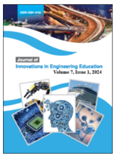

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Tribhuvan University

Comparative engine testing of Bio-CNG and Gasoline: Performance and emission impacts in a 175 CC engine

Sangam Bhusal[a], Yudeep Poudel [a], Srijan Bastakoti[a], Sachin Adhikari[a], Rupesh Lal Karn[a] and Laxman Palikhel[a,*]

[a] *Department of Automobile and Mechanical Engineering, Thapathali Campus, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal*

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Abstract

Bio-CNG has emerged as a potential replacement for conventional fossil fuels used in road vehicles, a major source of global air pollution. This research aimed to perform comparative performance and emission analysis under various conditions to observe its viability. A Bajaj, 175 CC powered gasoline, 4-stroke, and carbureted engine was chosen and converted to the bi-fuel system that operates either with gasoline or bio-CNG using an electronically controlled solenoid valve. The engine power and traction forces were measured under the road's 0°, 4°, and 8° inclination at no load and 5 kW load coefficients. Vehicle exhaust emission levels (CO, CO_2, HC, and lambda) were measured at the idle rpm of the engine (1240 RPM for petrol and 1022 RPM for bio-CNG). The experimental data from the chassis dynamometer revealed significant reductions in power and traction force under various conditions. Furthermore, emissions analysis from exhaust gas analyzer showed remarkable reductions of 98% for CO and 89% for HC, but there was a 16.67% increase in CO_2 levels. This research provides insights into the potential benefits and challenges of bio-CNG conversion for small-engine vehicles and suggests possible measures to improve the performance of converted vehicles.

1. Introduction

The growing pollution, limited availability, and unpredictable costs associated with fossil fuels have prompted a search for alternative fuels. These alternatives aim to support sustainable transportation and energy solutions while prioritizing environmental well-being in Nepal and the global automotive sector. Among various options, bio-CNG is considered to be a promising alternative to fossil fuels because of its lower harmful tailpipe emissions such as carbon monoxide (CO), carbon dioxide (CO_2), Hydrocarbons (HC), and oxides of nitrogen (NO_x). Despite its potential to significantly reduce emissions from internal combustion vehicles, the adoption of this technology has yet to gain traction in Nepal [1], [2]. However, it is not a recent development in South Asia or worldwide; it was initially discovered in Italy in the early 1930s, during a global oil crisis [3]. Since then, significant advances have been in improving its performance in converted vehicles, with notable developments taking place in Canada between 1970 and 1984, before commercialization [4]. As of 2013, approximately 18.09 million natural gas vehicles worldwide were powered by Natural gas, and now countries like Bangladesh and India are increasingly using bio-CNG as a vehicle fuel alternative [5].

Bio-CNG, stands for Bio-Compressed Natural Gas which is produced from biodegradable waste (bio-gas), is a hydrocarbon mixture with a high amount of methane content of up to 97% at a pressure of 20-25 Mpa and is almost similar to CNG in terms of fuel properties, engine performance, and emission parameters [5]. But, CNG, a by-product of petroleum, has a slightly higher calorific value of 53,000 kJ/kg compared to bio-CNG, which can be produced from any biomass and has a calorific value of 52,000 kJ/kg [6], [7].Bio-CNG is created from biogas, formed by breaking down biomass in a digester. However, this biogas contains impurities that lower its calorific value, making it unsuitable as

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*Corresponding author:
laxmanpalikhel@ioe.edu.np (L. Palikhel)

a vehicle fuel. To make it usable, purification units in the manufacturing plant are set up to remove these impurities and turn it into a clean and efficient fuel for vehicles. After the purification, purified gas is stored in a high-pressure CNG cylinder of up to (200-250) bar and installed in vehicles using a conversion kit to propel the vehicle such types of vehicles are called bio-CNG vehicles and depending upon fuel used in the engine CNG engine is classified into 3 categories: dual fuel, bi-fuel and dedicated [8], [9]. The physiochemical properties comparison is shown in Table 1.

Table 1: Physiochemical properties of Bio-CNG compared to gasoline [10]

Properties	**Bio-CNG**	**Gasoline**
Calorific value (KJ/kg)	52000	45000
Octane number	120-130	85-95
Flame propagation speed (m/s)	0.41	0.5
Auto ignition temperature (°C)	540	258
Stoichiometric $(A/F)_{s\ mass}$	17.2	14.7

Bio-CNG has a high methane level and only 2-8 % carbon dioxide having a calorific value of 52000 kj/kg which is much higher than that of petrol and a density of 0.75 and a higher value of octane number 120-130 makes it more suitable for use in an IC engine vehicle [10], [11]. However, it has a lower flame propagation speed of 0.41m/s than gasoline of 0.5m/s and a high ignition temperature of 540 degrees Celsius than gasoline of 258 degrees Celsius which can result in a significant reduction in overall power output that can be overcome by adding hydrogen in CNG (HCNG) and Spark advancer, and improving Compression ratio [12].

A comparative study on a 3.5 kW, four-stroke engine highlighted bio-CNG as a promising alternative to diesel, noting its higher calorific value and significantly lower carbon emissions. Both fuels delivered a comparable brake power of approximately 3.53 kW under a maximum load of 12.15 kg and an engine speed of around 1527 RPM. Bio-CNG demonstrated higher indicated and friction powers, at 5.79 kW and 2.3 kW, respectively, and exhibited a greater indicated mean effective pressure, reinforcing its potential as a viable substitute for gasoline and diesel [13]. Additionally, a separate evaluation on a gasoline engine revealed that bio-CNG resulted in brake power reductions of 19.25% and 10.86% and decreases in brake-specific fuel consumption (BSFC) by 15.96% and 14.68%, respectively, while also reducing tailpipe emissions. These findings indicate bio-CNG's potential as a sustainable fuel option despite some performance trade-offs [14].

Despite the increasing interest in bio-CNG as an alternative fuel, several research gaps persist, especially concerning small engine vehicles such as the 175 CC gasoline engine. Although bio-CNG has been examined in larger engines, there is a notable absence of in-depth comparative studies on its performance and emissions in small engines across different load conditions and road inclinations. Additionally, the impact of electronically controlled solenoid valves on optimizing performance and emissions in bi-fuel systems remains underexplored. This research aims to fill these gaps by providing crucial insights into the advantages and challenges associated with converting small-engine vehicles to bio-CNG.

2. Method and methodology

The sequence of research steps is shown in the Figure 1.

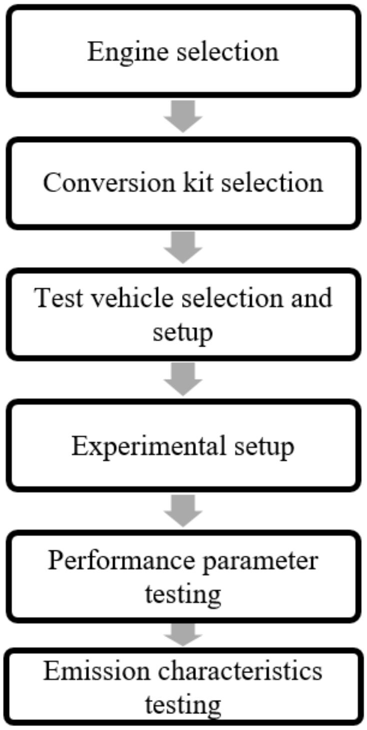

Figure 1: Sequences of research steps

2.1. Engine selection

A 175cc, 4-stroke Bajaj engine on which conversion was carried out. The detailed Specification of the Engine is tabulated in Table 2.

2.2. Venturi CNG kit

The conversion phase consists of installing a suitable Mijo Premium Venturi CNG kit that fulfills the criteria

Table 2: Engine Specifications [15]

Engine Specifications	**Details**
Engine type	Single cylinder, 4-stroke, air-cooled
Engine displacement	175 cc
Bore × Stroke	63.5 mm × 66.2 mm
Compression ratio	8.5:1
Transmission	4-speed manual gearbox
Fuel system	Carburetor

Figure 2: Mijo premium CNG conversion kit

Figure 3: Test vehicle

of ISO 15500:2020 including a CNG cylinder (Type 1: are made entirely of metal, typically aluminum or steel), Mixture, Reducer, change-over switch, Solenoid, and filling valve, engine modification, and comprehensive safety inspection. The conversion kit is shown in Figure 2.

2.3. Test vehicle selection and setup

The existing chassis of the three-wheeler vehicle was converted into bio-CNG and a petrol-powered 4-wheeler vehicle for the test (the gross weight of the converted vehicle is 280 kg). The vehicle on which the conversion was done to make it a bi-fuel vehicle is shown in Figure 3.

2.4. Experimental setup

The experimental data was collected after the engine was run for ten minutes to establish a stable operating condition. Two types of fuel were used: conventional gasoline and bio-CNG. The graphs display the performance of gasoline and bio-CNG at inclinations of 0% (0°), 7% (4°), and 14% (8°) for no load and 5 kW load coefficients. The grade on a chassis dynamometer was maintained using MAHA software by creating a resistance force on the roller bed of a dynamometer which was then transmitted to vehicle wheels to simulate the effort required to cope with the different slope conditions.

The dynamometer uses eddy current brakes for the required resistance that would have been required by uphill and downhill motions due to gravity pulls and the desired grade is obtained by changing the resistance. The performance test was carried out at the Vehicle Fitness Testing Centre located at Teku, Kathmandu using the MAHA LPS 3000 chassis dynamometer with roller set, measuring 3345 mm in length, 1100 mm in width, and 520 mm in height, supports an axle load of 2.5 tons. The roller is 750 mm long with a diameter of 318 mm and an axle separation of 540 mm, accommodating wheels as small as 12 inches in diameter. It features a 260 kW eddy current brake, operates on a 230 V / 50 Hz power supply, and requires a 16 A slow-blow fuse. The system can test speeds up to 260 km/h, wheel power up to 260 kW, and traction up to 6 kN, with an accuracy of ±2%. Initially, the vehicle was placed on the roller bed of a chassis dynamometer. Different load coefficients and grade conditions were given to the roller bed. Its performance parameters such as torque, brake power, and fuel consumption on both modes (bio-CNG and petrol) were tested by rotating the dynamometer's rollers on their axes by running the wheels over the rollers. The schematic diagram of the experimental setup and the performance parameter testing are shown in Figure 4 and Figure 5 respectively.

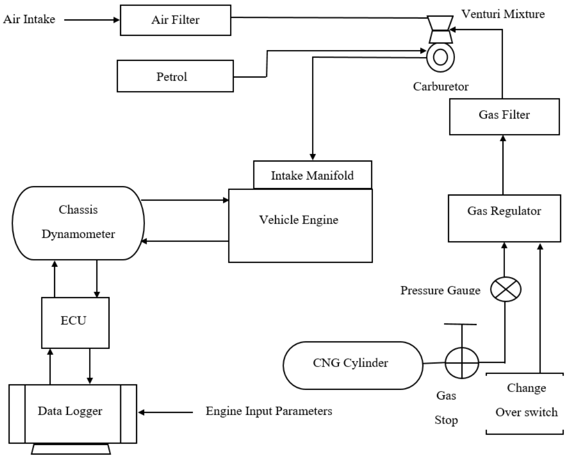

Figure 4: Schematic diagram of experimental setup

Figure 5: Vehicle placed on roller bed of chassis dynamometer for performance parameter testing

2.5. Performance parameter testing

2.5.1. Torque

Torque is one of the key performance metrics used to evaluate the acceleration and pulling power of a vehicle. It refers to the rotational force that the engine can generate, which is transmitted to the wheels via the transmission system. The greater the torque, the greater the vehicle's ability to accelerate from a standstill, climb hills, and tow heavy loads.

During the torque testing, the vehicle is driven onto the rollers of the dynamometer and secured in place. The engine is then run through a series of tests, including acceleration and deceleration, to measure its torque output at different engine speeds and loads. The product of torque and angular speed gives the power developed by the engine.

To measure the torque at the wheels, the following formula can be used:

$$T = \frac{N \times r \times m}{2\pi \times 60 \times m_G} \tag{1}$$

Where T is Torque (Nm), N is Wheel speed (rpm), R is Wheel radius (m), m is vehicle mass (kg), and m_G is Gear ratio, the ratio of the rotational speed of the engine to the rotational speed of the wheels.

2.5.2. Brake power

Brake power is a measure of the power output of an engine or motor when it is running under load. It is less than the indicated power since heat is lost to overcome the total friction generated in the engine which is summed as friction power. Friction power consists of pumping friction during intake and exhaust, mechanical friction in bearings, valves, and components such as oil and water pumps.

$$B.P = I.P - F.P \tag{2}$$

Where B.P is brake power, I.P is indicated power, and F.P is friction power.

In the context of vehicle testing, brake power is often used to measure the power output of an engine or motor. This is typically done by using a dynamometer, which applies a load to the vehicle's drive wheels while the vehicle is running at a specified speed, the dynamometer measures the torque and rotational speed of the wheels. From these measurements, the brake power can be calculated using the following formula:

$$\text{Brake Power (kW)} = \frac{2\pi N T}{60 \times 10^3} \tag{3}$$

Where N is the rotational speed of the wheels in revolutions per minute (RPM), T is the torque applied to the wheels by the dynamometer in Newton meter (Nm), and π is the mathematical constant (π approximately equal to 3.14).

2.5.3. Fuel consumption

Fuel consumption of a vehicle refers to the amount of fuel that the vehicle consumes over a certain distance or period of time. It is typically measured in kilometers per liter (km/L).

$$F.C = \frac{d}{f} \tag{4}$$

Where F.C is fuel consumption, d is the distance traveled (km), and f is the fuel used (Liter).

The vehicle is driven through different driving scenarios, including acceleration, cruising, and deceleration. The distance traveled is measured by a meter that is installed in the vehicle.

2.6. Emission characteristics testing

The portable gas analyzer Horiba MEXA-584L was used to measure the vehicle's emission level that was carried out in idle mode, which means the engine was running but the vehicle was not in motion. Initially, the gas analyzer probe was inserted into the exhaust tailpipe. The device was left there for a few minutes to allow it to accurately measure the emission parameters such as CO, CO_2, HC (NDIR non-dispersive infrared), and lambda.

Table 3: Standard value of measured parameters [16]

Emission Parameter	Standard Value
CO	0.00% . to 10.00% vol.
CO_2	0.00% to 20.00% vol.
HC	0 ppm to 10000 ppm vol.
LAMBDA	0.000 to 9.999

3. Results

3.1. Performance Analysis of Vehicle

3.1.1. No load and plain road condition

The characteristics curve in Figure 6 shows the comparison of bio-CNG and gasoline as they perform in a vehicle under various conditions. In terms of instant RPM and velocity under no load coefficient and plain road conditions, the comparison revealed that gasoline had an initial advantage while bio-CNG lagged behind due to its narrow range of flammability.

But as the comparison went on, it became clear that the maximum speeds for gasoline and bio-CNG were reached at various RPMs: for gasoline, it was 56.76 km/h at 3865 RPM, and for bio-CNG, it was 49.06 km/h at 3341 RPM. Despite these variations, it was discovered that the overall RPM and velocity characteristics of gasoline and bio-CNG were comparable. This indicates that both fuels eventually had similar performance characteristics despite having different initial performances.

3.1.2. Performance at different road conditions

The initial lag of bio-CNG was discovered to be a problem, but as the curve developed, it began to exhibit almost identical characteristics to those of gasoline. The relationship of traction force with rpm for plane load condition is shown in Figure 7. At this condition, the maximum traction force was measured to be 297.9 N in the gasoline mode and 278.3 N in the bio-CNG mode. The relationship of traction force with rpm for 7% grade condition is shown in Figure 8. At 5kW Load coefficient, the maximum traction force measured in bio-CNG and gasoline modes was 282.4 N and 302 N respectively. The relationship between traction force and rpm for a 14% grade is illustrated in Figure 9. The curve indicates that the maximum traction force measured was 300.2 N in gasoline mode and 284.8 N in bio-CNG mode.

It was found that the reduction in traction force experienced when using bio-CNG fuel in comparison with petrol is relatively less. The average reduction at 0% grade, 7% grade and 14% grade is 11.59%, 18%, and 23.04% respectively. It was found that with the rise of grading percent, an average reduction of traction force in Bio-CNG power goes on increasing. These results imply that the vehicle's traction force output is lower when using bio-CNG fuel than gasoline. This is because bio-CNG has a lower energy density, meaning that for the same volume of fuel, bio-CNG provides less energy. This can lead to lower engine performance and power output, affecting traction.

The relationship between output power and RPM for plane 0% grade, 7% grade, and 14% grade is shown in Figures 10,11, and 12 respectively. At a 0% grade, the maximum brake power was 2.81 kW in gasoline mode and 2.30 kW in bio-CNG mode, resulting in an average reduction of 27.45% when using bio-CNG. At a 7% grade, the maximum brake power was 2.84 kW for gasoline and 2.33 kW for bio-CNG, with an average reduction of 32.45%. At a 14% grade, the maximum brake powers measured were 2.81 kW in gasoline mode and 2.29 kW in bio-CNG mode, showing an average reduction of 40.69%.

As the grade percentage increased, the brake power of bio-CNG relative to gasoline consistently decreased. This reduction in brake power when using bio-CNG can be attributed to several factors. Bio-CNG has a lower energy density compared to gasoline, resulting in less energy available for combustion and thus lower brake power output. The optimal air-fuel ratio for bio-CNG is higher than that of gasoline, affecting combustion efficiency and reducing brake power. Engine tuning is typically dome for optimal performance with gasoline; when running on bio-CNG, the tuning may not be optimal, leading to less efficient combustion and lower brake power output.

Following a comprehensive analysis of brake power performance in a dual-fuel vehicle operating under various conditions, it was determined that when running on Biodegradable Compressed Natural Gas (bio-CNG), the brake power output exhibited a marginal decrease compared to its counterpart, petrol fuel, across two performance grades.

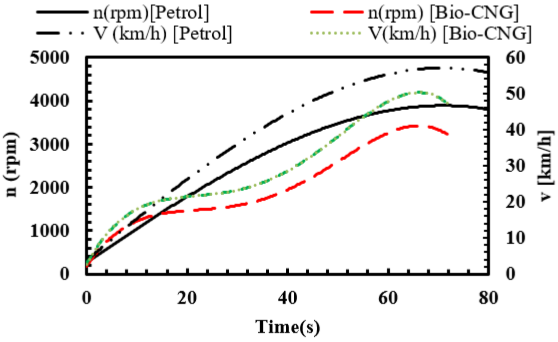

Figure 6: Characteristics curve on both mode

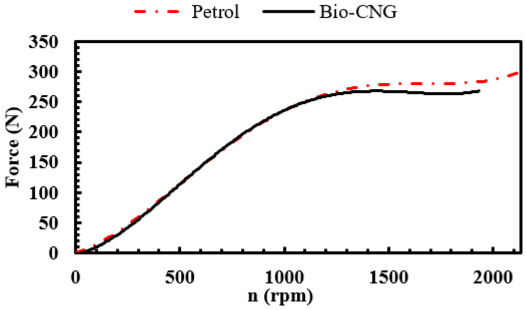

Figure 7: Force on both modes at 0% grade

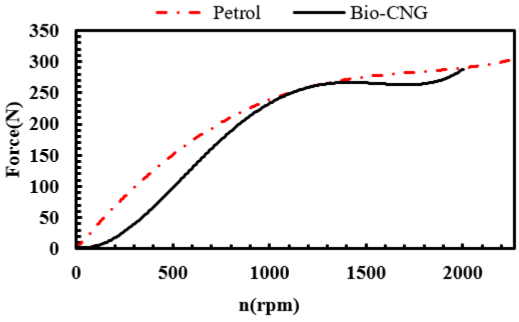

Figure 8: Force on both modes at 7% grade

3.2. Analysis of exhaust gas emission:

The Horiba exhaust gas analyzer was used to measure the amount of pollutants in the vehicle's exhaust system while it was in idle mode with an engine running at 1240 RPM for gasoline and 1022 RPM for bio-CNG.

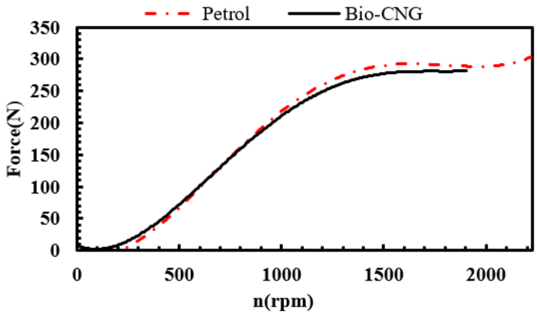

Figure 9: Force on both modes at 14% grade

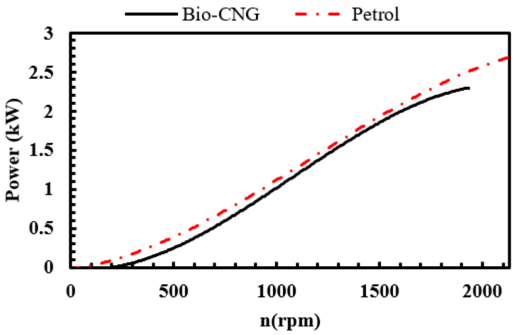

Figure 10: Power on both modes at 0% grade

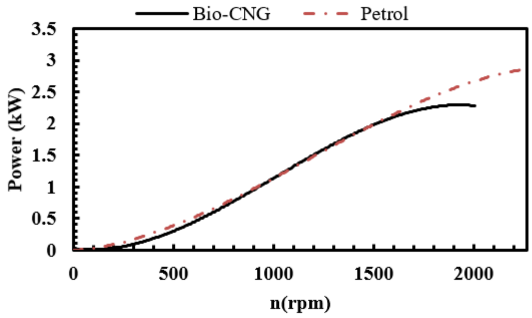

Figure 11: Power on both modes at 7% grade

The emission composition of dual-mode is illustrated in Table 4.In terms of emissions, bio-CNG mode stands out as a better option than gasoline. The hydrocarbon (HC) emissions, a measure of environmental impact, significantly improved, dropping from a peak of 265 PPM in petrol mode to just 29 PPM in bio-CNG mode. The CO emissions during petrol mode were 2.1%, while in bio-CNG mode, the emissions were 0.04%. The significant drop in CO emissions suggests that bio-CNG may be a cleaner and greener alternative fuel to gasoline. The CO_2 emissions during petrol mode were 1.44%, while in bio-CNG mode, the emissions were 1.68%. The in-

Table 4: Emission data obtained from Gas analyzer

Engine Condition	**HC (PPM)**	**CO (%)**	**CO_2 (%)**	**Lambda (λ)**
During Petrol Mode	265	2.1	1.44	1.022
During Bio-CNG Mode	29	0.04	1.68	1.729

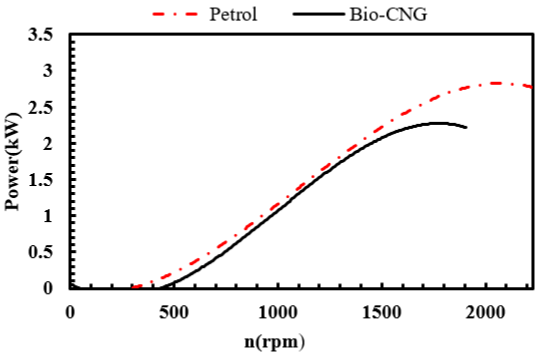

Figure 12: Power on both modes at 14% grade

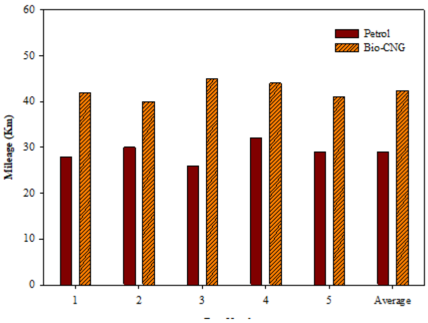

Figure 13: Fuel efficiency comparison between Gasoline and Bio-CNG

crease in CO_2 emissions in bio-CNG mode could be due to the higher oxygen content in bio-CNG, which leads to more complete combustion and higher CO_2 emissions. The lambda values during petrol and bio-CNG modes were 1.022 and 1.729, respectively. The lambda value indicates the air-fuel mixture ratio and a higher value indicates a leaner air-fuel mixture. The higher lambda value in bio-CNG mode indicates a leaner air-fuel mixture, leading to better combustion and reduced emission.

After conducting a comprehensive examination of emission parameters in dual fuel mode, a remarkable transformation was witnessed. Carbon moNO$_x$ide (CO) emissions witnessed a staggering reduction of 98%, While hydrocarbon (HC) emissions decreased commendably by 89%. When the vehicle was in bio-CNG mode, there was a noticeable increase in carbon dioxide (CO_2) emissions of 16.67%. These findings emphasize the significant progress made in mitigating vehicular emissions and advancing toward a cleaner and more sustainable future for our environment.

3.3. Mileage

The average mileage from five test runs for gasoline and bio-CNG was 29 km/l and 42.4 km/kg, respectively, indicating that bio-CNG provides better mileage than gasoline. Bio-CNG engines tend to operate at higher efficiency due to the cleaner burning properties of bio-CNG, which leads to more complete combustion and better fuel economy. Bio-CNG has a lower carbon content compared to gasoline, resulting in less carbon buildup within the engine, which helps maintain engine performance and efficiency over time. The relation of fuel efficiency for petrol and Bio-CNG is shown in Figure 13.

4. Discussion

and advantages of converting conventional internal combustion engine vehicles to operate on bio-compressed natural gas (bio-CNG) alongside gasoline, creating bi-fuel vehicles. Experimental results using an exhaust gas analyzer reveal significant reductions in harmful exhaust emissions, with carbon moNO$_x$ide (CO) decreasing by 98% and hydrocarbons (HC) by 89%. Although carbon dioxide (CO_2) levels increased modestly by 16.67%, indicating more complete fuel combustion in bio-CNG mode, the overall reduction in emissions highlights the environmental benefits of this conversion.

Performance analysis revealed that although bio-CNG initially lags behind gasoline, it ultimately matches gasoline in vehicle performance characteristics. At a 5 kW load coefficient on road inclinations of 0°, 4°, and 8°, power reductions were 27.45%, 32.45%, and 40.69%, respectively, while traction force reductions were 11.59%, 18%, and 23.04%. Bio-CNG exhibits remarkable fuel efficiency despite these reductions, providing significantly more mileage per unit, making it a more economically advantageous choice.

5. Conclusion

The research highlights the transformative potential of bio-CNG conversion for small-engine vehicles in Nepal, offering substantial environmental benefits. Major findings are highlighted below.

- **Performance Metrics:** While bio-CNG initially exhibits lower power and traction forces under varied load conditions and road inclinations, it ultimately matches gasoline in vehicle performance metrics. This includes maintaining comparable acceleration and handling characteristics.
- **Fuel Efficiency:** Despite initial performance compromises, bio-CNG achieves superior mileage per unit compared to gasoline. This efficiency translates to substantial long-term cost savings and economic viability.
- **Environmental Impact:** Compared to gasoline, bio-CNG conversion significantly reduces carbon moNO_xide (CO) and hydrocarbon (HC) emissions by 98% and 89%, respectively. Although carbon dioxide (CO_2) levels increase marginally by 16.67%, indicating enhanced combustion efficiency, the overall reduction in emissions underscores its environmental benefits.

Recommendation

To further enhance the performance of a bio-CNG-converted vehicle, it is recommended to increase the compression ratio to capitalize on bio-CNG's high octane rating, thereby boosting both power output and fuel efficiency. Implementing a spark advancer to optimize ignition timing can accelerate flame propagation, ensuring more complete combustion and reduced emissions. Additionally, equipping the vehicle with high-pressure fuel cylinders can maximize storage capacity, extending the driving range and improving overall fuel efficiency, ultimately making the bio-CNG system more efficient and user-friendly.

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Conflict of interest

The authors herby declare for no conflict of interest.

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