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Evaluation of a diesel engine performance and emission using biogas in dual fuel mode

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This article contributes to:
7 AFFORDABLE AND CLEAN ENERGY
SUSTAINABLE DEVELOPMENT GOALS

Highlights:

- Biogas as an environmentally friendly and cost-effective alternative for dual-fuel diesel engines was studied.
- Biogas reduces NO_X and CO_2 emissions, slightly decreases efficiency, but increases fuel consumption (BSFC).
- Biogas is promising for dual-fuel diesel engines.

Abstract

Environmental pollution and the gradual depletion of fossil fuels have recently shifted the focus to alternate fuels. Hence, more diversified research on alternate fuels is necessary to deal with the global energy crisis. Biogas extracted from biomass is an excellent alternative to fossil fuels due to its low cost and good mixing ability. It is mainly generated by anaerobic digestion of organic waste products in a digester tank. The present paper investigates the performance and emission characteristics of diesel engine in dual fuel mode with biogas as main fuel and diesel as pilot fuel without any engine modification. The main aspect of the paper is to critically study the effect of supplementation of biogas on diesel engine efficiency and emission level of important constituent gases such as CO_2 and NO_X. Our findings demonstrate that the essential performance result of engine, such as Brake Thermal Efficiency (BTE) and Mechanical Efficiency for the biogas-air mixture of 20% (DB20), was slightly decreased. At the same time, there was a reduction in brake-specific fuel consumption (BSFC) compared to pure diesel. Furthermore, the exhaust emission of NO_X and CO_2 was lowered when the engine was operated in dual fuel induction mode. The results of engine performance were found to be better than the results of other researchers for engines of same specifications and operating conditions. Hence, biogas serves as a viable alternative fuel and contributes to cleaner combustion, offering a promising solution for reducing the environmental impact of diesel engines. The study provides critical insights into optimizing dual fuel systems for enhanced performance and sustainability.

Keywords: Kitchen wastes; Biogas; Performance; Dual fuel mode

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1. Introduction

Rapid industrialization and growth in population have increased the consumption of energy worldwide and in that regard, India stands third largest energy consumer worldwide [1]. There is a growing demand for energy and the services associated with it to meet the requirements of human social and economic development, welfare, and health. Due to increasing liquid fuel consumption, depleting resources, and heavy pollutant loads from burning traditional fossil fuels, the world must focus on developing reliable alternatives [2]–[4]. Energy harvesting policy from conventional sources in the current scenario has become unsustainable to meet the rising energy demand from either domestic or industrial purposes and forecast higher energy demand due to socio-economic development by 2050.

Due to the rapid consumption of conventional resources of energy, the world has been triggered to find an alternative and clean energy source. Moreover, the extensive use of petroleum-based fuels causes air pollution which is becoming a major environmental concern in recent times [5]. Alternative renewable sources include hydro energy [6], solar energy [7]–[10], wind energy [11], and biofuel [12]–[14]. A significant study on alternative fuels for engines has been reported in different works, but fossil fuels have yet to be replaced [15]. This is due to a lack of comprehensive research output that may ensure improved engine performance and a reduction in emissions [16]. Emerging techniques and research policies of institutions towards waste to-wealth drive, Municipal solid wastes (MSW) have been regarded as a promising biodegradable biomass that can be converted into a potential volume of biogas, and the residues left may be used for compost preparation other than landfilling [17]–[19]. Waste Biomass in the form of Kitchen waste undergoes a bacterial digestion process in the absence of oxygen and produces the potential volume of biogas recovery efficiently. Therefore, the anaerobic digestion of kitchen wastes into biogas can be suitably utilized as a potential green alternative fuel [20], [21]. Das and Panda [22] were able to produce biogas from kitchen waste with a high methane content of 68%. Biofuels derived from waste biomass are regarded as a better alternative fuel to petroleum fuels. Apart from others, biogas derived from waste biomass has a significant contribution towards renewable sources of energy. Biogas is also regarded as a clean and green energy source due to its low content of pollutants and high drivability.

Furthermore, due to the high diffusion rate of biogas with air and high flammability, biogas can be used as an alternative non-fossil fuel for IC engines [23]–[25]. Prabhu et al. [26] experimentally investigated the performance and emission analysis of diesel engines using a preheated mixture of biogas and air. The engine performance was reported to be enhanced with the use of preheated biogas. However, the operation and maintenance cost of the system increases with the inclusion of a heat exchanger used for preheating biogas. The case study carried out by Himsar Ambarita [27] reveals that output power increases with the use of biogas in dual-fuel mode in the diesel engine. Bouguessa et al. [28] experimentally studied the performance of diesel engines using a mixture of hydrogen and biogas up to 80% engine load. However, they did not investigate all engine performance parameters. So, biogas as an alternative fuel is suggested as a promising alternative for its coherence towards clean and green energy sources. It can be added with diesel in an appropriate proportion in dual fuel injection mode to balance engine performance and emission. Prabhu et al. [29] ptimized the performance and emission parameters of diesel engines by using an artificial neural network (ANN) model.

In the present work, an attempt is made to investigate important performance parameters of diesel engines such as brake power, brake-specific fuel consumption, brake thermal efficiency, and mechanical efficiency in dual fuel mode. The performance and emission characteristics are obtained without any engine modifications. The findings are expected to provide the required knowledge to create an alternate strategy to improve biogas use. In the subsequent sections, this paper will delve into several key aspects. Section 2 outlines the composition, properties of biogas, and specifications of the engine. Section 3 describes the methodology employed in this study, detailing the experimental procedure and measurement of engine parameters. Section 4 analyzes the findings, offering insights into the observed trends. Finally, Section 5 concludes with a discussion of the implications of these findings and suggests a scope for future research.

2. Materials

2.1. Composition of Biogas

Biogas comprises potential amounts of methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S,) and amounts of moisture (**Table 1**). Methane contributes a lot to Global Warming Potential (GWP). Therefore, the gases like methane, carbon monoxide (CO), and hydrogen sulphide (H_2S) need to be combusted properly in the presence of oxygen (O_2) to reduce the level of emissions [30]. Biogas collected from an anaerobic digestion process can be used as an alternative fuel for heating, domestic cooking, transportation oil, and electrification purposes [31]. Pure biogas termed biomethane can also compete with other bio-oil as well as fossil fuels.

Table 1. Various components of biogas

Constituent Gas	% Volume
Methane (CH_4)	60 – 70
Carbon Dioxide (CO_2)	20 – 30
Hydrogen (H_2)	5 – 10
Nitrogen (N_2)	1 – 2
Water Vapour (H_2O)	0.3
Hydrogen Sulphide (H_2S)	Traces
Constituent gas	% Volume

2.2. Fuel Properties

In the current context of clean and sustainable fuel, biomethane can be upgraded in both quality and quantity to meet the domestic, agricultural, and power sector requirements (**Table 2**). However, more emphasis has been placed on scaling up biogas as a contender for fossil fuels [32], [33]. Biogas is a reliable fuel for IC engines due to its non-reactive characteristics [34]. Therefore, in this paper, we have attempted to investigate the performance and emission characteristics of diesel engines without any engine modification.

Table 2. Fuel properties of biogas

Parameters	Biogas	Diesel
Lower Calorific Value (MJ/kg)	24.52	42.5
Specific gravity @ 15 °C	0.001	0.832
Maximum ignition velocity (m/s)	0.25	-
Cetane number	-	51
Flame temperature, °C	870	2055
Stoichiometric A/F ratio	15.75	15
Self ignition temperature, °C	550	355
Viscosity @ 40 °C	-	3.32

3. Experimental Procedure

The experiment was conducted using a single-cylinder, 4-stroke diesel engine with provision to operate in dual fuel mode. The biogas used in the test has been produced in a floating drum-type digester of 1 cubic meter capacity. The gas production unit is associated with a purification unit to remove the moisture and carbon dioxide present in the raw gas. The experiment was carried out with the modified 4-stroke diesel fuel engine with a single cylinder 5.2 KW with a maximum engine speed of 1500 rpm, water-cooled engine as illustrated in **Figure 1** and specifications listed in **Table 3**. The actual experimental set up has been displayed in **Figure 2**. Provision has been made for mixing biogas and air within a chamber that supplies the mixture to the intake manifold of the engine utilizing a T-joint. During the Suction stroke, air-mixed biogas is inducted into the cylinder. The quantity of the mixture of biogas and air can be controlled by a set of valves under different loading conditions. During the dual fuel operation mode of diesel engines, biogas serves as primary fuel whereas diesel is used as pilot fuel. The primary benefit of utilizing this method is that it allows for the delivery of biogas to the engine following compression when a certain quantity of diesel is used as pilot fuel. Initial conditions for starting the engine included idling and a period during which there was no load on the engine. All of the mechanical supports and arrangements were made available to achieve more accurate measurements. The engine was made to run under this condition for a specific time and then with different loads. Readings were recorded for each loading condition of the engine.

Table 3. Engine specifications

Description	Specification
Make	Kirloskar
Engine	4 stroke Single cylinder
Brake power	5.2 KW
Method of Cooling	Water cooling
Stroke length	110 mm
Bore	87.5 mm
Rated Engine Speed	1500 RPM
Compression ratio	16:1
Type of Ignition	Compression Ignition

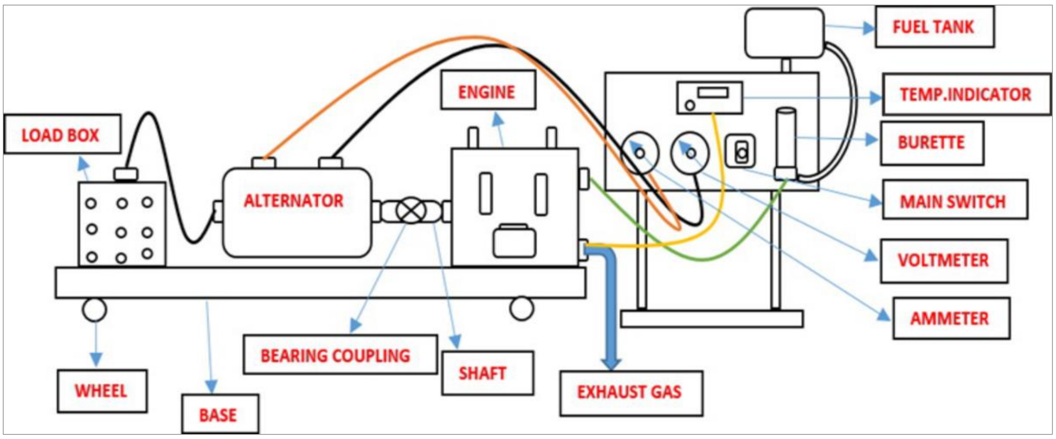

Figure 1. Schematic diagram of the experimental set up

Figure 2. Actual experimental set up

1. Engine 2. Eddy Current Dynamometer 3. Rotameter 4. RPM Indicator 5. Load Indicator 6. Temperature Indicator 7. Pressure Gauge 8. CPU 9. Fuel Tank 10. Burette 11. Air Pipe

The brake power of the engine is defined as the actual power available at the crankshaft that is calculated by Eq. (1).

$$BP = \frac{2\pi N\tau \times 0.75\ kW}{4500} \tag{1}$$

then,

$$\tau = (W_1 - W_2) \times R_e \tag{2}$$

$$R_e = \frac{D + d}{2} \tag{3}$$

where, W_2 = Spring balance reading in kg; Re = Effective radius of brake drum rope in m; D = Diameter of brake drum in m; d= Rope diameter in m; N= Engine speed in rpm.

Brake Specific Fuel Consumption (BFSC) is then calculated using Eq. (4), where X_c is the volume of fuel consumed in T second. Finally, Brake Thermal Efficiency (BTE) is formulated by Eq. (5).

$$BSFC = \frac{Mass\ of\ fuel\ consumption}{brake\ power} = \frac{X_c \times Specific\ gravity\ of\ fuel \times 3600}{BP \times T_{Sec} \times\ 1000} \tag{4}$$

$$\eta_{bth} = \frac{BP \times 3600}{massoffuelconsumed \times calorificvalue} \times 100 \tag{5}$$

4. Results and Discussion

The engine performance and emission investigation are carried out for two different blends of biogas in dual fuel mode and pure diesel with the help of the same engine. The experiments were repeated three times, and the mean value was taken for all performance and emission parameters. The blends of biogas and diesel contain a maximum of 20% biogas. This is due to the reason that 20% mixture shows better performance and beyond that the Brake Thermal Efficiency (BTE) declines. Brake Specific Fuel Consumption (BSFC) also increases beyond 20% due to the lower calorific value of biogas as compared to diesel.

4.1. Brake Power

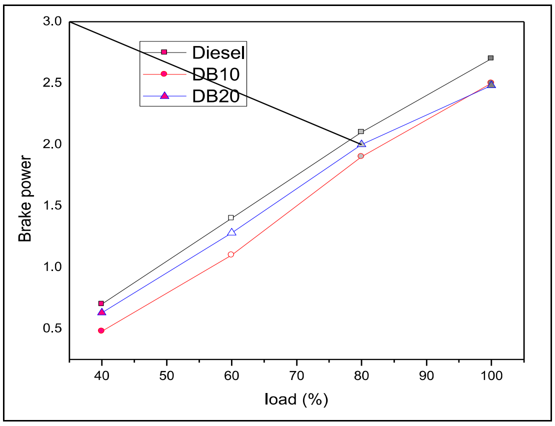

Figure 3. Effect of load on brake power at a constant engine speed of 1500 rpm

Figure 3 shows the effect of engine load on the brake power of an engine. As the engine load increases, brake power for all cases increases. Due to diesel's higher Calorific Value (CV) than biogas, the brake power of an identical engine running on diesel is greater than that of an engine running on biogas. In addition, a delay in ignition increases the temperature in the combustion chamber, leading to increased engine speed. The brake engine power decreases with the increase of biogas mixed with diesel due to lower energy contents in the fuel mixture. It is also observed that conventional diesel fuel compared with diesel and biogas mixture has higher brake engine power. Compared to natural gas or methane, the diluted CO2 in biogas decreases the volumetric heating value of the fuel, which in turn results in a reduction in brake power output and an increase in brake-specific fuel consumption.

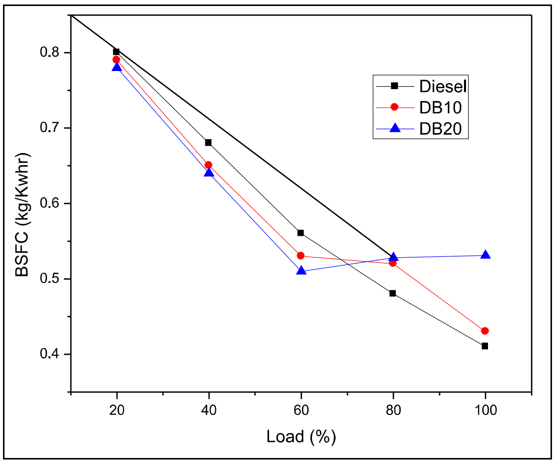

Figure 4. Effect of load on BSFC at a constant engine speed of 1500 rpm

4.2. Brake Specific Fuel Consumption (BSFC)

The effect of engine load variation on BSFC is displayed in **Figure 4**. The amount of fuel consumed, and engine brake power affect the BSFC. In comparison to pure conventional diesel, the BSFC decreases as the proportion of diesel in the combustion of diesel and biogas grows. At high load conditions, the brake thermal efficiency is decreased, leading to decreased BSFC. The variation of BSFC with load is obtained for Diesel 10 DB, Diesel 20 DB and diesel at a constant engine speed of 1500 rpm. With the increase in engine load, BSFC decreases for all fuel blends. However, there is not much decrease in BSFC after a load of 60 %. Since fuel consumption is more than diesel, there will be reducing atomization and vaporization resulting in an increase in BSFC and decrease in BTE.

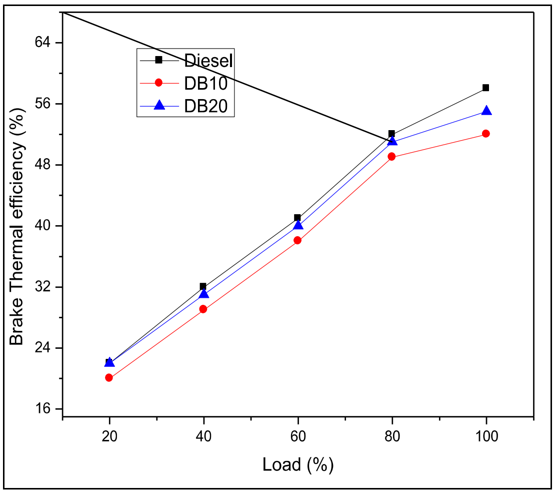

Figure 5. Effect of load on brake thermal efficiency at a constant engine speed of 1500 rpm

4.3. Brake Thermal Efficiency (BTE)

The BTE decreases as the load on the engine increases as seen in **Figure 5**. This may be due to the lower energy content of biogas, which is attributed to higher BSFC and lower

CV. Figure 5 shows the variation of BTE at different loads. At full load conditions, BTE decreases by 12% with 20 DB and 16 % with 10 DB than diesel. This decrease in BTE is due to the poor combustion characteristics and volatility of diesel-biogas fuel in dual fuel mode as compared to diesel. A comparison of BTE and BSFC obtained in the present experimental investigation with the results of other researchers [35],[36], as presented in Table 4. It is observed that the BTE increases in the present experimentation for the engine of same specification considering 50% load on engine. However, there is little increase in BSFC compared to other research work.

Table 4. Comparison of BTE and BSFC

Parameters	Jagadish and Gumtapure [33]	Leykun and Mekonen [35]	Results of present work
BTE (%)	28	25	35
BSFC (Kg/KWhr)	0.5	0.36	0.56

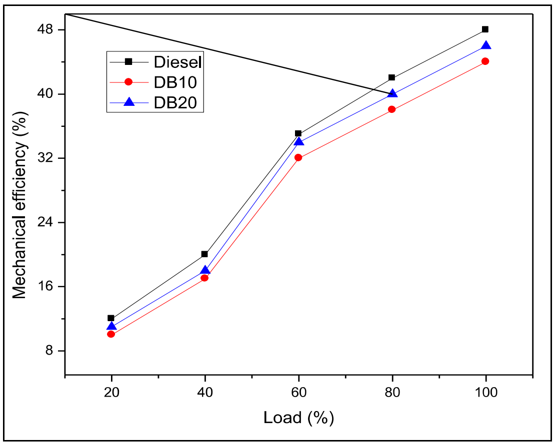

Figure 6. Effect of load on mechanical efficiency at a constant engine speed of 1500 rpm

4.4. Mechanical Efficiency

Mechanical efficiency explains the effective conversion of input heat energy into work output. For an internal combustion engine, it is the ratio between the brake power and indicated power. Figure 6 shows that the mechanical efficiency of both fuels increases with an increase in engine load. The figure also explains that mechanical efficiency increases lower in dual-mode fuel mixtures than in pure diesel. As the load increases, more fuel is consumed, increasing efficiency.

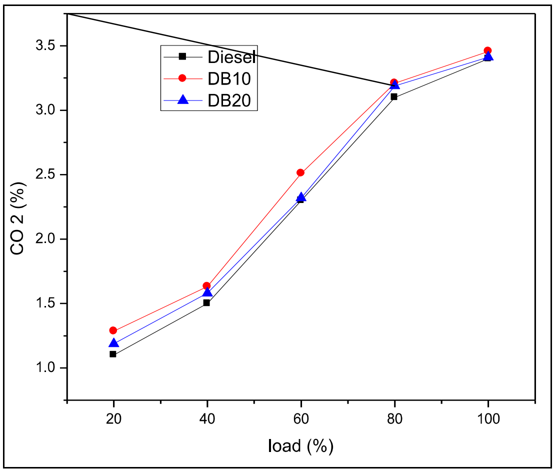

Figure 7. Effect of load on CO_2 at a constant engine speed of 1500 rpm

4.5. Carbon Dioxide (CO_2) Emission

Figure 7 shows the emission of CO_2 which is affected strongly by the loading of the engine. It is explained from the figure that, at 60% loads and 1500 rpm, the emission of CO_2 for both biogas diesel and pure diesel remains the same. When the load increases, the concentration of CO_2 also increases in both fuels. Since pure diesel fuel has higher CV, it produces higher CO_2 after burning even though biogas contains CO_2 as one of the constituent gases. The result also shows the potential contribution of reducing Global Warming Potential (GWP) by converting methane gas into carbon dioxide.

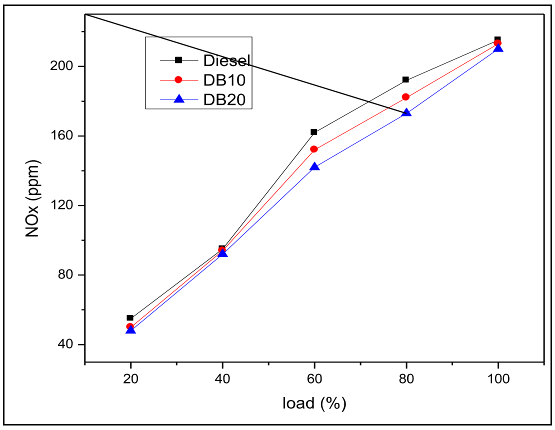

Figure 8. Effect of load on NO_X at a constant engine speed of 1500 rpm

4.6. Oxides of Nitrogen (NO_X) Emission

Figure 8 shows that as the load increases, NO_X concentration in exhaust emissions rises for both diesel and dual-fuel (biogas and diesel) modes. This is due to the higher combustion temperature at higher load and engine speed. In dual-fuel mode, the fuel mixture contains biogas, and the significant amount of CO_2 in biogas absorbs heat during combustion, raising the combustion temperature. As a result, NO_X emissions increase at higher loads. However, NO_X emissions in dual-fuel mode are lower than in diesel-only mode.

5. Conclusion

In this study, the performance and emission test of a single-cylinder 4-stroke diesel engine using biogas–diesel dual mode fuel injection in various proportions under different load and engine speed conditions has been carried out. Performance and emission of the engine have been investigated followed by the conclusion listed below.

- Engine efficiencies increase by using biogas and diesel blends of 20% than lower blends in dual fuel mode.
- Consumption of diesel at various load and rpm conditions is reported as 40% saving
- by using biogas. However, 20% of biogas with diesel shows better results.
- BSFC increases by increase of biogas concentration with diesel as compared to pure diesel.
- There is a reduction in emission levels by using biogas as a fuel for engines. The reason for emission reduction is due to the low calorific value of biogas than diesel. In addition, the excess amount of CO_2 content in biogas also helps in reducing the combustion temperature in the mixture of biogas-diesel.
- NOx is reduced as the concentration of biogas increases in the fuel as compared to pure diesel.
- Brake power is found to decrease with an excess biogas supply in the fuel as compared to pure diesel. This is because of lower calorific value and moisture content in biogas which affect adversely combustion.
- BTE in the present investigation is improved compared to the results of other researchers for engines of the same specifications and operating conditions. At the same time, there is a slight increase in BSFC.

In the present work, the biogas used as fuel for diesel engines could not be purified due to lack of purification facilities. The purification of biogas enhances the methane gas percentage, resulting in improved engine performance and reduced emissions of gases. It can be considered future work for this present investigation. Further research can also be conducted using a preheated mixture of air-biogas in diesel engines to conduct performance analysis.

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Authors' Declaration

Authors' contributions and responsibilities - Manas Ranjan Padhi: Methodology, Performance investigation; Debashree Debadatta Behera: Emission Analysis; Shiv Sankar Das: Review & Editing.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

Abbreviations

BP	: Brake Power (KW)
BSFC	: Brake Specific Fuel Consumption (kg/KWh)
BTE	: Brake Thermal Efficiency (Dimensionless)
CV	: Calorific Value (kJ/kg)
DB	: Diesel and Biogas dual fuel mode (Dimensionless)

References

[1] M. Ozcanli, "Castor-oil methyl ester/butanol/diesel fuel blend as an alternative for compression ignition engines," *Journal of Biotechnology*, vol. 208, p. S32, Aug. 2015, doi: 10.1016/j.jbiotec.2015.06.089.

[2] P. A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability

issues and climate change mitigation," *Cogent Engineering*, vol. 3, no. 1, p. 1167990, Dec. 2016, doi: 10.1080/23311916.2016.1167990.

[3] W. Purwanto, J. C. T. Su, M. L. Rochman, B. Waluyo, K. Krismadinata, and A. Arif, "Study on the Addition of A Swirling Vane to Spark Ignition Engines Fueled by Gasoline and Gasoline-Ethanol," *Automotive Experiences*, vol. 6, no. 1, pp. 162–172, 2023, doi: 10.31603/ae.7981.

[4] B. Waluyo and B. C. Purnomo, "Exhaust Gas Emissions of Homogeneous Gasoline-Methanol-(Ethanol) Blends," *Automotive Experiences*, vol. 5, no. 2, pp. 173–181, Apr. 2022, doi: 10.31603/ae.6599.

[5] T. Kivevele, T. Raja, V. Pirouzfar, B. Waluyo, and M. Setiyo, "LPG-Fueled Vehicles: An Overview of Technology and Market Trend," *Automotive Experiences*, vol. 3, no. 1, pp. 6–19, 2020, doi: 10.31603/ae.v3i1.3334.

[6] D. R. Adhikari, K. Techato, and R. Jariyaboon, "A systematic literature review on renewable energy technologies for energy sustainability in Nepal: Key challenges and opportunities," *International Journal of Renewable Energy Development*, vol. 13, no. 2, pp. 206–222, Mar. 2024, doi: 10.61435/ijred.2024.60032.

[7] S. Susilawati, A. Nugraha, A. S. S. Buchori, S. Rahayu, F. Fathurohman, and O. Yudiyanto, "Design and implementation of automatic fish feeder (AFF) using microcontroller powered by solar cell: A Contribution to the fish farmers," *Mechanical Engineering for Society and Industry*, vol. 3, no. 1, pp. 47–53, Mar. 2023, doi: 10.31603/mesi.8276.

[8] R. A. Rahman, S. Sulistyo, M. S. K. T. S. Utomo, D. Ragil, and B. M. Suyitno, "Experimental evaluation on the power characteristic of direct-photovoltaic charging for thermal storage equipment," *Mechanical Engineering for Society and Industry*, vol. 4, no. 1, pp. 115–122, Jul. 2024, doi: 10.31603/mesi.11493.

[9] F. I. Abam *et al.*, "Thermodynamic modelling of a novel solar-ORC with bottoming ammonia-water absorption cycle (SORCAS) powered by a vapour compression refrigeration condensate for combined cooling and power," *Mechanical Engineering for Society and Industry*, 2023, doi: 10.31603/mesi.10365.

[10] Y. D. Herlambang *et al.*, "Study on Solar Powered Electric Vehicle with Thermal Management Systems on the Electrical Device Performance," *Automotive Experiences*, vol. 7, no. 1, pp. 18–27, 2024, doi: 10.31603/ae.10506.

[11] E. Achdi, B. F. T. Kiono, S. H. Winoto, and M. Facta, "Improving cross-axis wind turbine performance: A Lab-scale investigation of rotor size and blades number," *Mechanical Engineering for Society and Industry*, vol. 4, no. 1, pp. 82–91, Jul. 2024, doi: 10.31603/mesi.10837.

[12] A. K. Das, M. R. Padhi, D. Hansdah, and A. K. Panda, "Optimization of Engine Parameters and Ethanol Fuel Additive of a Diesel Engine Fuelled with Waste Plastic Oil Blended Diesel," *Process Integration and Optimization for Sustainability*, vol. 4, no. 4, pp. 465–479, Dec. 2020, doi: 10.1007/s41660-020-00134-7.

[13] S. Babel, J. Sae-Tang, and A. Pecharaply, "Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application," *International Journal of Environmental Science & Technology*, vol. 6, no. 1, pp. 131–140, Dec. 2009, doi: 10.1007/BF03326067.

[14] D. I. Setyanansyach, M. Setiyo, and T. Raja, "Review and Bibliometric Analysis of Biogas Power Plants in Indonesia," *Advance Sustainable Science, Engineering and Technology (ASSET)*, vol. 5, no. 3, p. 2303015, 2023, doi: 10.26877/asset.v5i3.16806.

[15] L. M. Olalekan, O. Olatunde, F. I. Oluwafemi, and A. A. Olamide, "Mathematical modeling and cost comparison for electricity generation from petrol and liquified petroleum gas (LPG)," *Mechanical Engineering for Society and Industry*, vol. 2, no. 2, pp. 57–63, 2022, doi: 10.31603/mesi.6697.

[16] L. Matsakas, Q. Gao, S. Jansson, U. Rova, and P. Christakopoulos, "Green conversion of municipal solid wastes into fuels and chemicals," *Electronic Journal of Biotechnology*, vol. 26, pp. 69–83, Mar. 2017, doi: 10.1016/j.ejbt.2017.01.004.

[17] K. Paritosh *et al.*, "Organic Fraction of Municipal Solid Waste: Overview of Treatment Methodologies to Enhance Anaerobic Biodegradability," *Frontiers in Energy Research*, vol. 6, Aug. 2018, doi: 10.3389/fenrg.2018.00075.

[18] S. Mujiarto, B. Sudarmanta, H. Fansuri, and A. R. Saleh, "Comparative Study of Municipal Solid

Waste Fuel and Refuse Derived Fuel in the Gasification Process Using Multi Stage Downdraft Gasifier," *Automotive Experiences*, vol. 4, no. 2, pp. 97–103, 2021, doi: 10.31603/ae.4625.

[19] F. B. Elehinafe, O. B. Okedere, Q. E. Ebong-Bassey, and J. A. Sonibare, "Data on Emission Factors of Gaseous Emissions from Combustion of Woody Biomasses as Potential Fuels for Firing Thermal Power Plants in Nigeria," *Mechanical Engineering for Society and Industry*, vol. 1, no. 2, pp. 75–82, 2021, doi: 10.31603/mesi.5548.

[20] A. Kasinath *et al.*, "Biomass in biogas production: Pretreatment and codigestion," *Renewable and Sustainable Energy Reviews*, vol. 150, p. 111509, Oct. 2021, doi: 10.1016/j.rser.2021.111509.

[21] N. H. S. Ray, M.K. Mohanty, and R.C. Mohanty, "Biogas as Alternate Fuel in Diesel Engines: A Literature Review," *IOSR Journal of Mechanical and Civil Engineering*, vol. 9, no. 1, pp. 23–28, 2013.

[22] A. K. Das and A. K. Panda, "Effective Utilisation of Kitchen Waste to Biogas by Anaerobic Co-digestion," in *Recent Developments in Waste Management*, 2020, pp. 1–10.

[23] B. J. Bora and U. K. Saha, "Comparative assessment of a biogas run dual fuel diesel engine with rice bran oil methyl ester, pongamia oil methyl ester and palm oil methyl ester as pilot fuels," *Renewable Energy*, vol. 81, pp. 490–498, Sep. 2015, doi: 10.1016/j.renene.2015.03.019.

[24] D. Barik and S. Murugan, "Effects of diethyl ether (DEE) injection on combustion performance and emission characteristics of Karanja methyl ester (KME)–biogas fueled dual fuel diesel engine," *Fuel*, vol. 164, pp. 286–296, Jan. 2016, doi: 10.1016/j.fuel.2015.09.094.

[25] R. Jyothilakshmi, "Biogas Technology in Current Indian Scenario as Applicable to its Production, Maintenance and Utilization of the Slurry as Organic Manure after its Enrichment," *Research & Reviews: Journal of Engineering and Technology*, vol. 4, no. 3, 2015.

[26] A. V. Prabhu, A. Avinash, K. Brindhadevi, and A. Pugazhendhi, "Performance and emission evaluation of dual fuel CI engine using preheated biogas-air mixture," *Science of The Total Environment*, vol. 754, p. 142389, Feb. 2021, doi: 10.1016/j.scitotenv.2020.142389.

[27] H. Ambarita, "Performance and emission characteristics of a small diesel engine run in dual-fuel (diesel-biogas) mode," *Case Studies in Thermal Engineering*, vol. 10, no. February 2017, pp. 179–191, 2017, doi: 10.1016/j.csite.2017.06.003.

[28] R. Bouguessa, L. Tarabet, K. Loubar, T. Belmrabet, and M. Tazerout, "Experimental investigation on biogas enrichment with hydrogen for improving the combustion in diesel engine operating under dual fuel mode," *International Journal of Hydrogen Energy*, vol. 45, no. 15, pp. 9052–9063, Mar. 2020, doi: 10.1016/j.ijhydene.2020.01.003.

[29] A. V. Prabhu, A. Alagumalai, and A. Jodat, "Artificial neural networks to predict the performance and emission parameters of a compression ignition engine fuelled with diesel and preheated biogas–air mixture," *Journal of Thermal Analysis and Calorimetry*, vol. 145, no. 4, pp. 1935–1948, Aug. 2021, doi: 10.1007/s10973-021-10683-9.

[30] M. A. O. Mydin, N. F. Nik Abllah, N. Md Sani, N. Ghazali, and N. F. Zahari, "Generating Renewable Electricity from Food Waste," *E3S Web of Conferences*, vol. 3, p. 01012, Aug. 2014, doi: 10.1051/e3sconf/20140301012.

[31] T. M. Tien, P. X. Mai, N. D. Hung, and H. T. Cong, "A study on power generation system using biogas generated from the waste of pig farm," in *International Forum on Strategic Technology 2010*, Oct. 2010, pp. 203–207, doi: 10.1109/IFOST.2010.5668012.

[32] H. S. Sorathia and H. J. Yadav, "Energy analyses to a CI-engine using diesel and bio-gas dual fuel- A review study," *International Journal of Advanced Engineering Research*, vol. 1, no. 11, pp. 212–217, 2012.

[33] N. N. Mustafi, R. R. Raine, and P. K. Bansal, "The Use of Biogas in Internal Combustion Engines: A Review," in *ASME 2006 Internal Combustion Engine Division Spring Technical Conference (ICES2006)*, Jan. 2006, pp. 225–234, doi: 10.1115/ICES2006-1306.

[34] A. K. Das, S. Nandi, and A. K. Behera, "Experimental Study of Different Parameters Affecting Biogas Production from Kitchen Wastes in Floating Drum Digester and its Optimization," *International Journal of Latest Technology in Engineering, Management & Applied Science*, vol. 6, no. 7S, pp. 98–103, 2017.

[35] C. Jagadish and V. Gumtapure, "Experimental investigation of methane-enriched biogas in a

single cylinder diesel engine by the dual fuel mode," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 1, pp. 1898–1911, Mar. 2022, doi: 10.1080/15567036.2019.1647314.

[36] M. G. Leykun and M. W. Mekonen, "Investigation of the Performance and Emission Characteristics of Diesel Engine Fueled with Biogas-Diesel Dual Fuel," *Fuels*, vol. 3, no. 1, pp. 15–30, Jan. 2022, doi: 10.3390/fuels3010002.