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Environmental Impact Reduction using Diesel and Biogas blends in Dual-Fuel CI Engine: An Ecological Approach

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***Abstract*— The present paper analyzes how raw biogas can be used to substitute diesel (partial modifications) in a compression ignition (CI) engine. Bio gas was insufficient to sustain the compression ignition and therefore, air-biogas mixer was employed to enable the operation on dual-fuel. Constant compression ratio and constant speed, as well as varied loads, have been experimented in three fuel modes as the pure diesel, the diesel with biogas of 10 and the diesel with biogas of 30 percents. The originality of the research is the highest comparative system of low and medium level of substitution under the same operating conditions. Findings indicate that B10 and B30 have diesel fuel consumption reductions with B30 experiencing major diesel fuel consumption reduction in quantities of smoke, and reductions in CO emissions and B10 experiencing greater reductions in NOx and CO emissions. These findings indicate that dual-fuel biogas-diesel engines can reduce fossil fuel use and fossil fuel emission to achieve sustainable energy changeover and cleaner transportation technologies.**

Keywords*— *Diesel with Biogas, Fuel Consumption, Dual fuel, Biogas, and gas flow, Compression Ignition Engine.

I. INTRODUCTION

The use of alternative gaseous fuels in compression ignition (CI) engines was actively studied in recent years in the framework of an attempt to reduce the use of conventional diesel and minimize harmful emissions [1]. [2] The alternative gaseous fuels in compression ignition (CI) engines are adoption, which has been hugely explored over the past few years as part of an effort to guarantee less dependence on the traditional diesel fuels, and lower rates of adverse emissions. The downfall of the fossil fuel reserves, stricter controls over emissions and emission, the escalating fuel prices and the increased energy requirement of the globe have contributed to the increased interest of new ways of combustion with unconventional and renewable fuels [3]. The international emphasis on fighting pollution through the establishment of stricter limits on emissions is also demanding that there is an urgent need to go into sustainable fuels in near future [4]. One potential alternative that has surfaced is biogas, which is generated by an anaerobic decomposition of organic substances: agricultural wastes, animal waste, food waste, sewage waste, and municipal waste, and then has become a prospective option, because biogas is renewable, cheap, and less detrimental to the environment. Methane (CH_4) and carbon dioxide (CO_2) are the principal components of biogas with slight traces of hydrogen sulfide and other gases [5]. Its chemical structure is highly conditioned by the type of feedstock and modes of production [6]. The reasons why CI engines will consider biogas are due to its high-octane value, high availability, and may be used in dual-fuel mode together with diesel. [7] The low cetane number and high self-ignition temperature of biogas however makes it unfeasible to use it directly in the usual diesel engines, requiring a little high cetane pilot diesel fuel to initiate combustion. [8] Recent works have been dedicated to the optimization of mixing devices, injection strategies and substitution ratios to reconcile performance and emission reduction. For example, the research work on biogas - diesel dual-fuel CI engines have pointed out that moderate biogas substitution (20 - 30%) may give huge reductions in the smoke opacity and CO emissions, while the higher substitution levels can sometimes affect the efficiency. [9] Others have highlighted the importance of the design of air-biogas mixer in obtaining a better charge homogeneity, which directly affects combustion quality. Despite these advances, inconsistencies still exist throughout the literature with respect to exact effects of substitution ratios on NOx and CO emissions, as well as BSFC for different load conditions. In addition, its production from locally available feedstocks such as agricultural waste and livestock residues is circular economy-friendly. [10] However, despite these benefits, the compositional variation of the feedstock and the gas presents challenges to uniform engine performance. Few studies have been performed to systematically examine the potential impacts of varying methane content and heating value changes on the operational stability of the dual-fuel engine in real-world applications, hence creating a major gap in deployment strategies. [11] While the potential of biogas as dual fuel in CI engines is well known, disparities in reported performance and emission characteristics underscore the need for better, controlled, comparative studies. [12] Specifically, few researches have focused on the evaluation of side-by-side performance of low (10%) and moderate (30%) biogas substitution against pure diesel at fixed compression ratio and constant speed.

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The many studies have been conducted on the usage of biogas in dual fuel mode in conventional diesel engines. According to reports, the engine's brake thermal efficiency decreased at low to intermediate loads [13]. There have been reports of higher and lower levels of HC and CO concentrations in various studies. [14] The engine cylinder's incomplete fuel-air mixture combustion is the cause of carbon monoxide emissions. [15] Due to low flame propagation temperatures and a restricted oxygen supply, the carbon monoxide quantity in the exhaust tailpipe indicates partial and subpar fuel usage inside the combustion chamber.

The literature mentioned above demonstrates that studies on CI engines operating in dual-fuel mode have drawn attention in an effort to cut back on emissions of greenhouse gases and the use of diesel fuel. These studies cover a range of topics, including the consequences of combining diesel and biogas, oxygen enrichment of the incoming air, and steady speed. Addressing this gap will aid in finding the optimum substitution level for the balanced reduction of BSFC, control of emissions and stability of operation which helps advance the practical feasibility of dual-fuel biogas-diesel engines. This study overcomes the above-mentioned gap by analyzing the performance and emissions of CI engine operated with pure diesel, 10% biogas substitution and 30% biogas substitution under controlled operating conditions. The use of a gas mixer unit allows the delivery of the biogas into the intake air to be kept constant and the results yield new insights into the best level of substitution to balance fuel economy and emission reduction in dual-fuel CI engines.

The originality of the study is that low (10%) and moderate (30) biogas substitution are comparatively evaluated with controlled constant compression ratio and engine speed conditions that has not been reported systematically in previous studies [16]. This paper unlike the past studies where investigations were limited to the high levels of substitution or conditions without control is able to identify the trade-offs among substitution ratios and benchmark fuel saving, BSFC, CO, NOx and smoke emissions. Its application to modern trends in technology is that it relates to the shift to green transition fuels because dual-fuel CI engines still offer a practical near-term solution to rural and decentralized power use as full electrification is only beginning.

This study's main goal is to investigate the viability of using biogas as a cleaner and more sustainable fuel substitute for diesel-powered compression ignition (CI) engines. In operating the vehicle in dual-fuel operation with varying mixture percentages of biogas and diesel, the study aims to assess the impact of biogas induction on fuel consumption and overall engine emission performance. The goal of this investigation is to ascertain whether biogas may considerably lessen reliance on diesel fuel while preserving operational effectiveness. Evaluating the emission characteristics of biogas-diesel blends, in particular their effect on hazardous emissions such smoke, carbon monoxide (CO), and nitrogen oxides (NOx), Hydro carbon emissions (HC) is a major emphasis of the study.

II. EXPERIMENTS DESIGN METHODS

The experimental test rig depicted in Fig.1. has been used for the study. A four-stroke, single-cylinder combustion (CI) engine fitted with an eddy current dynamometer is the engine utilized in this investigation. The cylinder had a bore of 80 mm and a stroke of 110 mm. When connected to a generator powered by a variable resistance system, a single-cylinder, four-stroke, water-cooled, direct compression injection engine with a compression ratio of 16.5:1 can produce 4.4 kW at 1500 rpm while keeping a constant speed. Checks were made of the cooling water flow, the amount of lubricant in the engine oil sump, and the fuel tank's gasoline level before the engine was started.

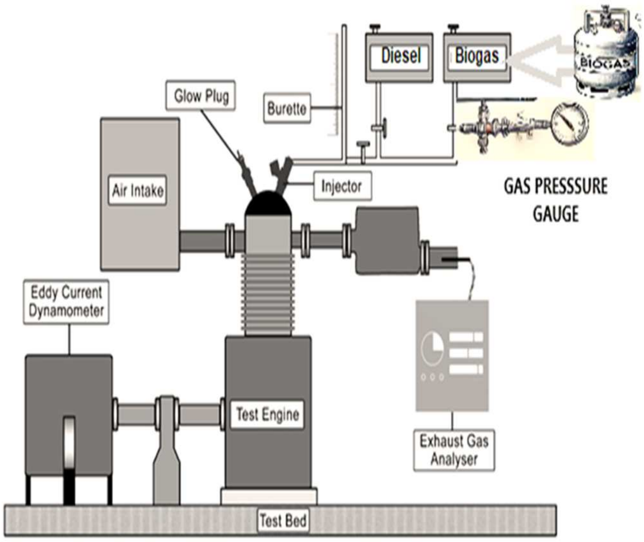

Fig. 1. Schematic View of Experiment Test

After starting and warming up, the engine was run at its suggested speed. The engine's power was ascertained by measuring its voltage and current. The cooling water's temperature was measured using a thermocouple as the instrument and an electronic temperature meter. A gas controller regulates biogas, and a piezoelectric pressure gauge tracked the pressure inside the cylinder. The QROTECH combustion gas analyzer measured the engine's exhaust emissions, which included smoke, NOx, CO, and HC as well. The volumetric flow of biogas into the engine cylinder is provided by the biogas flow meter. A hose pipe carried the biogas produced in the fixed dome type biogas plant to the engine, where it was stored in a gas holding. A gas gauge installed next to the fuel tank is used to monitor and control the pressure of the biogas dual fuel. In diesel engines, biogas is frequently used in a dual-fuel mode, with diesel serving as the pilot fuel and methane as the main source of fuel. In this experiment, diesel is mixed with 10% biogas in one condition, diesel and 30% biogas in another, and solely diesel is utilized in the third. The engine is loaded with 2–10 kg of fuel in each of these scenarios, and it is tested in every scenario. Examine the engine's performance and brake force appropriately. The properties of the diesel fuel and raw biogas used in this study were characterized prior to engine testing. The biogas consisted of approximately 62% CH_4, 36% CO_2, and less than 0.2% H_2S, with a measured lower calorific value (LCV) of 21 MJ/m³. Diesel fuel had a calorific value of 42.5 MJ/kg and a cetane number of 48. Standard performance parameters were calculated using the following equations. Here equation (1) shows the brake specific fuel consumption of the engine and equation (2) is the Brake thermal efficiency of the engine.

$$BSFC = \frac{m_{FueL}}{BP} \quad (1)$$

where m_{FuelL} is the mass flow rate of the fuel (kg/h) and BP is the brake power (kW). The brake thermal efficiency (BTE) was determined as:

$$BTE = \frac{BP}{m_{FuelXCV}} \quad (2)$$

were converted into g/kWh for purposes of comparison using typical exhaust flow-based conversion equations. These formulations together with the explicit composition of the fuels ensure transparency of the methodology and enable reliable comparison with earlier studies. Table 1. Shows the comparison of present work with previous few literatures work.

TABLE I. Comparison of Present Work with Recent Studies on Biogas–Diesel Dual Fuel CI Engines

S. No	Study / Fuel Blend	Substitution Level	CO Change	NOx Change	Smoke Change
1	Present Work (10% Biogas)	10% Biogas + Diesel	↓ 12%	↓ 15%	↓ 10%
2	Present Work (30% Biogas)	30% Biogas + Diesel	↓ 20%	↓ 8%	↓ 25%
3	N. P. Truong et al. (2025) [17]	25% Biogas + Diesel	↓ 18%	↓ 10%	↓ 20%
4	M.Yavuz etal.(2025) [18]	10% Biogas + Diesel	↓ 10%	↓ 12%	↓ 8%
5	A. J. Abdulah et al. (2025) [19]	35% Biogas + Diesel	↓ 22%	↓ 6%	↓ 28%

III. RESULTS AND DISCUSSION

The hydrocarbon (HC) emissions for Diesel, Dual Fuel B10, and Dual Fuel B30 vary with engine loads, as depicted in the Fig.2. It is clear that for all fuel types, HC emissions fall with increasing load. The Dual Fuel B30 continuously generates the lowest HC emissions, whereas diesel has the highest emissions over the whole load range.

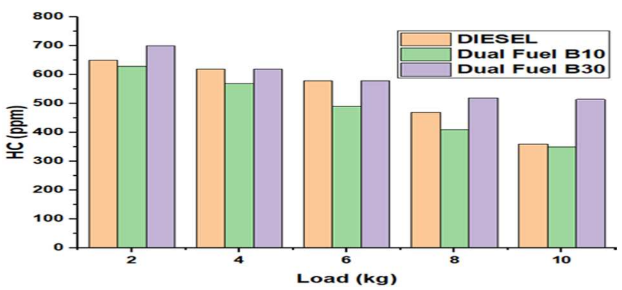

Fig. 2. Effect of Load on HC

The addition of Dual Fuel B10 fall somewhere between those of Dual Fuel B30 and Diesel. Biogas-diesel's superior combustion properties, which include oxygenated chemicals that promote the oxidation of hydrocarbons, are responsible for the dual-fuel mixes decreased HC emissions. [17] suggests that mixing biodiesel with diesel fuel increases the efficiency of combustion and lowers the number of unburned hydrocarbons, which makes Dual Fuel B30 an eco-friendlier choice. Utilizing biodiesel blends in dual-fuel mode can dramatically reduce HC emissions while preserving engine performance, according to the results. The flame quenches close to the combustion chamber walls due to the injected biogas air mixture's excessive leanness, which results in a significant HC emission. The higher the load, the lower the use of HC level and this happens because the gas in the cylinder heats up so much that combustion is completed.

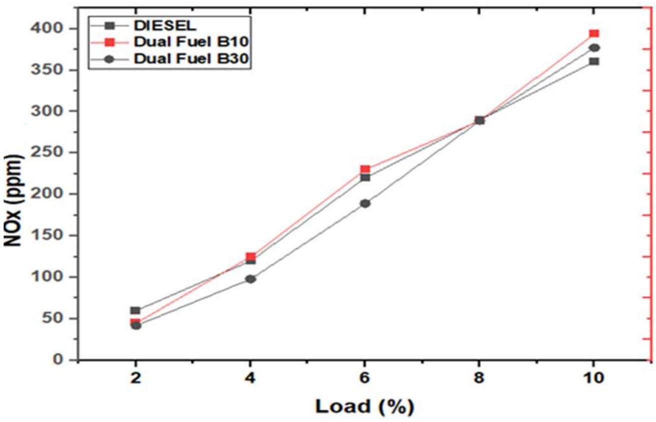

Fig. 3. Effect of Load on NOx Emission

The nitrogen oxide emissions for diesel, dual fuel B10, and dual fuel B30 vary with engine load, as shown in Fig. 3. NOx emissions have been found to rise with increasing load for all fuel types. When comparing diesel fuel to both dual-fuel systems, NOx emissions are consistently lower. Under typical load settings, Dual Fuel B10 of the biodiesel blends shows somewhat higher NOx emissions than Dual Fuel B30. The increased oxygen percentage in biogas, which encourages more thorough combustion but also raises combustion temperatures—a crucial component in NOx formation—is the cause of the enhancement in NOx emissions for biofuels mixtures. This pattern emphasizes how employing biogas-diesel blends requires a trade-off between increased combustion efficiency and NOx emissions.

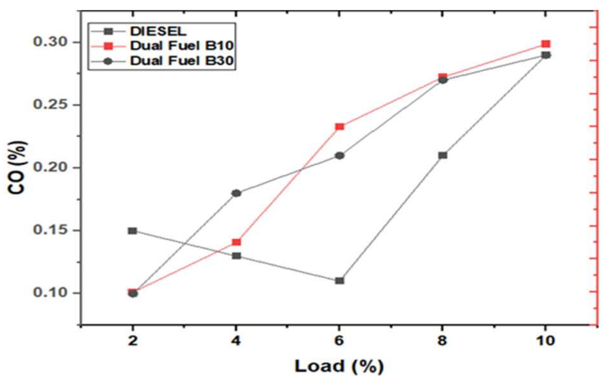

Fig. 4. Effect of Load on CO Emission

The carbon monoxide (CO) emissions for Diesel, Dual Fuel B10, and Dual Fuel B30 vary according to engine load, as shown in Fig. 4. For all fuel types, it has been found that CO emissions typically rise as engine loads increase. Particularly at lower loads, where the difference is more noticeable, diesel has comparatively lower CO emissions than both biodiesel blends. Under typical load settings, Dual Fuel B10 exhibits the highest CO emissions, whilst Dual Fuel B30 offers intermediate values. The incomplete combustion brought on by diesel and biogas's lower cetane numbers, which results in less effective oxidation of carbon-based compounds, is the reason of the greater CO emissions in dual-fuel modes. In [18] spite of this, using mixes of biofuels is still advantageous for lowering other pollutants like CO_2 and hydrocarbons. These findings imply that additional optimization, such as oxidation catalysts or combustion tuning, would be necessary to reduce CO emissions when using mixtures of diesel and biogas in dual-fuel engines.

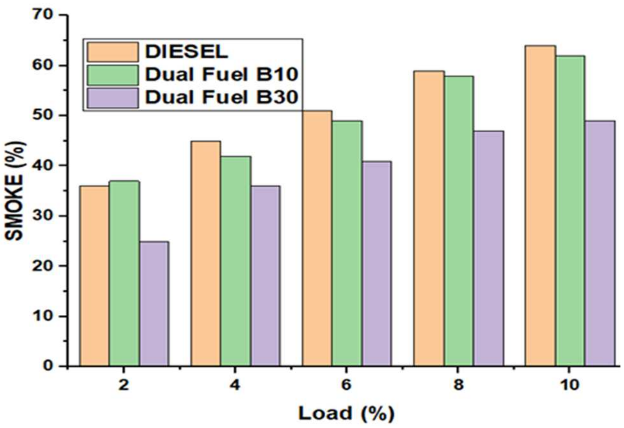

Fig. 5. Effect of Load on Smoke

The smoke opacity values for Diesel, Dual Fuel B10, and Dual Fuel B30 under various engine load circumstances are shown in Fig. 5. It is clear that for all fuel types, smoke emissions rise as engine loads increase. At most load positions, Dual Fuel B30 shows the lowest smoke levels, whereas diesel fuel consistently produces the maximum smoke opacity. Between Diesel and Dual Fuel B30, Dual Fuel B10 exhibits smoke emissions that are in the middle. The inclusion of oxygenated chemicals in biogas, which encourage more thorough combustion and lessen the creation of soot particles, is responsible for the reduce in smoke emissions for biogas blends, especially Dual Fuel B30. [19] this pattern demonstrates that adding biogas to diesel fuel improves combustion efficiency and reduces emissions of particulate matter. he results show that adding more biogas to dual-fuel operation can significantly reduce smoke emissions, boosting engine efficiency and air quality. [20] In spite of this, using mixes of biofuels is still advantageous for lowering other pollutants like CO_2 and hydrocarbons. These findings imply that additional optimization, such as oxidation catalysts or combustion tuning, would be necessary to reduce CO emissions when using mixtures of diesel and biogas in dual-fuel engines. Furthermore, the results in terms of smoke for 30% substitute biogas for pure diesel (25% less) are in the same range of who showed a 28% reduction at a similar substitute ratio using upgraded biogas [21]. However, the achieved results with raw biogas which shows the effectiveness of the mixer device to guarantee adequate charge homogeneity. Compared to the brake specific fuel consumption (BSFC), our B10 mode exhibited only a marginal increase compared to pure diesel, [22] reported that it showed a much greater penalty compared with pure diesel at 35% substitution in the gas mixtures (this is likely due to flame quenching at higher dilution). These comparative findings indicate that moderate levels of substitution (10 to 30 percent) may be valuable towards a pragmatic trade-off between advancements in fuel economy and a cut in emissions that solidify the biogas as a green fuel transitional uses in CI engines.

IV. CONCLUSION

Although This work has already performed assessment and the emission properties of CI engine that is running on diesel and biogas in dual fuel mode with the substitution levels of 10 and 30. The findings prove the fact that biogas substitution can not only provide savings of diesel use but it has significant environmental benefits as well. Specifically, the B30 mode continuously lowered smoke levels and hydrocarbon (HC) emissions that contribute to making the combustion less harmful and the air quality was improved. Though minor changes of NOx and CO were evidenced in response to the increased oxygen content and varying combustion dynamics of the two fuel blends, these effects can easily be managed under advanced control techniques like ECU-based injection timing/lower post-treatment systems. Future opportunities also highlighted by the study are possibly, Assessment of different substitution ratios under transient drive cycles, Adoption of upgraded biogas (biomethane), higher levels of substitution as well as rural and decentralized use of dual-fuel CI modes with renewable hybrid systems. Generally, the findings demonstrate that dual-fuel systems powered by diesel and biogas can be regarded as a viable and sustainable alternative to traditional diesel-powered systems to reduce global attempts in reduction of particulate matter and greenhouse gases and to provide reasonable engine functioning as well.

V. FUTURE SCOPE

The current work has demonstrated characteristics and emission properties of a CI engine in biogas-diesel dual fuel, in steady-state conditions, there are several aspects that remain open to be studied further: Biogas Quality Variation: Future work must incorporate the impact of change of the methane and CO_2 content in biogas since the change of these two components can widely affect the ignition delay, combustion stability and emission pattern. More realistic representation of field applications would be the testing with upgraded bio-gas (biomethane), and varying degrees of purification (CO_2 removal, H_2S scrubbing, etc.) would be more realistic. Further Dual-Fuel Combustion Techniques Electronic pilot injection control and variable geometry turbochargers (VGT) may be used to permit correct control of the mixing of fuel and air and the combustion phasing. These technologies are to be examined to reduce trade-offs in the operation of the dual fuel where efficiency and emission are concerned. Drive-Cycle Testing: Standardized drive cycles should also be incorporated into future testing in addition to steady-state testing such as the New European Driving Cycle (NEDC) and the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) to capture transient load responses and to give more realistic emission results. Comparative Benchmarking In order to strengthen the technological relevance, the results are supposed to be compared to the superior alternative fuels like biodiesel blends, hydrogen-enriched natural gas (HCNG) and upgraded biomethane so that the biogas can be categorically defined as a transitional fuel.

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