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Investigating the emissions and performance of hydrogen enriched-biogas-*Parinari polyandra* biodiesel in a direct injection (DI) engine

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HIGHLIGHTS

- The hydrogen enriched biogas biodiesel blends gave the lowest HC, NOx and CO emissions.
- There was a marginal increase in the BTE of the fuel blends compared to the diesel fuel.
- Shorter ignition was observed in the fuel blends due to improved combustion.

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ABSTRACT

Owing to strict emission-policies, vehicle manufacturers are mandated to control emissions from diesel engines. To comply with such policies, one of the novel steps adopted in this study, is the use of hydrogen enriched biogas (HE-B) from chicken droppings and pig manure admixed biodiesel. Different fuel-samples were made available. The ratio of biodiesel to hydrogen enriched biogas B(HE-B) in the blends is 85:15 %vol/vol respectively. Biodiesel/diesel and the inducted HE-B were metered at 0.5, 0.75 and 1.0 kg/h with air at the intake manifold of the DI engine and the combustion characteristics of the fuels were compared. The fuel-sample, metered at 0.75 kg/h, gave the best BTE (36.5%) compared to those of the blended fuels whose values are 31.0, 32.4 and 29.4% for the B(HE-B)0.5 kg/h, B(HE-B)1.0 kg/h and diesel respectively, whereas, the CO emissions increased in the following order: B(HE-B)0.75 (0.4 g/kWh) < B(HE-B)1.0 (0.53 g/kWh) < B(HE-B)0.5 (0.54 g/kWh) < diesel (0.72 g/kWh), while for HC emissions, the order is B(HE-B)0.75 (5.0 g/kWh) < B(HE-B)1.0 (11.0 g/kWh) < B(HE-B)0.5 (12.0 g/kWh) < diesel (21 g/kWh). For the NO_x emissions, the established trend is B(HE-B)0.75 (81 g/kWh) < B(HE-B)1.0 (107 g/kWh) < B(HE-B)0.5 (111 g/kWh) < diesel (149 g/kWh).

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Abbreviations

HE-B	Hydrogen enriched biogas
B(HE-B)	Biodiesel hydrogen enriched biogas
B–B	Biodiesel biogas blend
CO	Carbon monoxide
NOx	Nitrogen Oxide
BTE	Brake thermal efficiency
HC	Hydrocarbons
HRR	Heat release rate
B-100	Neat biodiesel
D-100	Conventional diesel
aTDC	after the top dead center
bTDC	before the top dead center

Introduction

The growing demand for fossil refined oil imports has given increased concerns to the Nigeria National Petroleum Cooperation. Furthermore, since processed fossil fuel emits greenhouse gases (GHGs), Nigeria is under persistent pressure to take actions in tackling issues related to emissions [1]. The rise in oil consumption and imports of refined products is expected to linger with the expansion of Nigeria's economy. The continuous increase in Nigeria's population, over-dependence on fossil fuels, increase in manufacturing activities and the increasing concerns of the price of fossil fuel, have led to the need for a sustainable eco-friendly energy source as alternative fuel [1,2].

Considerations for renewable energy as replacement-fuel for fossil fuel is also important for minimizing energy imports from other nations, which in turn culminates in the diversification of power generation sources, all aimed at ensuring a healthy environment [3]. These then serve as primary motivators for alternative energy-sources which are broadly available and environmentally friendly. Alternative fuels such as hydrogen, biodiesel-producer gas, biogas and liquefied petroleum gas (LPG) are all promising energy-sources [1,3].

The production of first-generation biofuels from food crops, has been criticized due to food shortages and sustainability concerns. Nigeria is making significant progress in the use of renewable energy, particularly in the use of second-generation biofuels such as *parinari polyandra* biodiesel, while research into the complete use of biodiesel and its blends in diesel engines in Nigeria and the world at large, is still ongoing. Despite the gradual drift from fossil fuels towards biodiesel and biodiesel/their blends in diesel engines, biodiesel synthesis is still faced with some obstacles. The lack of biodiesel processing facilities for crude *parinari polyandra* biodiesel production is a significant challenge, because it decreases fuel-demand by limiting the market to those who have the equipment to process these seed oils [4]. Growing *parinari polyandra* in Nigeria will require many new advanced facilities, constituting a large capital investment in what has been considered a niche market [5]. This is necessary for *parinari polyandra* to compete with many other biomass crops grown in Nigeria. Also, transportation is another challenge, which contributes to the relative scarcity of process facilities. In areas where biomass is not available, fossil fuels are likely to be economically preferable [6–9]. An increase in the production of parinari polyandra oil may require further investment in agriculture. Lack of awareness is another problem associated with this crop. Some of the potentials associated with *Parinari polyandra*, is that it is mostly cultivated in the tropical savanna region which comprises of Cameroon, Ivory Coast, Mali, Senegal, Sudan, Ghana and Nigeria. In addition, it has been widely acknowledged that the *Parinari polyandra* fruit is underutilized, possibly due to its inedibility or lack of comprehensive investigation or knowledge on its seeds and fruit qualities [10,11], however, high its lipid yield ($>$ 70%) is desired. In lieu of the aforementioned, *Parinari polyandra* remains a promising crop, with high biomass and biofuel yields relative to other key energy crops [2,5]. The relative potential of *Parinari polyandra* also helps it stand out amongst other crops [12]. Increasing biodiesel production will boost all of the advantages of substituting fossil fuel with biomass, such as reducing GHG emissions and providing a long-term energy source. As a crop, it takes an average of 10–15 years to mature in the agricultural market [10], hence, the global demand for *Parinari polyandra* biodiesel is anticipated to grow rapidly in the coming years.

Ogunkunle and Ahmed [10] conducted an experiment with the use of *Parinari polyandra* biodiesel in a diesel engine where they recorded low HC, CO and NOx emissions. In another study, the authors used *Parinari polyandra* biodiesel-diesel blends in a KM 178 F (A) engine to determine the performance characteristics and the physicochemical properties of the fuel blends; the results showed that at full load, the BTEs of the B5D95, B10D90, B15D85, and B20D80 fuel mixtures were 17.26%, 15.29%, 13.07% and 11.95% respectively compared to that of the neat biodiesel whose BTE was 22.59% at 100% load [11]. Furthermore, the physicochemical properties of the blends in terms of kinematic viscosity and density were higher compared to those of the diesel fuel. This is an indication that the neat biodiesel is unsuitable for diesel engines due to its high viscosity when in contact with air which may result in longer ignition delays due to low heat release rate (HRRs), high knocking potential, low BTE, and poor atomization, thus, there is need to select a fuel additive that will help to overcome the limitations of *Parinari polyandra biodiesel* and *one of* such measures is the adoption of hydrogen enriched-biogas which improves the atomization properties of *Parinari polyandra* biodiesel and also improves its physicochemical properties, combustion and performance characteristics with reduced emissions.

Owing to the special qualities of gaseous fuels, they can be used in ICEs since they produce minimal emissions. Due to their high H_2/C ratio, gaseous fuels are thought to be ideal for ICEs [1]. However, with the inherent high self-ignition temperatures of gaseous fuels, they can be used as lean mixtures at high compression ratios, thus improving thermal efficiency and lowering the resulting emissions. In order to compensate for unsustainable hydrogen, H_2 and biogas can be obtained from renewable sources [12]. Furthermore, their excellent air blending properties make them ideal for ICEs. Biogas has the potential to be a viable energy source being a gaseous fuel [13]. Anaerobic digestion of biomass produces biogas, which is predominantly composed of methane (50–75%) and carbon dioxide (25–45%). Biogas combustion with diesel fuel can result in low-emissions; nevertheless, the presence of carbon dioxide in biogas causes delays, thus reducing engine efficiency [14]. Introducing hydrogen in biogas mixtures is one technique that can help to overcome the aforementioned lapses without inducing higher emissions in the exhaust section. For natural gas/methane-powered engines, in which the fuel has some measure of hydrogen incursion, they tend to exhibit outstanding combustion characteristics due to the presence of H_2 which enhances combustion. Hydrogen releases water vapor and contains no carbon, which is necessary for carbon reduction [1,13,14]. Hydrogen addition to biogas during burning may negate the inert carbon dioxide's thermal energy absorption effects, thus improving engine performance [15].

Low BTEs and high BSFCs are characteristics of biogas-diesel-powered CI engines [16]. Nevertheless, carbon dioxide in biogas diminishes its energy content and impairs the burning quality of the fuel. In essence, biogas with high methane content (i.e., >65%) has a high total heating value which helps to improve engine BTE when it is used as fuel [17]. Nathan et al. [18] found that biogas of about 40% CO_2 had no effect on engine performance in spite of the resulting low hydrocarbons and carbon monoxide emissions. CO_2 emissions are heavily influenced by the intrinsic carbon dioxide concentration of biogas. Makareviciene et al. [14] reported that the key components of biogas are methane and carbon dioxide which influence the performance of an engine; for instance, a high methane level in an engine increases engine efficiency. Verma et al. [19] studied the emissions and BTE of a biogas admixed with diesel at 4.4 kW, 1500 rpm engine powered with H_2 supplement (5–20%). The results indicated that adding H_2 to the fuel-mix increased the engine's efficiency with a significant reduction in the engines emissions. In a biogas-fueled SI engine, Chung et al. [20] evaluated the addition of hydrogen on the DI engine. Their result showed that the HRR increased with increase in H_2-fuel ratio. Also, due to the high flame speed of H_2, it was discovered that the ignition delay was shortened. According to Gómez-Montoya et al. [21], H_2 addition (i.e., 5–20% H_2 vol/vol of fuel) in a biogas-diesel fueled engine increases the BTE and in-cylinder pressure with a reduction in carbon monoxide emissions. Suzuki et al. [22] investigated the performance of a multi-cylinder engine using H_2 and diesel mixed as fuel. The findings revealed that the CO, HC, and CO_2 emissions were lower at higher hydrogen concentrations.

The goal of modern-day research has been to develop and use hydrogen -enriched biogas (HE-B) in an internal combustion engine. Research has shown that biogas/diesel fuels have the capacity to improve engine BTE and minimize emissions. However, the presence of CO_2 in biogas increases ignition delays and lowers flame propagation. Hence, CO_2 concentrations in biogas can be reduced by incorporating H_2 into the biogas without inducing higher quantities of gaseous emissions. Despite the vast volume of works on the use of H_2 enriched biogas admixed fuel in diesel engines, there is no existing literature that bothers on the use of *Parinari polyandra* biodiesel and hydrogen -enriched biogas as fuel blends for DI engines; this aspect of research has not been given full consideration by other published literature, which then led to the motivation for this study. In addition, the experimental optimization of the blended fuels was conducted in order to establish the best fuel mixture for optimum engine performance, which in turn helps to conserve useful resources as well as provide sustainable energy; this also has not been considered by previous publications on the subject. Also, due to the fact that no literature has reported the consideration of *Parinari polyandra* biodiesel and hydrogen enriched biogas as fuel-blend for use in DI engines, alongside the unsuitability of the neat biodiesel for use in diesel engines/its associated oxidative instability, high viscosity/poor atomization etc., the biodiesel and hydrogen enriched biogas were blended in various proportions in order to find the blend that would give minimal emissions, efficient combustion and high engine performance. Therefore, the goal of this research is to evaluate the physicochemical properties, combustion, performance and emission characteristics of H_2 addition in the raw biogas admixed with *Parinari polyandra* biodiesel made from chicken droppings and pig manure as fuel-mix in a direct injection engine.

Materials and method/experimental set-up

Production of Parinari polyandra *biodiesel*

Dry seeds of *Parinari polyandra* were screwed-pressed in a mechanical press to produce the crude *Parinari polyandra*-oil. The oil was transesterified at 55 °C using alkaline catalyst. The catalyst was prepared in a 1:30 (weight: volume) ratio of CH_3-$OH + NaOH$ to oil ratio, and the mixture was stirred for 20 min, so as to obtain sodium methoxide. The mixture was transferred into a separating funnel and kept for 48 h so as to stimulate the separation of biodiesel and glycerol. The glycerol was gently decanted at the base of the separating funnel, after which the biodiesel was collected. The methyl ester resulting from the *Parinari polyandra* seeds was obtained and kept ready for use.

Experimental set-up for biogas production

Biogas plant-configuration

The anaerobic co-digestion reactor for processing chicken droppings and pig manure is as shown in Fig. 1. The reactor is made up of a digester and a biogas tank with a floating dome. Both the digester and the gas holder of the floating dome biogas tank were constructed with PVC (polyvinyl chloride). The digester diameter is 0.250 m while the gas holder's diameter is 1.01 m. Table 1 presents the detailed biogas production plant. Fig. 2 is an illustration of the test-run/monitored CH_4 and CO_2 production rate at different retention times. The gas holder was placed in such a way that it floats over the slurry, and a-10 mm pipe was used to transport the biogas from the biogas holder to the gas storage tank for further use (Fig. 3).

Biogas production

Pig manure and chicken droppings in the mass ratio of 75%:25% were employed as the feedstock for the stirred tank reactor. A measured amount of pig manure (3 kg/day) and

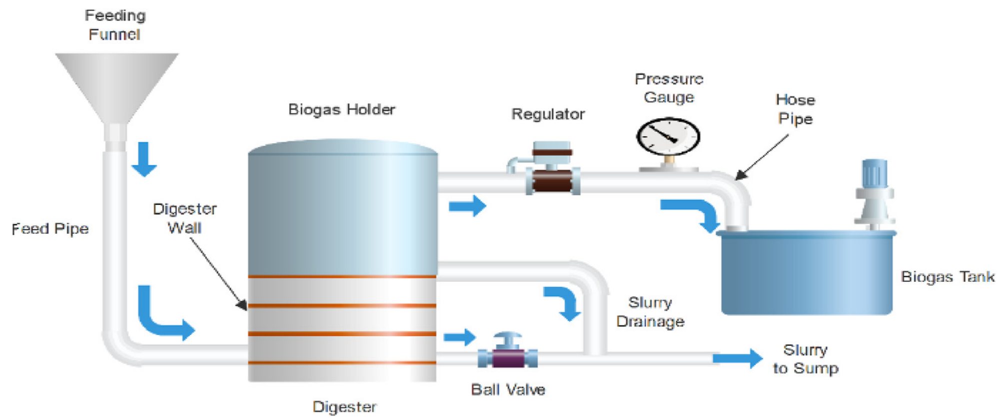

Fig. 1 – Schematic presentation of biogas plant.

Table 1 – Equipment-specification of the biogas production plant.

Parameter	Values
Plant type	Floating dome
Diameter of the digester (m)	1.20
Height of digester (m)	1.05
Operating temp. range (°C)	18–60
Digester total volume (m^3)	1.78
Volume of raw material used (m^3)	1.42
Total volume of gasholder (m^3)	1.15
Hydraulic retention time, days	Min 5–15
Gas holder height and diameter (m)	1.16, 0.92
Effective vol. of gas holder (m^3)	0.74
Effective vol. of digester (m^3)	1.20

chicken droppings (7 kg/day) were collected and blended with water in ratios of 1:3 and 1:1 following the approach adopted in refs (18–20) before being fed into the digester. Table 2 shows the properties of the feedstocks. The total amount of the inoculum formed (pig manure + chicken droppings + water) was measured and the mixture was fed into the digester. The Hanna 211 model pH meter (1–14) was used to determine the pH of the inoculum. The inoculum's pH was observed to be 5.9 on day 1, and it was found to steadily increase to 6.8 within a retention time of 17 days and remained relatively stable afterwards. The digester was able to produce a significant amount of biogas within 12–17 days retention time, and the ambient temperature during the digestion period was 34–38 °C. A digital gas flow meter was used to measure the biogas flow rate from the digester, which was then logged on a lab computer. The biogas production began from the first day, with 0.05 m^3 yield of methane recovered due to the lag phase of microbial activity experienced by the methane-producing microorganisms. Furthermore, from day 1–6, the amount of CO_2 gas produced, surpassed CH_4 gas by about 0.05 m^3. According to literature, acid-producing bacteria help to break down simple sugars, fatty acids, and amino acids into CO_2, acetic acid and H_2, thus resulting in improved CO_2 yield [15,16]. With the generation of CO_2 and CH_4 beginning on day one, it is clear that methanogenesis, hydrolysis, and acidogenesis are evidential processes that occurred on day-one despite the lower activity of the methane-forming bacteria. The methane gas production on day 1 suggested that the three stages of anaerobic digestion were taking place concurrently within the digester as described in Refs. [15,18,19]. The availability of readily biodegradable organic matter in the substrates, as well as the presence of methanogens, is associated with an increase in methane yield measured in the biogas digester. Furthermore, the high methane yield indicates that the methanogenesis stage of the anaerobic digestion process had reached its optimal conditions, thus signifying maximum methane yield. The CH_4–CO_2 content of the biogas was measured using an Agilent 7890-A gas chromatograph (Agilent Technology, United states of America) fitted with a thermal conductivity detector (TCD) with helium as the carrier gas. The %CO_2 in the biogas was measured with a CO_2 gas analyzer (Messer® CANgas, 99.995%) following the manufacturer's instructions. The methane and carbon dioxide yield during the biogas production are presented in Fig. 2.

Biogas plant cost analysis plays a significant role in determining the economics of a biogas plant. The operational costs involved are of two categories: (A) fixed cost and (B) variable cost. The cost of production of the biogas are stated as follows;

(i) Fixed-cost
Cost of biogas digester = $ 304
Purchase of gas-holder = $ 96:00
Cost of purchasing tubes = $ 35
Assembly cost = $40:00

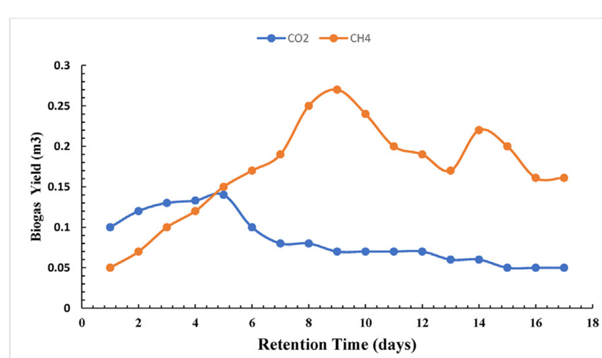

Fig. 2 – Volume-variation of CH_4 and CO_2 with retention time (days).

Total fixed cost = $475:00

(ii) Estimation of fixed cost

The pig manure and chicken droppings feed into the digester are 3 and 7 kg/day.
The cost of chicken droppings = $0.7:00/kg
The cost of pig manure = $1:00/kg
The cost of per kg of chicken droppings = $7:00
The cost of per kg of pig manure = $2.10
Total feedstock cost per day = $9.10
Biogas production quantity on an average daily basis is 0.5 m^3
Thus, daily expenditure in producing 1 m^3 biogas will be = $18.2

Test fuel properties

The gas compositions of the admixed biogas are presented in Table 3. The physicochemical characteristics of hydrogen and the obtained biogas from pig manure + chicken droppings via anaerobic digestion are presented in Table 4. The crude bio-oil, biodiesel and diesel properties are shown in Table 5.

Table 3 – The produced biogas composition.

Gases detected	Pig manure + Chicken droppings (%vol.)
H_2	1.51
N_2	5.20
CO_2	18.72
H_2S	0.17
CH_4	73.00
O_2	1.40

Description of the test engine

The test-engine in this investigation has six cylinders and a direct fuel-injection nozzle which is turbocharged as shown in Table 6. Fig. 3 depicts the schematic section of the engine. A high-pressure DI system (comprising of an 8-hole injector with a nozzle diameter of 0.3 mm), a turbocharger, an inter-cooler, a biogas cylinder, and a throttle valve that controls the flow rate of biogas-hydrogen-air mixture help to transport the fuel to the engine.

The quantities of biodiesel produced in the experiments were measured. The biogas-hydrogen mixture flow rate that

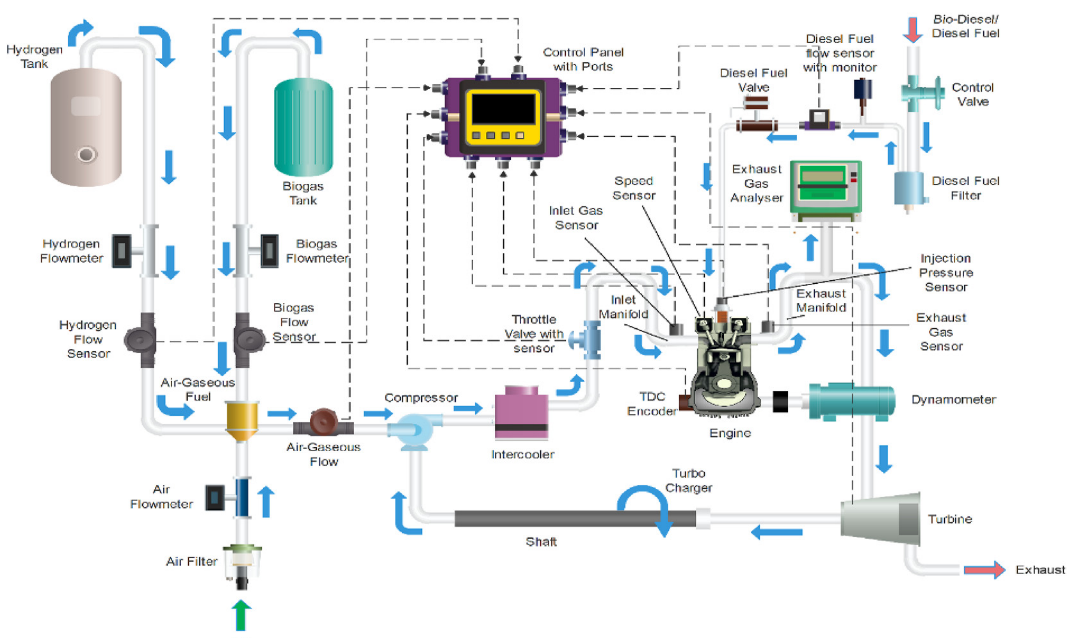

Fig. 3 – Schematic of test engine.

Table 2 – Parameters measured, flow conditions of the feedstock and the quantity of biogas producd.

Properties	Values
Feedstock	Pig manure and Chicken droppings in the proportion of 75%:25%
% total solid present in the feedstock	42.77
% volatile solid in the feedstock	35.03
Carbon/Nitrogen ratio of feedstock	24.63:1
pH/concentration of slurry	5.9–7.4
Feed rate of pig manure (kg/day)	3
Feed rate of chicken droppings (kg/day)	7
Pig manure: water ratio	1:3
Chicken droppings: water ratio	1:1
Biogas produced on daily basis (m^3/kg)	Max. 0.48–0.54

Table 4 – Physicochemical properties of the admixed biogas from pig manure + chicken droppings and hydrogen.

Parameters	ASTM D Test method	Hydrogen	Admixed biogas
Flammability limits (% vol. in air)	6793	4–75	7.6–14
Lower heating value (MJ/kg)	1945	119.92	26.24
Diffusivity in air (cm^2/s)		0.62	0.111
Density (kg/m^3)	3588	0.0838	1.21
Flame speed (m/s)	7424	292	25
Auto ignition temperature	–	585	650
Stochiometric A/F	4891	34.36	17.28
Boiling point, °C		−252.9	−120 to −150
Octane number	2699	130	130

Table 5 – Crude *Parinari polyandra* and physicochemical properties of the produced biodiesel

Fuel properties	Crude *Parinari polyandra* oil	*Parinari polyandra* biodiesel	*Fossil Diesel*
Heating value, MJ/kg	–	45.43	44.74
Cetane number	–	49.0	49.95
Specific gravity @ 40 °C	0.900	0.891	0.853
Cloud point, ∘C	–	4.06	−1.47
Viscosity @ 40 °C, cSt	51.63	3.97	2.98
Flash point, ∘C	–	134	75
Pour point, ∘C	–	1.00	−3.73

Table 6 – Specifications of multi-fueled diesel engine test rig.

Parameter	Specifications
Type	Direct injection, single cylinder, VCR engines
Bore stroke	125/155 mm
Compression ratio	17.5:1
Speed	1500 rpm
Injection pressure	220 bars
Cylinder configuration	6 in-line
Displacement volume	662 cm^3
Injection timing	27° bTDC
Rated power	5.5 kW
Fuel injection nozzle	8 holes

was fed to the intake manifold that would mix with the air was adjusted by passing it through the gas flow meter and setting it to the desired value. The gaseous fuel composition in percentage by volume contains 9% vol/vol H_2 and 6% vol/vol biogas. Then, these mixture types were selected from the flowmeter control panel; the amount of gas was processed numerically in LPM using the device, and the amount of gas given was kept constant. The engine control unit was used to control the injection system, as well as the engine's parameters. The engine's exhaust emissions and performance were measured at 1500 rpm with different load specifications (0, 25, 50, 75, and 100%).

Engine-operation

Different mass flowrates (0.5, 0.75, 1.0 and 1.25) kg/h of hydrogen-enriched biogas (HE-B) were employed in enriching the air inlet. Corresponding volumes of hydrogen-enriched biogas in the inducted air were kept constant at 15 %vol/vol for the hydrogen-enriched biogas fuel mixtures (9% vol/vol H_2 and 6% vol/vol biogas). Several trials were made before the authors arrived at 9%:6% (H_2: biogas) as ideal for blending with 85% biodiesel. For example, the authors used, different ratios of (H_2: Biogas) beginning from 10:5, 9:6, 8:7, 7:8, 6:9; 5:10, 4:11. However, the ratio 9:6 (H_2: Biogas) gave the best blend with 85% vol/vol biodiesel for optimum efficiency and minimal emissions. Due to the level of enrichment of the hydrogen-enriched biogas with the intake air, the volume of biodiesel consumed was constant. The hydrogen was injected in the biogas at ~ 1.3 bar. The flowrate of hydrogen and biogas was maintained at 3 LPM prior to the throttle valve. The gaseous fuel was mixed with the air in the engine intake manifold. At 1.3 bar, the pilot fuel was injected. The proportion of the volume of biodiesel admixed with hydrogen-enriched biogas-air mix at the intake section is presented in a later section.

The experimental set-up of the flow-process is illustrated in Fig. 3. The flow-scheme of H_2 consists of a cylinder, flowmeter, pressure regulators, flame trapper and a flame arrestor. The supplied H_2 from BOC gas company limited, Lagos, Nigeria was pressurized in a high-pressure cylinder and released at an exit pressure of 2 bar with the aid of a pressure regulator. The specification of the engine is presented in Table 6; the hydrogen-enriched biogas flow rates (i.e., 0.5, 0.75, 1.0 and 1.25) kg/h were delivered at high pressure to provide 15% vol/vol of each of the hydrogen-enriched biogas to 85% biodiesel. The produced fuel-mixtures are presented in Table 7 while the uncertainty measurements of the flow-variables are tabulated in Table 8.

Uncertainty measurements

When obtaining readings or measurements from experiments, accidental/logical errors may ensue due to incorrect calibration of the measuring devices. There are also variances in the design-precision and manufacture of equipment which makes them prone to errors while taking measurements, hence, experimental testing is important, especially when evaluating uncertainties. When evaluating uncertainties, it is essential to do this by majorly determining the measure of repeatability that is obtainable in a total of three batch measurements in a bid to admit a low level of insignificant magnitude of standard deviation. The method of Kline and McClintock (1) was adopted in calculating the percentage uncertainty of all the measured parameters (Table 5).

$$\Delta T = \frac{\partial U}{\partial x_1}\Delta x_1)\frac{\partial U}{\partial x_2}\Delta x_2)\frac{\partial U}{\partial x_n}\Delta x_n)(\frac{\partial U}{\partial x_n}\Delta x_n)(\frac{\partial U}{\partial x_n}\Delta x_n)^2]^{\frac{1}{2}} \quad (1)$$

where ΔT represents the total uncertainty.U – is dependent on the independent variables of x_1 , x_2 … … … … x_n, Δx_1,

Table 7 – Codes for the different test-fuels.

Parameter	Description	Acronym
D- 100	Fossil Diesel	D- 100
B- 100	*Parinari polyandra* biodiesel	B- 100
Biodiesel/@ (-B)0.5 kg/h	85 vol/vol biodiesels blended with 15 vol/vol **bio-gas** at flow rate of 0.5 kg/h	B(B)0.5 kg/h
Biodiesel/@ (HE-B)0.5 kg/h	85 vol/vol biodiesels blended with 15 vol/vol hydrogen-enriched biogas (HE-B) at flow rate of 0.05 kg/h	B(HE-B)0.5 kg/h
Biodiesel/@ (HE-B)0.75 kg/h	85 vol/vol biodiesels blended with 15 vol/vol hydrogen-enriched biogas (HE-B) at flow rate of 0.75 kg/h	B(HE-B)0.75 kg/h
Biodiesel/@ (HE-B)1.0 kg/h	85 vol/vol biodiesels blended with 15 vol/vol hydrogen-enriched biogas (HE-B) at flow rate of 1.0 kg/h	B(HE-B)1.0 kg/h

Note: All through the experiments, the total volume ratio of H_2 to biogas used is 15% vol/vol (9% vol/vol H_2 and 6% vol/vol biogas).

Table 8 – The percentage uncertainty and accuracies of all the measured parameters.

Properties	Accuracy (±)	Uncertainty (%)
Dynamometer (g)	± 50*g*	± 0.1
Measuring burette (cm^3)	± 0.25	±0.2
Heat release rate (HRR) (J/°CA)	–	±0.3
Pressure transducer (bar)	± 0.1 *bar*	±0.1
Carbon monoxide emission (%)	± 0.02 %	±0.3
Hydrocarbon emission (ppm)	± 5 *ppm*	±0.2
NOx emission (ppm)	± 5 *ppm*	±0.2
BTE (%)	–	±0.2
Engine speed (rpm)	±10 *rpm*	±0.1
Crank angle encoder	± 1°	±0.02
Timer (sec)	± 0.1	±0.2

Δx_2……… Δx_n *are the independent variable uncertainties.* , $\Delta T = \sqrt{(\text{Dynamometer})^2 + (\text{Measuring burette})^2 + (\text{HRR})^2 + (\text{Pressure transducer})^2 + (\text{CO})^2 + (\text{HC})^2 + (\text{NOx}) + (\text{BTE})^2 + (\text{Engine speed})^2 + (\text{Crank angle encoder})^2 + (\text{Timer})^2}$, $\Delta T = \sqrt{(0.1)^2 + (0.2)^2 + (0.3)^2 + (0.1)^2 + (0.3)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (0.1)^2 + (0.02)^2 + (0.2)^2}$, Thus, the overall uncertainty is. ±0.64 %

Results and discussion

Performance characteristics

BTE measures how efficiently a fuel is burned in the combustion chamber for subsequent heat-to-work conversion. The fuel's inherent qualities, such as kinematic viscosity, density, cetane number, high calorific value, and low O_2 concentration, affects the BTE. The variations in BTE of biodiesel-enriched biogas (B–B), biodiesel-hydrogen-enriched biogas (B(HE-B), diesel, and the neat biodiesel fuel with engine loads are depicted in Fig. 4. The brake thermal efficiency increased for all the tested fuels with corresponding increase in engine loads. However, B(HE-B) gave improved BTEs compared to those of the biodiesel and unblended diesel. At 100% load condition, the observed BTEs are 29.4, 27, 29 [31], 36.5 and 32.4% for the diesel, biodiesel, (B–B) 0.5, (B(HE-B)0.5, (B(HE-B)0.75, and (B(HE-B)1.0 kg/h fuels respectively. This result corroborates the findings of refs. [21–23]. Conventional diesel fuels (diesels) vary slightly in

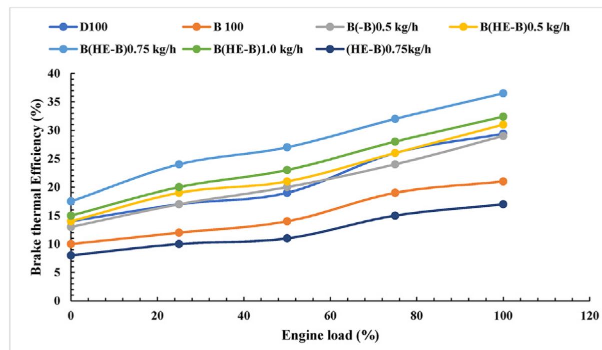

Fig. 4 – The variation of BTE with engine load.

composition owing to the different sources from which fossil fuel deposits are obtained. Although, the constituents are similar, their relative proportions in the different diesels obtained from fossil may have a resultant/overall effect on the engine characteristics induced by these varying fuel properties and composition. Refining technology also has a way of affecting the properties of the final diesel that results from fossils [23], this may have prompted the slight reduction of the BTE of diesel to 29.4%. The improvement in BTE for the (B(HE-B) is due to rapid combustion alongside evaporation and improved atomization that was inherent in the fuel blends relative to those of the diesel and neat biodiesel; this may be due to the inducement of better air-fuel mixing of the referred fuel. In addition, the B(HE-B)0.75 kg/h fuel provided the highest brake thermal efficiency relative to the other fuel-blends. According to Oni et al. [24], increased viscosity and poor air-fuel mixing, can result in large molecular weight, reduced calorific value and poor atomization of a fuel, thus resulting in low brake thermal efficiencies. The reduction in BTE of the B(B)0.5 kg/h fuel is due to the oxygen deficit imposed by biogas induction through the intake manifold. Incomplete combustion arises from lack of the required amount of oxygen mixed with a fuel, which in turn leads to slow conversion of the input fuel energy with a resultant increase in the fuel flow rate during the process of combustion. Paul et al. [25] reported a similar observation with respect to decreased BTE. Another reason could be the introduction of a high amount of air-biogas mixture, which leads to a reduction in flame propagation speed and an increase in reverse compression work.

Emission characteristics

CO emissions

The variation of CO emissions at several engine-loads is presented in Fig. 5. The CO emissions of the biodiesel-hydrogen enriched biogas B(HE-B) and the biodiesel-biogas (B–B) fuel mixtures gave similar trends with those of the neat diesel and biodiesel fuels at several load conditions.

Ganzoury and Allam [7] demonstrated that H_2 does not contain carbon atoms and thus produces better combustion rates. B100 has a high oxygen content that reduces the concentration of CO and improves combustion. The reduction in CO in the B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 operated dual fuel engine, is due to the absence of carbon in the H_2 fuel. But at 100% load the O_2 concentration in the blended fuels increased significantly thus resulting in a decrease in the formation rate of CO, which makes the overall CO concentration in the blends and biodiesel to decrease compared to diesel; similar trends were observed in the works of Refs (11, 17). The H_2 in the blended fuels reduced the carbon content in the fuel, hence, H_2 addition can minimize CO emissions. Additionally, Chung and Chun [20] reported that high flame propagation speed of hydrogen enriched biogas facilitates an increase in the cylindrical pressure and high combustion efficiency. Besides, the higher diffusivities of B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h in comparison to other fuels, provides better homogeneity of the combustible mixture, thus enabling more O_2 to be available to boost combustion whilst inducing a faster combustion reaction in the combustion chamber. Higher CO emissions from diesel, HE-B, and B–B occurred due to incomplete combustion, lesser combustion time and the possibility of flame-quenching. However, lesser CO emissions were recorded in the B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h with corresponding values of 0.54 g/kWh, 0.53 g/kWh and 0.4 g/kWh respectively due to improved combustion, which resulted in higher conversion of carbon monoxide to carbon dioxide, thus, the quantity of the emitted carbon monoxide decreased. This is as a result of the inclusion of hydrogen in the biogas/neat biodiesel. Thus, hydrogen enrichment of the biofuel decreased the CO emissions. Good mixture formation of the liquid and gaseous fuels is another reason for the reduced CO emissions in the B(HE-B)s [26–28]. In addition, the reduced CO emissions can be as a result of the improved combustion and lean air–fuel charge mixture of the B(HE-B)s. Thus, the recorded CO emissions of all the fuels are D-100 (0.73 g/kWh); B-100 (0.62 g/kWh); B (-B)0.5 (0.58 g/kWh); B(HE-B) 0.5 (0.54 g/kWh); B(HE-B) 0.75 (0.4 g/kWh) and B(HE-B) 1.0 (0.53 g/kWh) respectively. The obtained results are in agreement with the works of refs [4,11,16].

Hydrocarbon (HC) emissions

The profile of HC emissions as a function of engine load is presented in Fig. 6. However, higher HC-emissions are associated with poor atomization, higher viscosities, and poor combustion. The HC emissions are relatively lower for the B–B (0.5) and B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h relative to the biodiesel and diesel fuels. The reason for the lower HC-emissions in the B(HEB) is due to good fuel atomization, shorter ignition delay and low viscosity of the blends. The B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h fuels gave lower HC emissions at full load condition, thus resulting in better air-fuel mixing in the chamber. As shown in Fig. 6, under all the operating conditions, the HC emissions of the HE-B (0.75 kg/h) were found to be higher than those of the B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h fuels. The quantity of HC emissions surged at various engine loads when the hydrogen-biogas mix was introduced into the biofuel. The addition of biogas to hydrogen resulted in a rich mixture in the chamber and a lower percentage of O_2 in the air-fuel charge mix; aside from that, biogas has a lower flame velocity [9,25], thus as a result of incomplete combustion, the hydrocarbon emissions increased. The carbon dioxide in the biogas caused the fuel to absorb heat, which then lowered the in-cylinder temperatures as well as slowed down the HC oxidation process. Other factors that led to greater HC emissions include overlapping of the valve, poor mixing of gaseous and liquid fuel, longer delay in the ignition of the biogas-hydrogen fuel mix, the effect of crevice volume and wall quenching. Most researchers have recorded similar results in their documented quantities of HC-emissions for biogas-biodiesel dual-fuel systems [11,16,19,23,26,27]. According to Bora and Saha [28], the hydrocarbon emissions of biogas in an engine operating in dual-fuel mode, were greater as a result of the reduced flame velocity of the biogas, thus resulting in higher hydrocarbon emissions. They also discovered that as the compression ratio increased, the resulting HC emissions reduced. Some researchers [14,17,27,29] demonstrated that hydrogen addition to biofuel helps fuel-air mixture to burn more thoroughly/faster and thus reduces the level of unburned hydrocarbon emissions. However, upon adding the *Parinari polyandra* biodiesel to the HE-B, lower HC emissions were recorded for the

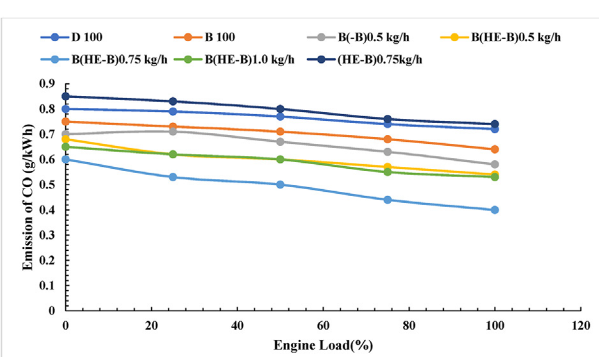

Fig. 5 – Variations of carbon monoxide emissions with various engine load.

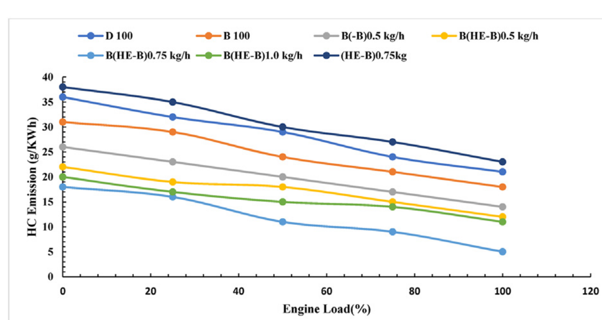

Fig. 6 – HC emissions versus engine load.

B(HE-B) 0.5, B(HE-B) 0.75 and B(HE-B) 1.0 kg/h with corresponding HC emissions of 12 g/kWh, 5 g/kWh and 11 g/kWh respectively. These results corroborate the results from the works of refs. [7,19].

NOx emissions

The production of NO is largely influenced by compression ratio, combustion temperature, retention time and the amount of oxygen. Nitrogen oxide production is aided by higher O_2 concentrations and increased combustion temperatures inside the combustion chamber. NO_x creation inside the engine cylinder is based on the principle of combustion science, with the oxidation of nitrogen in air being the primary reason. Fig. 7 presents the variation of NO_x emissions with engine load for the diesel, biodiesel, B–B, HE-B and B(HE-B) fuels. Due to the addition of biodiesel, the NO_x emissions from the burnt B(HE-B) were significantly reduced. This occurred as a result of the presence of CO_2 from biogas which reduces the oxygen content of the charged mix, thus resulting in a drop in the overall cycle-temperature; thus, as a result of the combined action of these processes, NO production was reduced [30]. Furthermore, hydrogen addition to the biogas, increased the NO_x emissions owing to an increase in the premixed combustion phase that accompanies the H_2 induction which is associated with an increase in flame temperature and high NO_x emissions. The B(HE-B)0.75kg/h-fuel lowered the NO_x emissions at full load condition when compared to those of other fuels. Furthermore, increasing the gas flow rates resulted in higher NO_x emissions in general, and hydrogen inclusion in the biodiesel gave a boost in the magnitude of the NO_x emissions received for the selected fuel-combinations. The addition of hydrogen in biogas caused a significant increase in the resulting NO_x emissions at several engine loads. The quantity of NO_x emissions decreased in the following order of magnitude: (HE-B)0.75 (171 g/kWh) > D (100) (149 g /kWh) > B–B 0.5 (112 g/kWh) > B (100) (111.5 g/kWh) > B(HE-B)0.5 (111 g/kWh) > B(HE-B)1.0 (107 g/kWh) > B(HE-B)0.75 kg/h-fuel (81 g/kWh); similar results were found in the work of ref. [21].

Combustion characteristics

Heat release rate (HRR)

Fig. 8 shows the relationship between the HRR with degree crank angle for all the fuels at full load. An increase in the

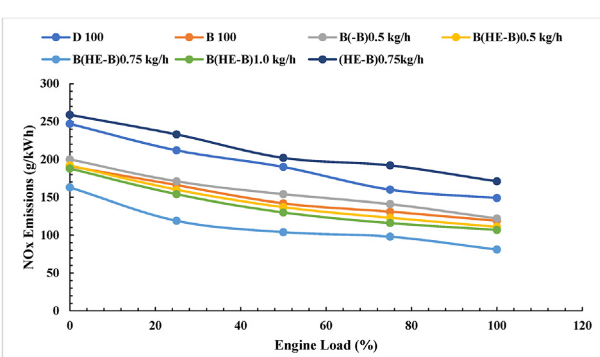

Fig. 7 – NOx emissions versus engine load.

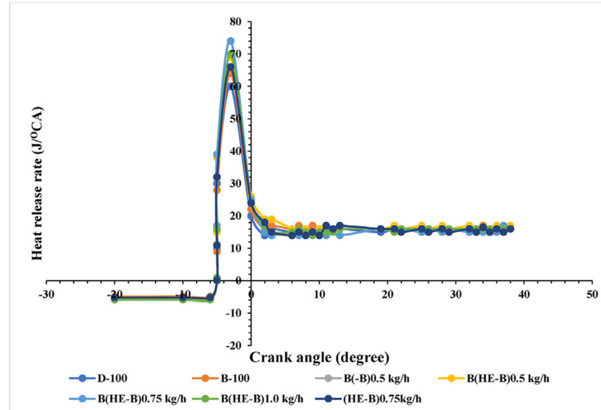

Fig. 8 – Variation of HRR with the crank angle.

cetane number of the fuel blends also increased the diffusion rate of the fuels rather than allowing the fuels pass through a lengthy pre-mix combustion phase. The fuels' heat release rate curves follow a similar form compared to that of the diesel fuel due to the shorter ignition delay of the fuel blends, which impacted higher peak pressures and HRRs in the pre-mix burning phase. The greater HRRs are also due to the fuel mixture's low viscosity and high calorific value. Higher heat release rates for the hydrogen-induced fuels were caused mostly by the rise in the gas's calorific value and flame speed, which in turn led to progressive combustion. As a result, hydrogen induction had a greater effect like lengthening the premixed combustion phase at the expense of diffusion-induced combustion; similar findings were reported in refs [23, 28 31]. Comparing the B(HE-B)0.75kg/h-fuel to the fossil diesel at full load, premixed combustion was on the rise. The HRR curves for the B–B-0.5 and B(HE-B)0.5 kg/h fuel blends are closer to that of the conventional diesel fuel. Higher heat release rates were obtained for the B(HE-B)1.0kg/h-fuel in their pre-mixed phases due to the presence of oxygen and hydrogen in the blends, which then increased the fuel blends' combustion rates at higher flowrates. This result is in line with those of previous reports [11,16–19]. The sudden rise in the heat release rates indicate the start of combustion. During the ignition delay period, the HRR increased abruptly as a result of the increased burning of fuel in the chamber.

In-cylinder pressure

The variation of cylinder pressure with crank angle is critical in determining the measurable meaningful information about the engine's combustion progress. The cylinder pressure slightly decreased as the gas flow rate of all the fuels increased. The in-cylinder pressure variation of the fuel-blends, follows the same pattern with that of the diesel fuel. Throughout the pre-mixed burning phase of the DI engine, the generated cylinder pressure was dependent on the flow rate of the burnt fuel. Mustafi et al. [26], reported that H_2 enriched biogas mixed with diesel results in shorter ignition delay with a higher cylinder pressure and thus improved the fuel-combustion at maximum pressure. At higher cylinder temperature, specifically at higher loads, the degree of ignition delay becomes shortened as a result of the progressive advancement of the combustion process before it approaches the TDC

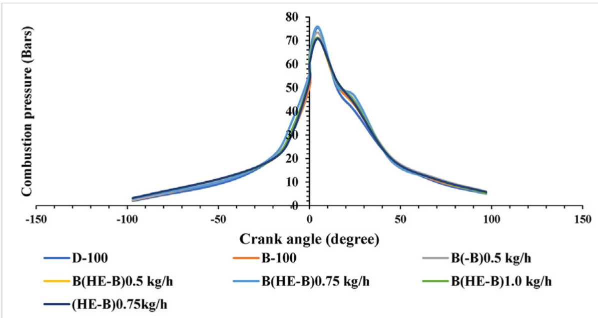

Fig. 9 – Variation of combustion pressure with crank angle of the engine's shaft.

[6,15]. The enrichment of hydrogen -biogas in the biodiesel fuel further boosts the phenomenon that induces pressure rise [22]. Thus, it can be said that the higher rate of flame propagation of hydrogen-enriched biogas leads to advances in combustion and reduces the total duration of combustion [3,14]. The maximum cylinder pressure of the fuel blends is very close to that of the diesel fuel (74.19) bar. The pressure values for all the fuel-blends are 73.09, 74.11, 74.12, 74.16, 74.14 and 73.98 bar for the B-100, B–B- 0.5, B(HE-B)0.5, B(HE-B)0.75, B(HE-B)1.0 and (HE-B)0.5 kg/h (Fig. 9); these corroborates the findings of refs [6, 10, 32]. The higher pressures measured are due to the large amount of energy dissipated in the engine which is caused by the combustion of diesel fuel, whereas, all the fuel blends exhibited slightly slower burning rates and a decrease in the amount of air entering the cylinder for every increase in the amount of hydrogen-enriched biogas flowing per hour into the combustion chamber. The neat biodiesel gave lower pressures compared to those of other fuels as well as the blended fuels. The addition of hydrogen improved the peak cylinder pressure of the B(HE-B) fuel. The peak cylinder pressures of the B(HE-B) occurred slightly after the top dead center (aTDC) relative to those of the diesel, biodiesel and (B–B) fuels at 100% load condition.

Conclusion

The production of different fuel blends using hydrogen enriched biogas obtained from chicken droppings and pig manure admixed with *Parinari polyandra* biodiesel at different flowrates were investigated in this study with the aim of achieving low emissions and high engine performance in a DI engine. In terms of the measured BTEs, higher engine performance and low fuel emissions (NO_x, CO and HC) were observed for the B(HE-B)0.75kg/h-fuel compared to those containing hydrogen gas at other flowrates. The proportion of hydrogen-enriched biogas with the biodiesel was maintained at 15:85% vol/vol for all the tested fuels.

Further conclusions can be stated as follows

- similar characteristics were observed in the combustion properties of the biogas-diesel and B(HE-B)-fuel at 100% load condition. There was a significant increase in the HRR and in-cylinder pressure of the B(HE-B)s due to the rapid combustion induced at the premixed combustion phase compared to the case of the neat biodiesel and biogas-biodiesel fuel systems.
- the results indicated that the B(HE-B)- fuel showed a marginal decrease in NOx, HC and CO emissions at full load conditions compared to those obtained for the fossil diesel.
- the BTE of all the blended fuels increased and there was a marginal increase in the BTE of the B(HE-B)s compared to those of diesel fuel. Hence, the brake thermal efficiency (36.5%) of the B(HE-B)0.75kg/h-fuel was highest.

Therefore, the use of hydrogen enriched biogas with *Parinari polyandra* biodiesel in a DI engine is a sure way to impose reduced emissions as well as improve engine performance better than that obtained for diesel fuel.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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