al.* (2016) discovered that the use of LPG increased BSFC and gas emissions while decreasing brake engine torque. Although there are many studies in recent years concerning the use of biogas and LPG in four-stroke SI engines, there are no studies on the use of LPG, gasoline and biogas in a two-stroke SI engine.

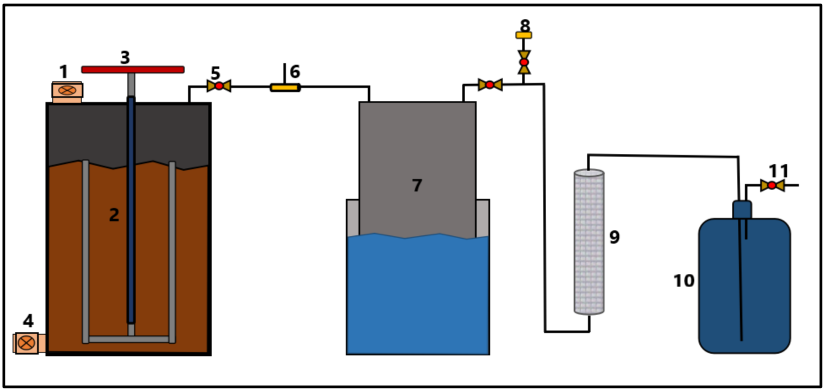
To fill in the aforesaid gap, this study aimed to test the purified biogas fuels from various biomass substrates such as cow, swine and a 1:1 ratio of cow and swine manure mixtures as an alternative fuel source in the two-stroke SI engine generator and compared with benchmark fuels (gasoline with 2T engine oil and LPG) without changing the compression ratio of the original spark engine. Moreover, the study determined the engine performance parameters such as speed, brake power, BSFC and BTE under different throttling opening conditions (low- and high-load throttle) considered for power generation applications.

2. Methodology

2.1 Biogas Production

The experimental set-up of the biogas system was designed to produce biogas that was used to fuel the engine during the engine performance test. It consisted of a biogas digester, gas holder and purification system of hydrogen sulfide and carbon dioxide using steel wool and a water scrubbing system. The biogas system was composed of cow, swine and 1:1 cow-swine mixed manure used separately at different anaerobic digesters under mesophilic temperature and ambient temperature. The manures were collected from Manresa Farm, Upper Carmen, Cagayan de Oro City, Philippines. Each collected animal manure weighed 50 kg and was mixed with a manure-to-water ratio of 1:1.5 (Malolan *et al.*, 2021). Temperature sensor (DS18B20, RS Pro, United States) and pressure sensor (MPX5100, NXP Semiconductors, B.V. Inc., Taiwan) were used to monitor the temperature and pressure inside the biogas digester. Furthermore, because the research is a batch-feeding process, no organic load was fed inside the digester. After being placed in the digester, the selected manures were stirred daily to ensure that the bacteria and the substrate were well-mixed and homogenous.

Figures 1 and 2 show the schematic diagram and actual experimental set-up, where the gas produced (raw biogas) was stored in the gas holder before going to the removal system.



1 – manure inlet; 2 – digester tank; 3 – stirring rod; 4 – digestate outlet; 5 – gate valve; 6 – pressure and temperature sensor; 7 – floating drum; 8 – outlet for testing methane - gas analyzer; 9 – H_2S removal; 10 – CO_2 water scrubbing removal; 11 – outlet for testing purified biogas - gas analyzer

Figure 1. Schematic diagram of biogas system

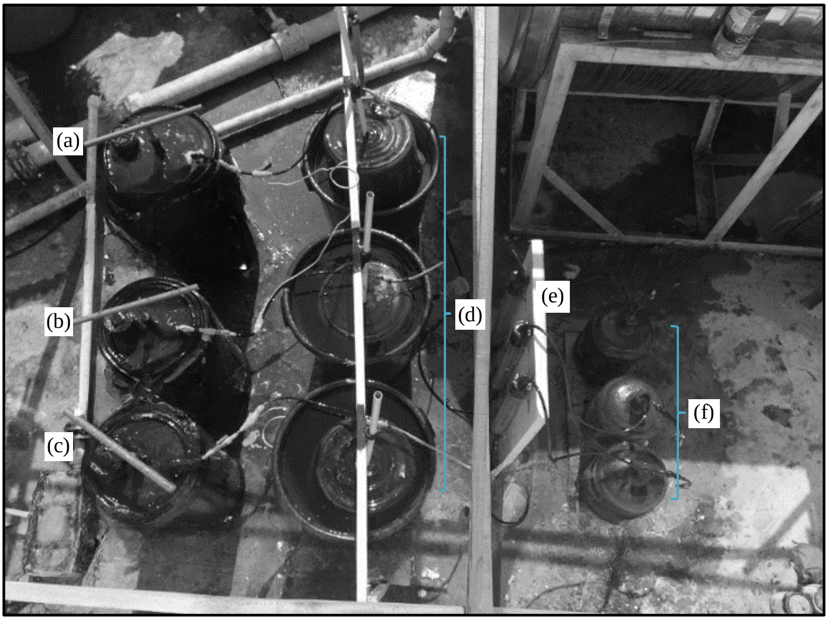


Figure 2. Actual experimental set-up of biogas production: swine-cow manure digester tank (a); cow manure digester tank (b); swine manure digester tank (c); floating drums (d); H_2S scrubbers (e); CO_2 water (f)

The CO_2 and H_2S impurities were removed using a water-scrubbing system. Since H_2S is highly corrosive and can damage both the engine and the purification system, it was removed first followed by CO_2 to increase the heating value of biogas fuel. The biogas composition of various manure (cow, swine and cow-swine mixture) was analyzed using a portable infrared-type methane gas analyzer with 100% methane volume detection (BH-90 Henan Bosean Electronic Technology Co., Ltd., China). Then the lower heating values of purified biogas was calculated using the natural gas calorific value calculator at 1 atm and 15 °C condition. The density was gathered using a methane density calculator with the same condition. In the third section of this paper, the composition of biogas used from gas analyzer and natural gas calorific calculator is shown. An anemometer (AVM-01, RS Pro, Taiwan) was used to gather both inlet velocity of engine throttle positions. The biogas temperature was gathered using a temperature sensor.

2.2 Engine Experimental Set-up

The test was carried out on the two-stroke, 43 cm^3, single-cylinder, SI gasoline engine (FPBC4300, Fortress, Philippines) with a compression ratio of 17:22. The engine used was readily available on the market, with its original fueling system configured for gasoline with 2T engine oil. Since it was intended to run on biogas, no modifications or changes were made to obtain desired data with various throttling opening positions.

The engine assembly was composed of a container carrying a mixture of gasoline and 2T engine oil connected to the two-stroke SI engine. The engine's intake manifold was connected to the gaseous fuel LPG. The digital tachometer (DT-2234C, RS Pro, China) and prony brake dynamometer were used to measure the brake engine speed and torque at room temperature. The two-stroke internal combustion engine was used to power a lawnmower. The engine's technical specifications are listed in Table 1.

2.3 Engine Testing

In conducting the performance test of the engine, all the instruments were calibrated to ensure the accuracy of the data gathered. It is important to conduct an engine start test to know if the engine starts using a specific fuel (biogas and benchmark fuels) according to SAE International's (2011) J1349 power test code procedures. This method is applicable in testing biogas extracted from anaerobic digestion. The engine starting test was done by feeding the gasoline with 2T engine oil first as a running start since the engine was not able to start with methane fuel. Then, the engine achieved its ignition combustion start-up to run smoothly in the two-stroke SI engine fueled by biogas fuel. The low-load and high-load throttle opening positions were used to gather engine parameters. A low-load throttle opening position is when the airflow remains constant in a fuel flow regulated to torque, whereas the high-load throttle opening position occurs when the gate of the fuel line is fully open at 100%, and the accelerator is at its highest position allowing maximum airflow in the system during suction. The engine parameters were tested for at least 10 seconds because the dynamometer used caused friction through slippage which can lead to excessive percentage error over a longer period of time.

Table 1. Specification of the two-stroke SI engine used

Engine parts	Description
Model	FPBC4300
Engine type	Single-cylinder; two-stroke; air-cooled; piston valve
Volume displacement	43 cm^3
Compression ratio	17:22
Maximum output	0.7 kW/6,500 rpm
Carburetor	Diaphragm type
Ignition system	Non-contact electronic ignition
Method of starting	Recoil type
Fuel tank capacity	1.2 L
Maximum speed of gear shaft/engine speed	8,500 rpm/11,000 rpm
Idle speed	2,350-2,900 rpm
Bore and stroke	B = 40 mm; S = 34.2 mm

2.4 Benchmark Fuels Set-up

Benchmark fuels are gasoline with 2T engine oil and LPG used to compare the performance of various biogas used in the study suited for the SI engine. After all the engine performance parameters were gathered, the data was then used as a benchmark for biogas fuel using various substrates and throttling openings.

2.4.1 Gasoline with 2T Engine Oil Set-up

The set-up used a 2T engine oil as a mixture of gasoline with a fuel ratio of 30:1. It means that 30 parts of gasoline were mixed with 1 part of 2T engine oil. The engine was intended to run on various biogas fuels with no modification for easily switching back to its original fueling system and for easy conversion method of gasoline to biogas with the same throttling opening positions. At first, the test engine was run idle through a 3 to 4 h conditioning period to properly "break in" the engine. Afterward, the mixture of the fresh air and gasoline with 2T engine oil was fed into the two-stroke engine to start the experiment with gasoline. During the experiment, the fuel tank was filled with gasoline mixed with 2T engine oil. After filling the fuel tank with the exact volume, the choke was adjusted, and the throttle was placed at a low-load position. The engine was started using the manual crankshaft, and the torque was gathered using a prony brake dynamometer coupled to the shaft and the speed of the engine was produced by using a tachometer. The speed that was gathered indicated that it had a corresponding brake torque applied with load throttle. The same procedure was used in gathering the data for the high-load throttle position. After performing the experiment, the engine was cooled to avoid overheating which may later cause engine failure, especially the piston. All gasoline with 2T engine oil tests were completed before switching to LPG fuel and biogas fuels because the engine purchase was preconfigured by the manufacturer for SI mode and originally designed to run with the mixture of gasoline and 2T engine oil. Figure 3 shows the actual set-up of the two-stroke SI engine.

2.4.2 LPG and Biogas Set-up

For gaseous fuel, LPG was used in the two-stroke SI engine. The set-up was composed of an 11-kg LPG tank (Pryce Gas, Philippines) with a mixture of 40% propane and 60% butane. The LPG fuel was connected directly to the intake manifold of the two-stroke SI engine and a weighing machine was used to measure the fuel consumption of the LPG. The LPG and the various biogas fuels were then tested. At first, gasoline with 2T engine oil was used to ignite the engine since it was not able to start with gaseous fuels. When the engine was adequately running, the fuel valve of the gasoline tank was turned off using a fuel petcock synchronizing with the opening of the LPG line valve. As the operation continued, the remaining gasoline with 2T engine oil was depleted and the gate valve of the LPG tank of the fuel line was opened to supply the two-stroke engine. With this valve, the LPG flowed directly to the carburetor of the engine's combustion chamber. It was noted that during the feeding of gaseous fuels, the flow rate was at the maximum level to keep the gasoline engine running and then reduced until the engine was stable. The dynamometer's weight is read on the weighing scale (kg) to determine the brake torque of the engine. Simultaneously, the tachometer read the speed (rpm) of the engine. The two-stroke SI engine performance parameters were then conducted with low- and high-load throttling conditions. The LPG had the same experimental procedure with biogas fuels when fed into the two-stroke SI engine as shown in Figure 4.

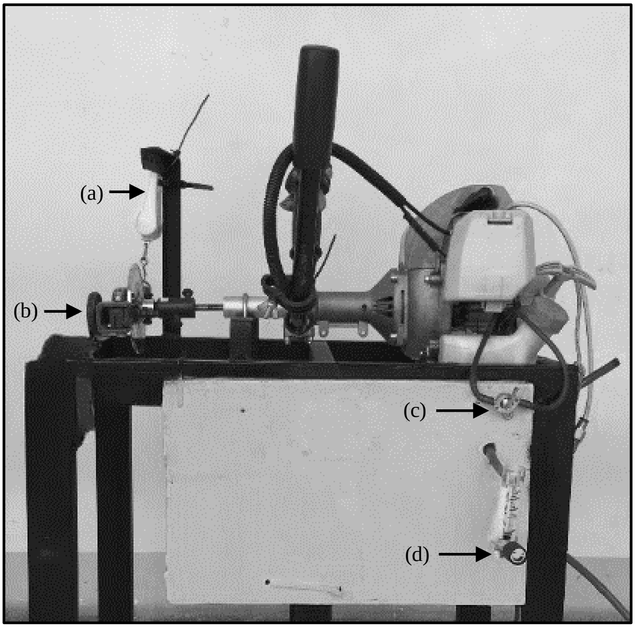


Figure 3. Actual set-up of the two-stroke SI engine: weighing scale (a), brake dynamometer (b), fuel petcock (c) and gas flowmeter (d)

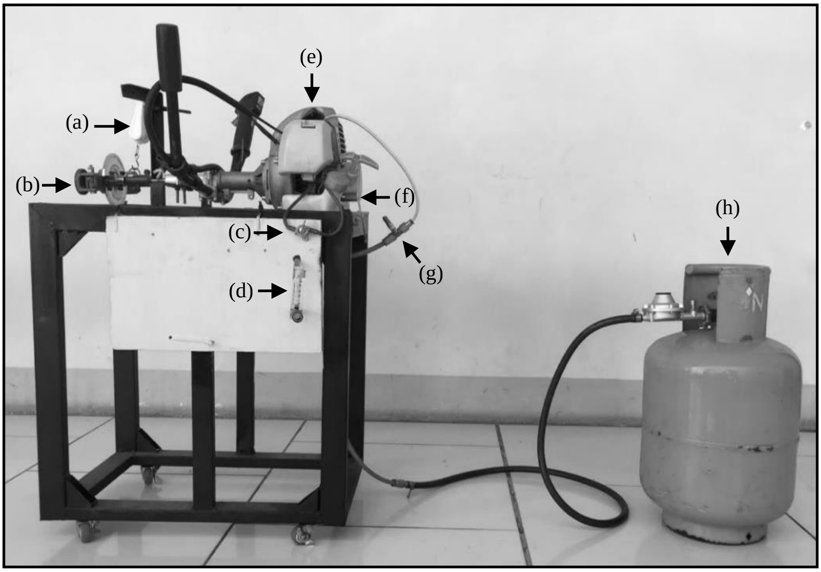


Figure 4. Actual experimental set-up of two-stroke engine fueled by LPG: weighing scale (a), brake dynamometer (b), fuel petcock (c), gas flowmeter (d), engine (e), fuel tank (f), gate valve (g) and LPG (h)

2.5 Performance Testing

The tests were performed on a fueled gasoline engine that can operate in two-stroke SI, air-cooled with a single cylinder. To determine the performance characteristics of the two-stroke SI engine, two separate tests were carried out on the engine. First, all engine performance parameters were tested using benchmark fuels: gasoline with 2T engine oil and LPG. Second, all engine performance tests were conducted in the same gasoline engine with different biogas fuels (cow, swine, and a 1:1 mix of cow-swine manure) at various engine throttling opening positions (high- and low-load) at room temperature.

Before the various biogas fuels (cow, swine and cow-swine manure) were fed into the engine, the biogas impurities (hydrogen sulfide and carbon dioxide) were checked using a methane detection gas analyzer and natural gas calorific value calculator before compressing in the biogas storage. When the engine was running fast, it created enough negative pressure at the intake manifold that suck the gaseous fuel during the performance test. Adjustment of the gaseous fuel supply was accomplished through a control valve located before the flow meter. Afterward, the gaseous fuel flowed towards the intake manifold of the engine and mixed with the intake air. The same procedure was used in gathering data for engine parameters at the same throttle setting on benchmark fuels. The two-stroke SI engine experimental test procedure and engine performance parameters such as engine brake power, BSFC and brake efficiency are discussed hereafter.

2.6 Equation for Engine Parameters

Standard engine parameters were considered for testing and investigating the performance parameters of the two-stroke SI engine proceeded as follows:

2.6.1 Brake Engine Power

Brake power is developed by transferring the mechanical power of the engine to the crankshaft due to combustion. The power generated by the engine was transmitted to the load through the coupling mechanism that connected the engine. A non-contact type tachometer was used to measure the speed of the engine, and a dynamometer was then used to measure the torque. The torque and speed, which indicated the power of an engine and defined as the force acting at a moment’s distance, were computed using Equation 1. It is important to determine the power since it is the indicator of the rate of work of an engine (Pulkrabek, 1995).

$$P_b = 2\pi TN \tag{1}$$

where N is the engine rotational speed (rev/s); T is the engine brake torque (N-m or joules); P_b is the engine brake power (W).

2.6.2 BSFC

Brake-specific fuel consumption is the amount of fuel an engine burns per unit of mechanical work (energy) it produces (Equation 2). There was a need to determine the rate of fuel burnt in the engine. Lower BSFC implies that a lesser amount of fuel is needed to generate certain power during a specific time (Pulkrabek, 1995). To determine the BSFC, the fuel difference of the initial and final mass of each benchmark fuel and various biogas fuels were used. Since power was already attained, the BSFC can be determined.

$$BSFC = \frac{\dot{m}_f}{P_b} \tag{2}$$

where $\dot{m}_f$ is the mass of fuel/mass of biogas (kg/s); P_b is the brake engine power (W); $BSFC$ is the brake-specific fuel consumption (kg/kW-h).

2.6.3 BTE

Brake thermal efficiency is the ratio of the output work to the input heat. Most engines are designed with theoretical-based power, and it is usually measured and expressed in terms of brake power divided by the heat generated (Equation 3) by the engine with the product of the mass flow rate of the benchmark fuel and its higher heating value (Pulkrabek, 1995).

$$\eta_{th} = \frac{P_b}{m_f Q_{HHV}} \times 100 \tag{3}$$

where $\dot{m}_f$ is the mass of fuel (kg/s); P_b is the brake engine power (W); Q_{HHV} is the fuel higher heating value (J/kg); and η_{th} is the BTE (%).

3. Results and Discussion

3.1 Biogas Fuel Composition

The biogas fuel composition of the purified biogas extracted from various animal manure is shown in Table 2. The biogas reached a total volume of 70L per day, and the biogas temperature and velocity in actual air condition during the experiment was 29.3 °C and 6.6 m/s at high-load throttle position; but 29.3 °C and 1.9 m/s when low-load was applied.

Table 2. Properties of biogas fuel composition

Properties	Biogas source		
	Swine manure	Cow manure	Swine-cow manure
Composition (Vol. %)	CH_4: 51% CO_2: 49%	CH_4: 55% CO_2: 45%	CH_4: 53% CO_2: 47%
Lower heating value at 1 atm and 15 °C (MJ/kg)	13.76	15.59	14.58
Density (kg/m^3)	0.671	0.671	0.671

3.2 Brake Engine Power and Brake Engine Speed

3.2.1 Benchmark Fuels

The brake power and brake engine speed produced by two-stroke SI engines were mainly dependent on an engine's cylinder mixture and type of fuel used. At both throttling positions, the LPG achieved a higher brake engine speed and a higher brake engine power compared with gasoline with 2T engine oil at 14,699 rpm and 548 W for high-load throttle and 12,226 rpm and 354 W for low-load throttle (Figure 5). This shows that the higher brake engine speed produced higher brake power and results in a decrease in the brake engine torque.

In the experiment, it was observed that LPG had a higher ignition temperature than gasoline with 2T engine oil because LPG used dry gas as a lubricating agent for the two-stroke SI engine. This caused a higher ignition temperature and higher compression ratios which increased the pressure of the engine compared with gasoline (Mohammed *et al.*, 2021). The engine's original fueling system was gasoline with 2T engine oil, and the manual specified that the engine idle speed was around 3,000-4,200 rpm, but the actual brake engine speed gathered was around 2,350-2,900 rpm with a torque of 0.624 to 0.771 J because the spring attached to the diaphragm type carburetor was removed to prevent the engine from stopping when tightened by the dynamometer.

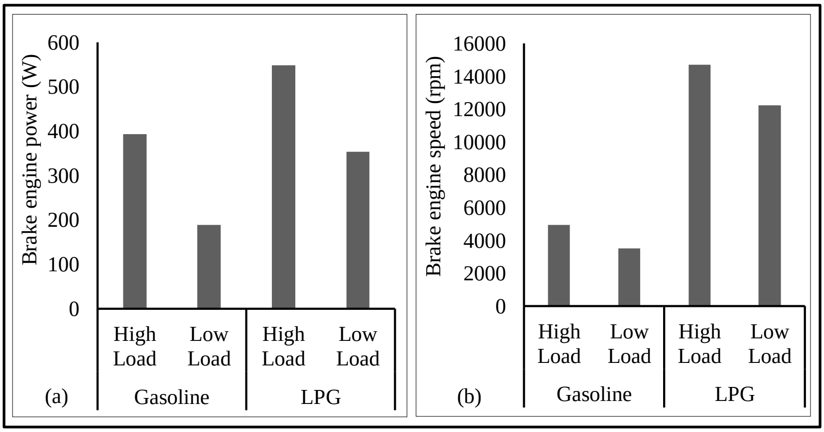


Figure 5. Brake engine power (a) and speed (b) of benchmark fuels

3.2.2 Biogas Fuels

Figures 6 and 7 show that swine manure achieved the highest brake engine power and highest brake engine speed on both throttling positions compared with cow and mixed manure of purified biogas fuels at 762 W and 10,443 rpm in high-load throttle and 327 W and 9,054 rpm in low-load throttle. As compared with the experiment data of Reddy *et al*. (2016), under high-load condition, the biogas fuel obtained a maximum brake engine power of 812 W because the brake power developed by the engine was found to increase with a corresponding increase in load. An increase in loading improved the combustion quality of the fuel and in turn, increased the power output. On the other hand, biogas had a comparatively lower laminar flame speed, and it cannot be ignited at the same crank angle of gasoline (Hotta *et al*., 2019). As a result, when too much fuel was injected into the engine, the engine shut off, and there was insufficient air to maintain the air-fuel mixture for the combustion process (Kwon *et al*., 2017). During the operation, the mixed manure substrates biogas fuel attained a stable brake engine speed that ranged from 9,500 to 10,500 rpm with applied brake engine torque. In both throttling positions, all biogas fuels attained a decrease in brake engine speed with an increase in the brake engine load because of the tightening of the bolt of the dynamometer. Throughout the experiment, the engine speed was always greater on methane-enriched biogas owing to the high content of calorific value (Chandra *et al*., 2011).

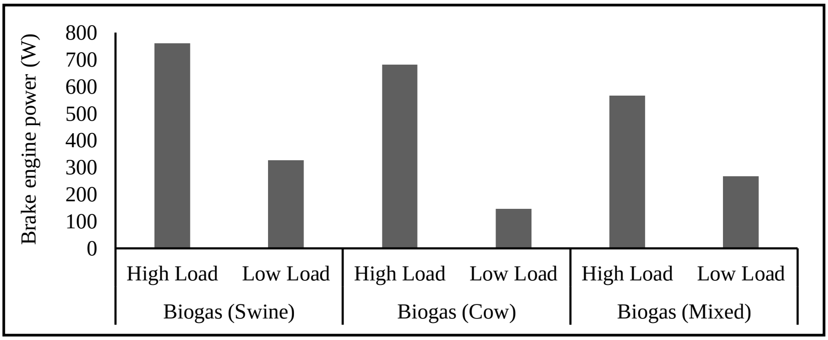


Figure 6. Brake engine power of various biogas fuels

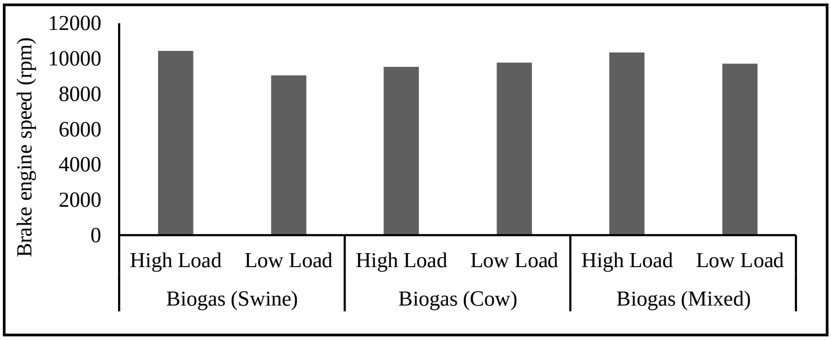


Figure 7. Brake engine speed of various biogas fuels

3.2.3 Comparison of Benchmark Fuels and Different Biogas

Among the three fuels, the highest brake power fueled by the two-stroke SI engine at high-load throttle condition was produced by the swine manure biogas at 762 W and the least brake engine power was produced by gasoline with 2T engine oil at 393 W. In the low-load throttle position, the maximum brake power output belonged to LPG with 354 W. Generally, the brake engine power increases with an increase in brake engine speed. According to Hotta *et al.* (2019), the power differences among the throttle positions were due to variations in the difference of the amount of fuel supplied with the decrease of throttle opening between the gasoline and biogas operation. Since the various biogas fuels and LPG were injected directly into the intake manifold of the engine, a large volume of intake air was replaced by both gaseous fuels when tested. Compared to gasoline with 2T engine oil, gaseous fuels had a better mixture formation that resulted in the increase of heat release rate, cylinder pressure and cylinder temperature. This, in turn, could increase brake engine speed and brake engine power which could eventually contribute to a complete combustion process of the engine (Duc and Duy, 2018). The trend of the graph in Figures 8 and 9 shows a clear advantage of using purified biogas in two-stroke engine operation for better power output over benchmark fuels because of the high methane percentage concentration of purified biogas fuels. An increase of 1.6 times in power output has been reported on methane enriched biogas when used in an SI engine (Chandra *et al.*, 2011).

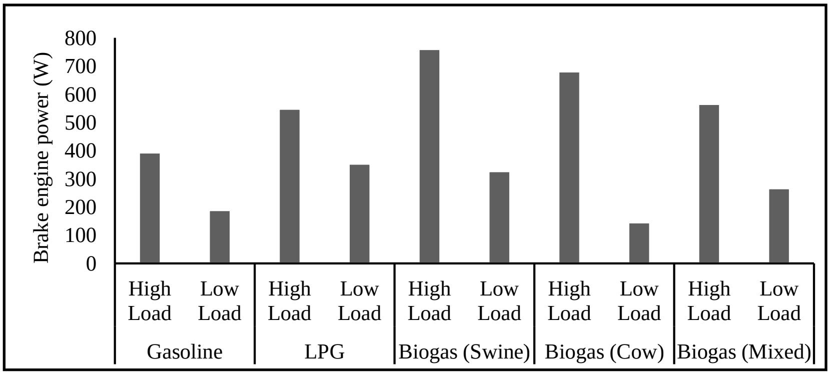


Figure 8. Comparison of brake engine power

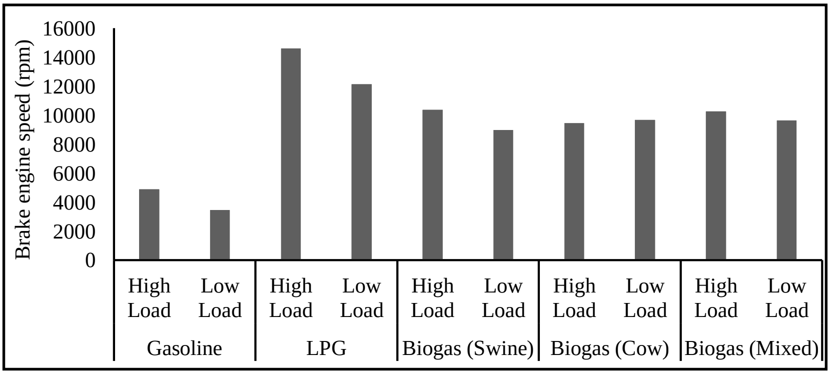


Figure 9. Comparison of brake engine speed

The various biogas fuels (cow, swine, cow-swine manure) had almost the same trend of brake engine speed ranging from 9,000 to 10,500 rpm. On the other hand, gasoline with 2T engine oil yielded the lowest brake engine speed at 4,950 rpm compared with LPG at a maximum of 14,699 rpm. It was found that biogas had a lower calorific value and combustion quality than LPG leading to variations in engine speed. As a result, engine speed decreased by 25.7% at the high-load throttle position and 27.1% at the low-load throttle position when operating in purified biogas. The same result was obtained by Muhajir *et al.* (2018), wherein the LPG yielded the highest engine speed indicating the gasoline engine's stability and better functions compared with gasoline.

3.3 BSFC

3.3.1 Benchmark Fuels

Figure 10 shows that, for low-load throttle, the brake power increased but its BSFC decreased. The BSFC was calculated using the brake engine power which indicated the efficiency of the engine that generates power from fuel. This showed that in low-load throttle, the BSFC of LPG was lower compared with gasoline which yielded the highest fuel consumption at 0.015 kg/kW-h.

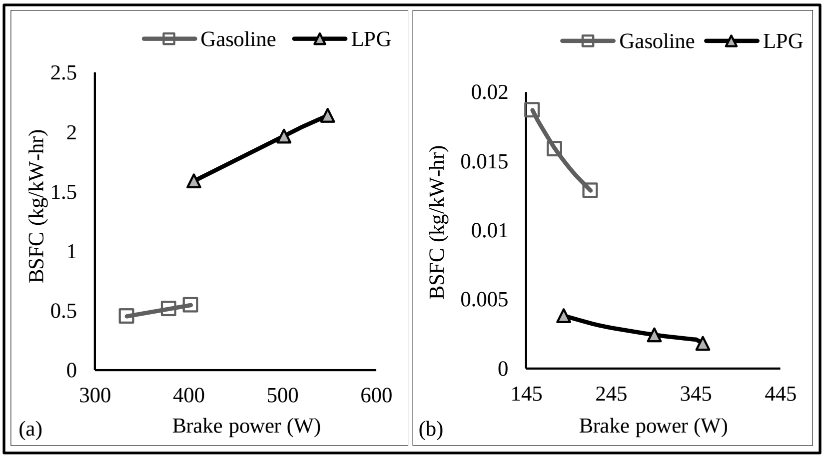


Figure 10. High (a) and low (b) load throttle BSFC of benchmark fuels

This is similar to the findings of Jindal *et al.* (2015), who found out that at higher loads, heat loss was reduced resulting in higher fuel consumption with better utilization of the engine. It was also observed that BSFC on the low-load throttle was significantly lower than on the high-load throttle because it consumed less fuel. This was supported by Duc and Duy (2018), who maintained that the engine fueled with gasoline and LPG defined the ignition delay as the time interval between the start of ignition, and the start of combustion of the engine fueled with LPG was longer than gasoline because of lower combustion rate and higher ignition point. In addition, LPG-fueled engine used less fuel than gasoline with 2T engine oil. When using LPG in two-stroke ignition engines, the burning rate of fuel increased and thus, the combustion duration decreased. As a consequence, the temperature and pressure of LPG became higher than gasoline fuel.

3.3.2 Biogas Fuels

The cow-swine manure yielded the highest BSFC at 2.19 kg/kW-h with 53% methane content for the high-load throttle opening position. The swine manure with a methane content of 51% had the lowest BSFC at 1.43 kg/kW-h. Consequently, as the brake engine power for biogas fuels increased, the BSFC also decreased, thereby improving fuel efficiency. The impact of engine operating conditions and fuel type on BSFC should be considered, as some engines optimized for low-speed operation might have a higher BSFC at higher speeds because of increased friction losses. Additionally, the type of fuel used can also impact BSFC, with biogas fuels containing a higher percentage of methane resulting in lower emissions and higher fuel efficiency. As shown in Figure 11a, the cow-swine manure had the highest brake fuel consumption for the high-load throttle position. However, it had the least brake engine power generated.

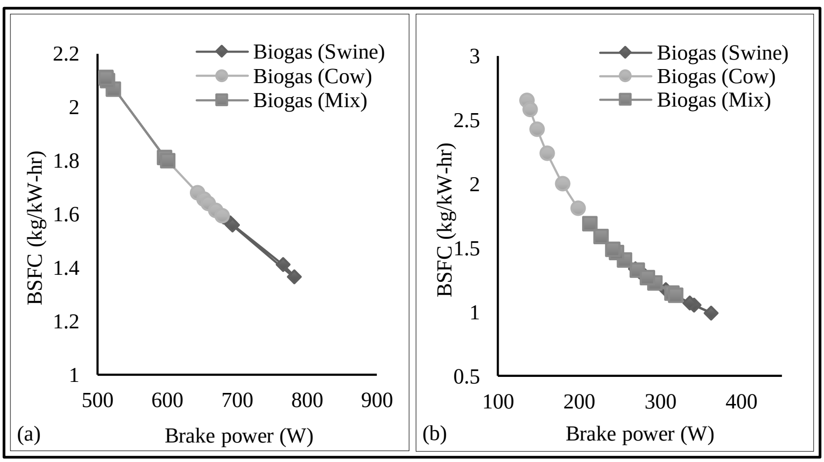


Figure 11. High (a) and low (b) load throttle BSFC of various biogas fuels

According to Arul Peter *et al*. (2020), the higher the percentage of purified biogas in the fuel, the higher is the BSFC due to the gaseous state of biogas. At low-load throttle position, the cow manure had the highest BSFC at 2.55 kg/kW-h with 53% methane content, while swine manure had the lowest BSFC at 1.13 kg/kW-h with 51% methane content (Figure 11b). Since the two-stroke gasoline engine ran on various biogas in the low-load throttle position, the cow manure consumed more fuel than in the high-load throttle position. As stated by Barik and Sivalingam (2013), when the BSFC decreases with an increase in engine load, the lesser fuel it requires at the high-load throttle position because of the increased cylinder temperature of the engine compared with low loads. Out of the three biogas fuels (cow, swine and cow-swine manure), the swine manure had the lowest BSFC in both the different throttling positions running on the two-stroke gasoline engine. Due to the higher methane content of biogas, the engine consumed more fuel, and biogas itself is a gaseous state fuel with a lower heating value.

3.3.3 Comparison of Benchmark Fuels and Different Biogas

The highest BSFC rates of the engine were run with purified biogas at 1.92 kg/kW-h of cow-swine manure for the high-load throttle position and 2.55 kg/kW-h of cow manure for the low-load throttle position (Figure 12).

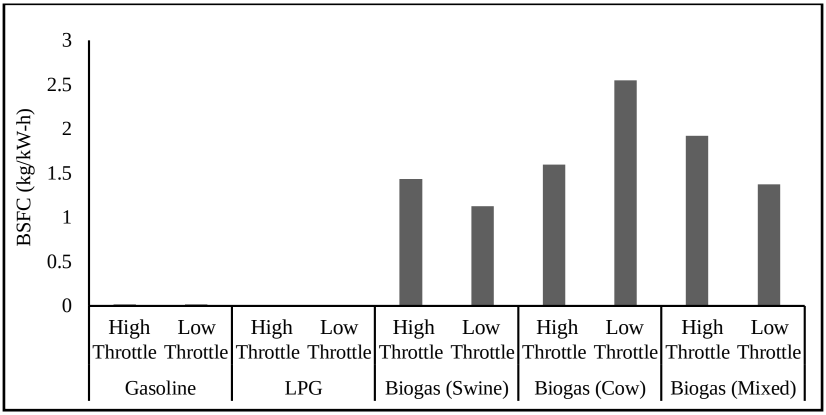


Figure 12. Comparison of BSFC

The BSFC of purified various biogas consumed more fuel than benchmark fuels because LPG is 8% more efficient on SI engines (Smith *et al*., 1997) owing to its higher-octane number, auto ignition temperature, great flame velocity and wider flammability limits making LPG a better fuel in SI engine (Erkuş *et al*., 2013). At the same time, gasoline with 2T engine oil operated on its original fueling system with natural aspiration on the engine. In comparison to biogas, the higher percentage of purified biogas in the mixture resulted in higher BSFC. The gaseous state of biogas is attributed to incomplete combustion because of the suction of the biogas-air mixture instead of air in the inlet manifold (Prabhu *et al*., 2018).

3.4 BTE

The BTE is used to evaluate the engine that converts the heat input of the fuel into mechanical energy. In both throttling positions, the swine manure biogas at 21.91% yielded the highest BTE compared with benchmark fuels at 1.41% of LPG fuel (Figure 13). This was due to the high methane concentration of purified biogas. The BTE of biogas fuels on both throttling opening positions was higher than benchmark fuels because biogas had a lower thermal value than gasoline. Furthermore, LPG had a lower thermal value than gasoline in terms of mass but, in terms of volume, gasoline had a higher lower-heating value (or lower calorific value) compared with LPG indicating that it released more heat energy when burned. This indicated that more fuel must be required to achieve a higher BTE. As a result, LPG and biogas had higher BTE values than gasoline. Since the fuel consumption rate is kept constant at minimal consumption and the calorific value of biogas is kept lean, BTE that depends on combustion quality increases because of the increased frictional losses (Reddy *et al.*, 2016). It is also observed that methane content is an essential factor affecting the performance of the engine. Fuel consumption also affects the BTE as it was observed to increase with the increase in brake engine speed. The rate of combustion of fuel was also observed to increase with an increase in combustion temperature.

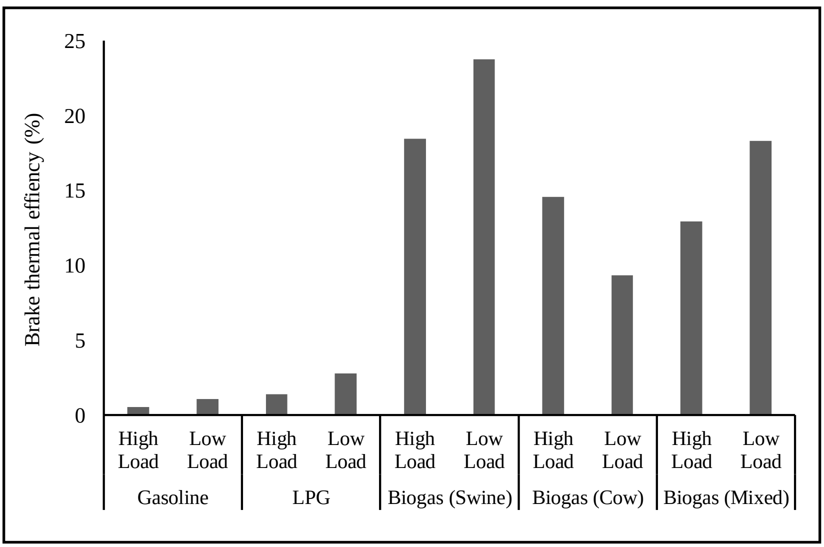


Figure 13. Comparison of BTE

4. Conclusion and Recommendation

Compared with gasoline, the LPG achieved the highest parameters at high and low throttling opening positions (548.368-W brake engine power, 14,499-rpm brake engine speed, 0.003-kg/kW-h BSFC and 1.41% BTE). Gaseous fuel for SI engines had a higher SI temperature resulting in an increased engine parameter. Of the three biogas used to run the two-stroke gasoline engine, the swine manure achieved the highest engine parameters at 761.485-W break engine power, 10,443-rpm brake engine speed, 1.431-kg/kW-h BSFC and 18.46% BTE. The conversion from gasoline to purified biogas-fueled engine was successful and could run in the two-stroke SI engine for small-scale operation. Moreover, the engine ran with stability and achieved the engine parameters required in this comparative study. Of all the various fuels, biogas almost acquired the highest engine parameters (brake power and BTE) in the two-stroke SI engine compared with LPG although LPG attained the highest brake engine speed at all throttling opening positions. In conclusion, biogas can be a viable option as an alternative fuel for two-stroke SI engines and SI engines in rural areas as the performance of the engine using biogas was comparable with that of gasoline and LPG fuels. This similarity in performance can be attributed to the energy content and properties of biogas and conventional fuels. These findings suggest that further research is necessary to fully evaluate the performance and potential of biogas in various engine types and operating conditions. However, the focus should be on the pressure, from optimal operating pressure to lower pressure for all fuels, which will then be tested in the two-stroke SI engine at various throttling opening positions. It is also recommended to determine the exhaust emission composition of an engine running on various fuels at different throttle settings. Furthermore, future research on biogas fuel compression for commercial purposes may be carried out.

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