IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

# Optimized Biogas Mixtures From Animal, Food, And Sugarcane Bagasse Wastes: Methane Enrichment, Engine Performance, And Cost Analysis

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**Abstract**

This work investigates biogas production from combined feedstocks of animal waste, food waste, and sugarcane bagasse at different mixing ratios, with performance compared to conventional diesel in generator operations. The study shows that the composition of raw materials significantly influences gas yield and quality. The best-performing blend (M-3), with a carbon-to-nitrogen ratio of about 25–28:1, provided stable digestion and the highest methane content, reaching 64.1% and a calorific value of 24,100 kJ/m³, which was roughly 26% higher than M-1. Gas chromatography analysis confirmed that co-digestion improved methane concentration, and subsequent purification raised methane levels to ~95%, with a density of 0.66 kg/m³ and an octane rating near 120, making it suitable for engine applications. Performance evaluation indicated that diesel consistently delivered superior torque, voltage stability, and brake thermal efficiency (BTE), achieving about 35.5% compared to ~24% for biogas. Depending on load, biogas exhibited 20–65% lower efficiency due to $CO_2$ dilution and slower flame speed, though its performance improved at higher loads. Cost analysis, however, revealed a major economic advantage: biogas operated at 0.78 rupees/min, compared with 1.34 rupees/min for diesel, making it about 41.8% more affordable. Thus, optimized mixtures, especially M-3, demonstrate strong potential as a renewable, economical, and sustainable fuel for decentralized power systems.

**Keywords:** Biogas; Diesel; Methane; Calorific value; Generator performance.

## 1. Introduction

The global demand for energy continues to rise rapidly, driven by population growth, industrialization, and urbanization. Fossil fuels such as diesel and petrol remain the dominant sources for decentralized electricity generation, especially in small power generators widely used in rural and semi-urban areas. However, this reliance comes at a heavy cost: increasing greenhouse gas (GHG) emissions, rising fuel prices, and accelerating climate change [1]. These challenges emphasize the importance of exploring renewable, sustainable, and cost-effective substitutes that can simultaneously address energy and environmental concerns [2-3].

Biogas, produced through anaerobic digestion (AD) of organic matter, has emerged as one of the most promising alternatives. It is typically composed of methane (50–70%), carbon dioxide (25–50%), and small fractions of hydrogen sulfide, ammonia, and other trace gases. Methane is the key determinant of biogas quality, influencing both calorific value and combustion performance. When upgraded to biomethane (~95% $CH_4$), its calorific value and combustion characteristics approach those of compressed natural gas (CNG), making it suitable for multiple applications including power generation, transport, and heating. Beyond its role as an energy carrier, biogas production also contributes to waste management and environmental protection by transforming agricultural residues, food waste, and animal manure into clean energy while reducing landfill burdens and methane emissions from uncontrolled decomposition [4-8].

The efficiency and stability of anaerobic digestion depend largely on the type and composition of feedstocks. Single-substrate digestion often leads to nutrient imbalance and process limitations. For instance, animal manure provides nitrogen and microbial inoculum but risks ammonia inhibition at higher concentrations. Food waste, while highly biodegradable and energy-rich, can cause rapid acidification that disrupts methanogenesis [9]. Sugarcane bagasse, a lignocellulosic by-product of the sugar industry, is carbon-rich but poorly biodegradable due to its fibrous cellulose–lignin structure. Co-digestion of these feedstocks offers a pathway to balance the carbon-to-nitrogen (C: N) ratio, stabilize pH, and improve methane yields. Studies suggest that the optimal C:N ratio for anaerobic digestion lies between 25:1 and 30:1, a range that supports microbial growth and efficient methane production [10-13].

While numerous studies have examined biogas production from individual feedstocks or binary mixtures, there is limited systematic research on the tri-mixture of animal waste, food waste, and sugarcane bagasse. Most existing works emphasize methane yield or calorific value at the laboratory scale but rarely connect these results to practical engine performance metrics such as brake thermal efficiency (BTE), torque, voltage stability, and combustion behaviour. Furthermore, few studies integrate biochemical characterization, engine testing, and cost analysis into a single comprehensive framework. This lack of holistic evaluation restricts the practical deployment of optimized biogas in small-scale generators as a reliable substitute for diesel.

This study introduces a systematic evaluation of optimized tri-mixtures of animal waste, food waste, and sugarcane bagasse for biogas production. The novelty lies in integrating three dimensions—methane enrichment and gas quality improvement, generator engine performance testing, and comparative cost analysis. Unlike earlier studies that focused on either production or utilization, this research bridges the gap between biochemical optimization and real-world application, providing insights into how feedstock ratios and upgrading techniques influence both technical and economic viability.

**Objectives**

The primary objectives of this research are:

1. To optimize feedstock mixtures of animal waste, food waste, and sugarcane bagasse to achieve balanced C:N ratios (25–28:1) for enhanced methane yield and stability.

2. To characterize raw and upgraded biogas in terms of methane concentration, calorific value, density, and octane number using advanced analytical methods.

3. To evaluate the performance of biogas in a generator engine, benchmarking against diesel fuel for key parameters such as torque, brake thermal efficiency, and voltage stability.

4. To conduct a detailed cost analysis comparing generator operation with biogas versus diesel, thereby assessing economic feasibility for decentralized power systems.

By addressing these objectives, this study not only fills a critical research gap but also establishes the novelty of combining feedstock optimization, engine testing, and cost assessment in a single framework. The findings are expected to demonstrate that optimized biogas mixtures from animal waste, food waste, and sugarcane bagasse can serve as a sustainable, cost-effective, and technically viable alternative to fossil fuels for decentralized power generation.

## 2. methodology

The experimental framework included feedstock selection, characterization, pretreatment, slurry preparation, anaerobic digestion, gas collection, purification, and performance evaluation using a laboratory-scale generator.

### 2.1 Feedstock Selection and Characterization

#### Food Waste

Food and vegetable waste was collected from local kitchens and markets. It consisted of fruit peels, vegetable trimmings, and leftover food. Non-biodegradable contaminants (plastic, glass, metals) were removed manually. The biodegradable fraction was chopped (<10 mm) and homogenized for uniformity.

**Animal Manure**

Fresh manure was collected from nearby livestock farms (cow, sheep, poultry). Due to its high nitrogen content and inherent microbial inoculum, it served as both substrate and inoculum. The manure was diluted with water (1:1 w/w) to form a slurry and sieved to remove fibrous impurities.

**Sugarcane Bagasse**

Sugarcane bagasse, obtained from juice vendors and jaggery processing units, was air-dried to reduce moisture content, ground (3–8 mm), and pretreated with 1% NaOH (1:5 w/v ratio) for 48 h. This pretreatment improved biodegradability by partially breaking lignocellulosic bonds. The treated bagasse was washed to near-neutral pH and squeezed to remove excess water.

**Characterization**

All substrates were characterized for key parameters [14]:

- Total Solids (TS) and Volatile Solids (VS) (organic fraction)
- Chemical Oxygen Demand (COD)
- Carbon-to-Nitrogen (C: N) ratio
- Moisture content and pH

These parameters guided the formulation of optimized feedstock mixtures to maintain C:N ratios of 25–28:1 for efficient microbial activity.

## 2.1 Experimental Setup

**Biogas Digester**

A laboratory-scale digester with 250 kg/day waste handling capacity was employed as shown in Fig. 1. The digester was loaded with homogenized slurry (10–15% TS) and operated under mesophilic conditions (30–38 °C) for 30 days. Stirring was performed daily to maintain homogeneity.

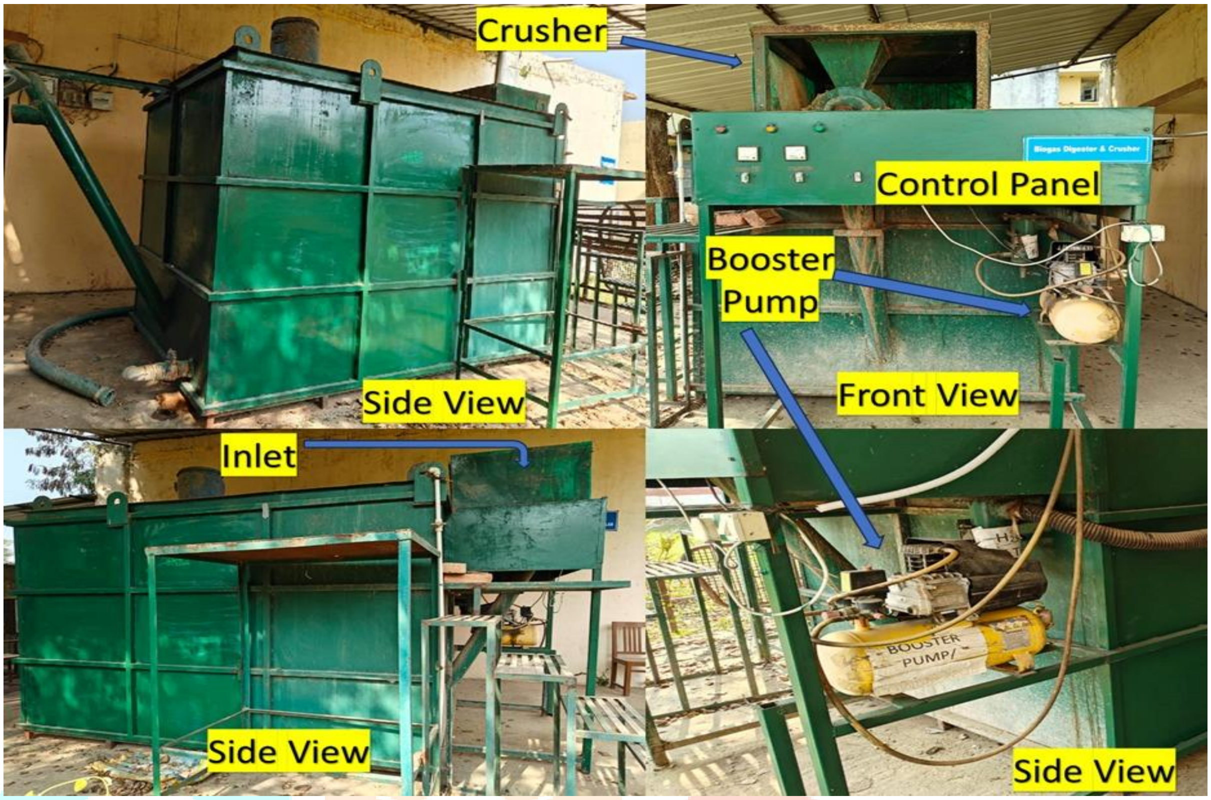


**Fig. 1.** Photograph of biogas digester and crusher

**Gas Collection and Floating Dome**

A floating dome collected generated biogas. The dome rose with gas accumulation and descended when gas was consumed. Gas was routed through a flexible pipe to a booster pump and filter unit.

**Biogas Upgrading (Filter Unit)**

A Pressure Swing Adsorption (PSA) unit was used to remove $CO_2$, $H_2O$, and $H_2S$, increasing methane concentration to 90–94%. Adsorbents included carbon molecular sieves and zeolites. Multi-column operation simulated continuous upgrading.

**Generator**

A 3 kVA laboratory-scale generator was modified to operate on purified biogas. Diesel was used as the baseline fuel. Comparative testing under different loads was conducted to evaluate performance indicators.

**2.3 Experimentation**

Fresh sugarcane bagasse was first air-dried under sunlight until its moisture content was reduced to a level suitable for handling. The dried material was mechanically chopped and milled to obtain particles of approximately 3–8 mm as shown in Fig. 2 (a), to increase surface area and improve subsequent treatment efficiency. The chopped bagasse was then subjected to a mild alkaline pre-treatment to enhance lignocellulosic deconstruction: a 1.0% (w/v) sodium hydroxide (NaOH, caustic soda) as shown in fig. 2 (b), solution was prepared and bagasse was soaked at a solid: liquid ratio of 1:5 (w/v) for 48 hours at ambient temperature. During this soaking period the slurry was stirred gently once every 12 hours to ensure uniform contact between the alkali solution and the bagasse fibres. After 48 hours the alkali-treated bagasse was washed repeatedly with potable water until the wash water reached near-neutral pH (≈7.0) to remove residual NaOH and solubilized inhibitory compounds. The washed bagasse was then drained and squeezed to remove excess water.

(a) (b)

**Fig. 2** Photograph of (a) Sugarcane bagasse (b) caustic soda

### 2.3.1 Formation of bagasse slurry

The neutralised, pre-treated bagasse was mixed with clean water in a ratio to form a homogeneous slurry. The initial bagasse: water ratio used for slurry formation was 1:1 (w/w) unless otherwise specified for a particular run. The slurry was mechanically mixed with a paddle mixer for 10–15 minutes to ensure uniform consistency and to break-up remaining fibre bundles.

### 2.3.2 Preparation of co-substrates and inoculum

Food waste (fruit and vegetable scraps) was sorted to remove non-biodegradable contaminants, chopped to <10 mm pieces and homogenized. Fresh animal manure (cow dung) was collected from nearby farms, sieved to remove large debris, and diluted 1:1 (w/w) with water to produce a pumpable slurry. Cow dung served as the biological inoculum and was added to each test mixture at 10–20% (w/w) of the total substrate mass.

### 2.3.3 Mixing and final slurry formulation

The pre-treated bagasse slurry, food/vegetable waste and inoculated animal manure were combined according to the experimental mixture ratios as shown in Table 1. The experimental mixtures were prepared as per suggested literature review and suggested by experts and it is based on the optimization of key parameters that influence biogas production and quality, especially the Carbon to Nitrogen (C: N) ratio, biodegradability, and buffering capacity. After combining the solid substrates, additional water was added to achieve the target slurry consistency and solids content. The final slurry solids concentration was adjusted to 10–15% total solids (TS) to promote efficient fermentation. The combined slurry was mixed thoroughly in a crusher/mixer (or homogenizer) for 10–20 minutes to ensure complete blending and to eliminate pockets of unmixed material. The homogenized slurry was visually inspected to confirm uniformity and then immediately transferred to the digester.

**Table 1** Various experimental mixture ratio

| Sample Name | Animal manure | Food and vegetable waste | Sugarcane bagasse |
|---|---|---|---|
| M-1 | 25% | 25% | 50% |
| M-2 | 40% | 20% | 40% |
| M-3 | 35% | 35% | 30% |

### 2.3.4 Digester Loading and Operation

Homogenized slurry batches were loaded into airtight, laboratory-scale batch digesters, each fitted with a gas outlet connected to the collection system. Digesters were maintained under mesophilic conditions (30–38 °C) for a retention time of 30 days. Slurries were stirred daily or intermittently (2–3 times/week) to prevent settling, scum formation, and ensure uniform microbial activity.

### 2.3.5 Monitoring, Sampling, and Safety

Temperature and pH were monitored daily. When pH dropped outside the optimal 6.5–7.5 range, sodium bicarbonate was added as a buffer. Total solids (TS) and volatile solids (VS) were measured at the beginning and end of each run to evaluate substrate degradation. NaOH and alkaline effluents were handled using personal protective equipment (gloves, goggles, apron), and wash water was neutralized before disposal.

### 2.3.6 Gas Collection and Analysis

Biogas was collected in gas-tight bags or storage cylinders via a booster pump. Daily gas volume was measured using the water-displacement method (or a calibrated gas meter when available). Gas samples were periodically analysed using gas chromatography (GC) to determine $CH_4$, $CO_2$, and $H_2S$ concentrations. Calorific value was assessed with a bomb calorimeter. For upgrading, raw biogas was purified using Pressure Swing Adsorption (PSA) with three adsorption columns packed with carbon molecular sieves/zeolites. This process removed $CO_2$, $H_2O$, and $H_2S$, enriching methane to 90–94%. Purified biogas was subsequently supplied to the generator for performance evaluation.

### 2.4 Data Collection and Measurement

A comparative performance analysis was conducted between biogas and diesel using a 3 kVA generator. Key parameters included fuel consumption rate, output voltage stability, engine speed, torque, brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE). Petrol served as the baseline fuel for the unmodified generator, while purified biogas was used in the modified version. At varying loads (80–1900 W), the generator was operated for 50 minutes per run. Fuel consumption was determined by weighing compressed biogas cylinders before and after operation using a digital scale. A stopwatch ensured precise time tracking. Recorded performance metrics enabled direct comparison between biogas and conventional diesel operation.

**2.4.1 Gas Chromatography (GC):** GC is commonly used to analyse the composition of biogas. This method helps quantify methane ($CH_4$), carbon dioxide ($CO_2$), hydrogen sulphide ($H_2S$), and trace gases. Methane is the primary energy component, while high $CO_2$ or $H_2S$ levels reduce quality and may cause corrosion.

**2.4.2 Calorific Value Measurement (Bomb Calorimeter):** The calorific value indicates the energy content of the biogas. Higher methane content corresponds to a higher calorific value. Using a bomb calorimeter, you can measure the exact energy yield, typically in $MJ/m^3$, which is essential for comparing biogas quality against other fuels like petrol.

**2.4.3 Pressure and Volume Measurement:** Analysing biogas pressure and volume generated under standardized conditions can help assess its efficiency. Basic methods include gas flow meters and pressure gauges.

### 2.4.4 Environmental and Economic Analysis

A comparative analysis will be conducted to evaluate the environmental and economic benefits of biogas production from co-digestion compared to conventional waste disposal methods. Economic Feasibility: A cost-benefit analysis will be conducted to estimate the economic feasibility of using agricultural, food, and animal waste for biogas production, considering capital and operational costs.

### 3. Results and Discussion

It emphasizes the outcomes of the study, providing a framework for interpreting, analyzing, and evaluating their relevance to the research aims. For better clarity and systematic understanding, the findings are arranged under distinct sections.

### 3.1 Optimization of Carbon-to-Nitrogen (C: N) Ratio and Biogas Quality

The carbon-to-nitrogen (C: N) ratio is a crucial factor influencing the stability and efficiency of anaerobic digestion, directly affecting microbial activity and methane yield. An imbalance in this ratio may cause nutrient limitations or inhibitory conditions, thereby reducing biogas production efficiency. The C:N ratio of different feedstock mixtures was determined using a CHNS elemental analyser, and the results are presented in Table 2.

**Table 2.** Compositional analysis of various biogas fuels

| Mixture | $CH_4$ (%) | $CO_2$ (%) | $H_2S$ (ppm) | CV (kJ/m³) | Estimated C: N Ratio (Approx.) |
|---|---|---|---|---|---|
| M-1 | 58.3 | 37.5 | 220 | 22100 | ~38–40:1 |
| M-2 | 62.7 | 33.2 | 190 | 23300 | ~30–32:1 |
| M-3 | 64.1 | 31.6 | 170 | 24100 | ~25–28:1 (Ideal range) |

M-1 exhibited a high C:N ratio (~38–40:1) due to a larger proportion of sugarcane bagasse, which is carbon-rich but nitrogen-deficient. This imbalance slowed microbial activity and limited methane production. Mixture M-2 (~30–32:1) showed better balance, with nitrogen from food and animal waste partially compensating for carbon-rich residues, resulting in improved methane yield. Mixture M-3 achieved the optimal range (~25–28:1), providing the best balance for microbial metabolism. At this ratio, hydrolysis and methanogenesis were enhanced, volatile fatty acid (VFA) accumulation was minimized, and methane yields were maximized. Biogas quality was further evaluated through gas chromatography (GC), which measured methane ($CH_4$), carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), and calorific value (CV) [15]. The methane concentration increased progressively from M-1 to M-3, demonstrating the positive effect of optimized C:N ratios on gas quality. Mixture M-3, with an ideal C: N balance, achieved the highest methane concentration (64.1%) and calorific value (24,100 kJ/m³). This improvement arises from synergistic effects in co-digestion: animal manure provided nitrogen and microbial inoculum, food waste supplied readily degradable organic matter, and sugarcane bagasse contributed structural carbon. Together, these substrates supported a diverse microbial community, enhanced substrate degradation, and diluted potential inhibitors such as excess ammonia from animal manure [16]. Thus, the results confirm that optimizing the C:N ratio through co-digestion not only stabilizes the anaerobic process but also significantly improves methane content and energy potential of biogas. The superior performance of Mixture M-3 highlights the importance of balanced feedstock composition in achieving high-quality biogas suitable for energy generation.

### 3.2 Biogas Generation Rate

The biogas generation rate of the three feedstock mixtures (M-1, M-2, and M-3) was measured using a gas flow meter, which recorded the volume of biogas produced per unit time. The experimental results, shown in Figure 3, indicate clear differences in gas yield among the mixtures. Mixture M-3 exhibited the highest biogas generation rate, outperforming M-2 and M-1. Specifically, M-3 produced approximately 12% more biogas than M-2 and 26% more than M-1, highlighting the benefits of optimizing feedstock composition and the carbon-to-nitrogen (C: N) ratio. The superior performance of M-3 can be attributed to several factors:

- **Optimal C:N ratio (25–28:1):** This ratio provided sufficient nitrogen for microbial growth while preventing ammonia inhibition, ensuring stable digestion.
- **Nutrient synergy:** Co-digestion of sugarcane bagasse (carbon-rich), animal manure (nitrogen-rich), and food waste (balanced composition) supplied complementary nutrients and trace elements essential for microbial communities [16].
- **Enhanced microbial activity:** The balanced substrate mixture promoted efficient hydrolysis and methanogenesis, leading to improved methane conversion rates [17].
- **Higher organic loading tolerance:** Mixed feedstocks supported greater organic loading compared to single substrates, enabling steady gas production without process instability [18].

These results confirm that optimized co-digestion strategies not only stabilize anaerobic digestion but also significantly enhance biogas generation rates, with Mixture M-3 demonstrating the most favourable performance for renewable energy applications.

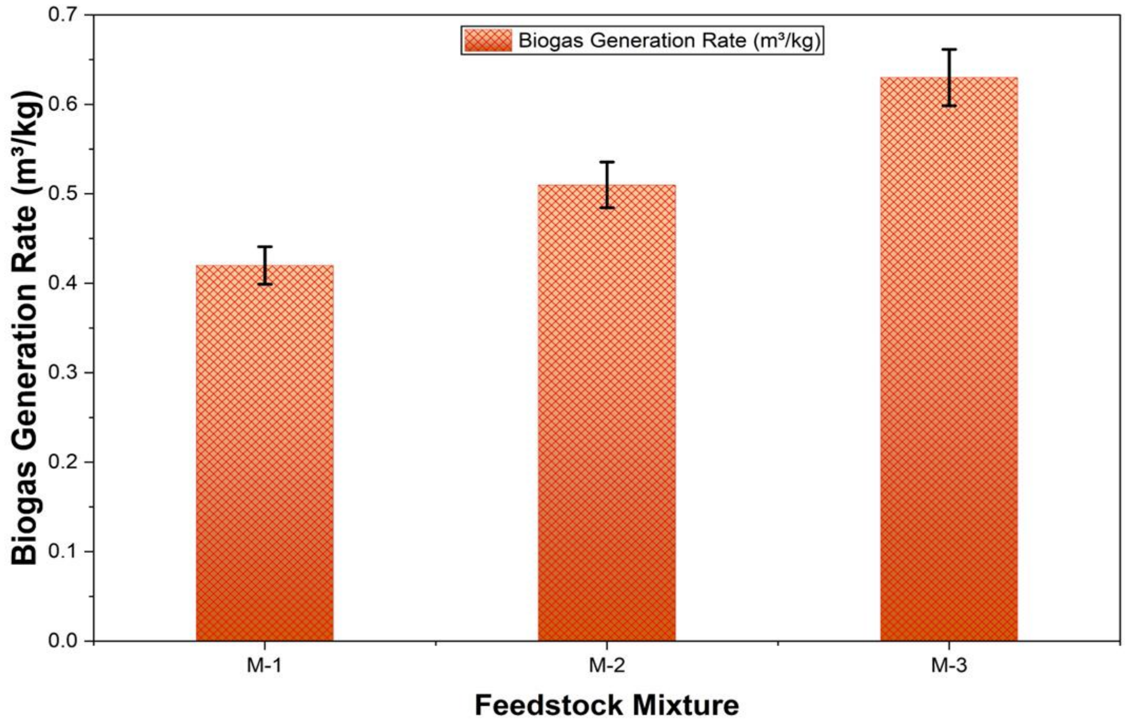


**Fig. 3** Biogas generation rate for M-1, M-2, and M-3 mixtures

Thus, the results confirm that M-3 outperformed M-1 and M-2 in terms of gas yield, owing to its optimized feedstock ratio and balanced nutrient profile. Following production, the raw biogas from all three mixtures was subjected to three-stage purification, where $CO_2$, $H_2O$, and $H_2S$ were removed. After filtration, the upgraded biogas contained ~95% methane ($CH_4$), with a density of 0.66 kg/m³ and an octane number of approximately 120. These properties indicate its high quality and suitability for use as a generator fuel. For comparative analysis, gasoline (Diesel) was selected as the benchmark fuel. The key properties of petrol used in this study are summarized in Table 3.

**Table 3.** Properties of gasoline fuel [18]

| Properties | Diesel |
|---|---|
| Density | ~830–850 kg/m³ |
| Octane number | 45–55 |
| Heating value | ~42–43 MJ/kg |
| Flash point | ~52–96 °C |
| Compression ratio | 14–25 |
| Air fuel ratio | ~18.5:1 |

### 3.3 Power generation analysis of biogas and diesel

During the experimental test, the biogas-powered generator operated for a duration of 50 minutes. Observations showed that 0.90 kg of fuel was consumed. A reservoir pressure of 4.1 bar was maintained for biogas, resulting in the consumption of 0.90 kg after scaling. To calculate the time required for the generator to run on 1 kg of biogas, the following analysis was conducted: Given that 0.90 kg of biogas lasted for 50 minutes, we can establish [31]:

$$0.90 \text{ kg} = 50 \text{ minutes}$$

$$1 \text{ kg} = Y \text{ min}$$

$$Y \text{ min} = (50 \text{ min} \times 1 \text{ kg})/0.90$$

$$= 55.5 \text{ min}$$

Thus, it can be inferred that 10 kg of biogas can sustain generator operation for approximately 555 minutes at a varying load capacity of 1900 W for a 3 kVA generator.

For comparison, the generator's gasoline (diesel) performance was also evaluated. It was observed that 10 liters of gasoline operated the generator under the same variable load of 1900 W for a duration of 701 minutes, after which the fuel was fully depleted.

**3.4 Load Handling Capacity and Electrical Voltage Performance**

The comparative evaluation of generator performance under varying loads is illustrated in Figure 4. Results indicate that the diesel-powered generator consistently delivered stable voltage across the tested load range (400–1900 W). Voltage decreased gradually from about 225 V at lighter loads to approximately 204 V at full load, reflecting its strong stability and reliable operation. This performance can be attributed to diesel's higher calorific value and superior combustion efficiency, which support efficient power generation even under heavy demand [18-19]. In contrast, the biogas-powered generator showed a more pronounced voltage drop, ranging from nearly 215 V at 400 W to around 170 V at 1900 W. This corresponds to a 10–20% lower voltage stability compared to diesel operation.

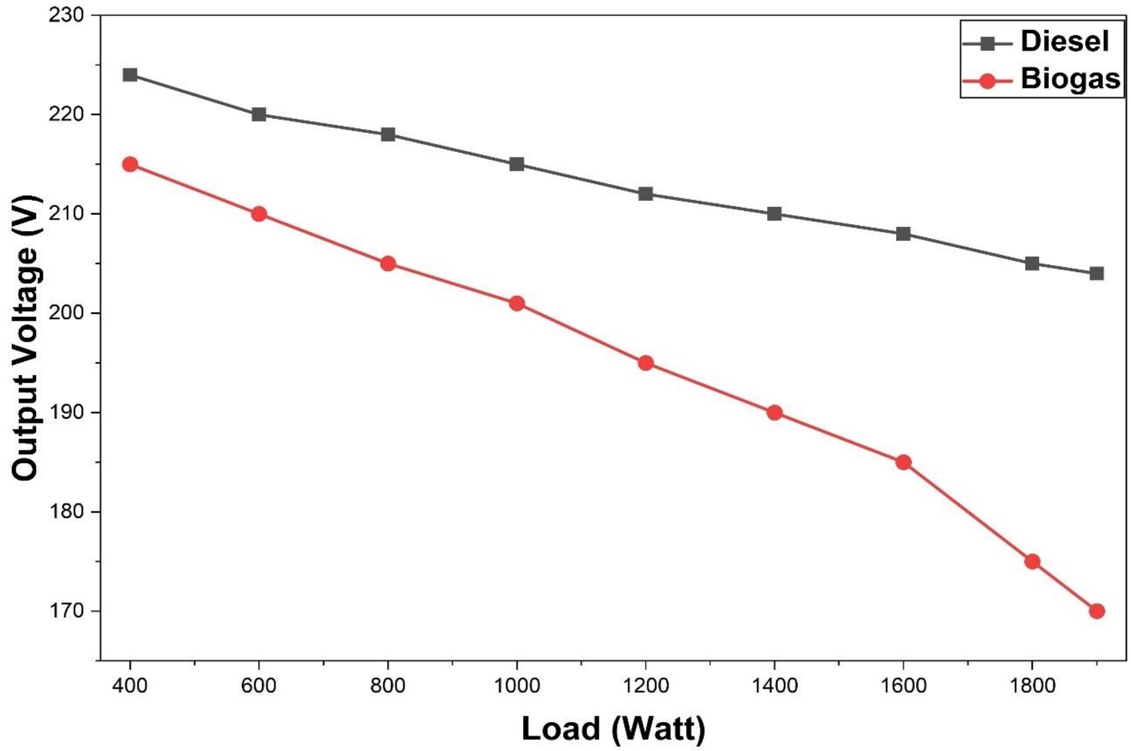


**Fig. 4** Comparison graph of generator load versus voltage output

The reduced performance is mainly linked to the lower energy density of biogas and fluctuations in methane content. Such characteristics can lead to unstable combustion, making it more challenging to sustain steady voltage output at higher loads. These findings suggest that while diesel generators can manage heavier loads without significant fluctuations, biogas-powered systems may require additional optimization. Improvements such as fine-tuned carburetion, advanced fuel pressure regulation, and enhanced purification to stabilize methane concentration could help minimize performance variability [20]. Overall, diesel generators provide superior voltage stability and load-handling capacity, making them more suitable where consistent power quality is essential. Biogas systems, however, present clear environmental and economic advantages as a renewable alternative, though further technical refinements are necessary to achieve comparable reliability [21].

**3.5 Engine Speed Variation Under Different Load Conditions**

The variation in engine speed under different loading conditions for diesel and biogas fuels is presented in Figure 5. The experimental results clearly show that diesel maintained consistently higher engine speeds than biogas across all tested load levels. This behaviour is largely due to diesel's higher calorific value and energy density, which promote efficient combustion and stronger power delivery compared to biogas. At a load of 1000 W, the diesel engine reached a peak speed of about 3050 rpm, whereas the biogas-fuelled engine recorded a maximum speed of roughly 2650 rpm. This corresponds to an approximate 13% reduction in speed with biogas operation. The lower performance of biogas is associated with its reduced methane content and the presence of inert gases such as $CO_2$, which dilute the combustible mixture and hinder complete combustion [22].

With increasing load beyond 1000 W, both fuels exhibited a gradual decline in engine speed. However, the reduction was more pronounced in the biogas-fuelled generator, highlighting the limitations of biogas in maintaining stable combustion at higher loads. Diesel engines, by contrast, benefit from superior ignition characteristics, higher combustion temperatures, and efficient fuel utilization, which collectively contribute to steadier engine operation. Another observation was that diesel engines responded more effectively to sudden variations in load, showing better speed stability and faster recovery [23]. Biogas engines, on the other hand, displayed greater fluctuations due to inconsistent methane concentration, lower energy density, and higher fuel volume requirements for equivalent power output. Overall, the findings demonstrate that diesel provides superior stability, faster response, and higher engine speeds, making it more reliable for generator applications under variable load conditions. Biogas, while a sustainable and eco-friendly alternative, requires further optimization in terms of fuel quality enhancement (e.g., methane enrichment and $CO_2$ removal) and engine modifications to reduce speed fluctuations and improve performance.

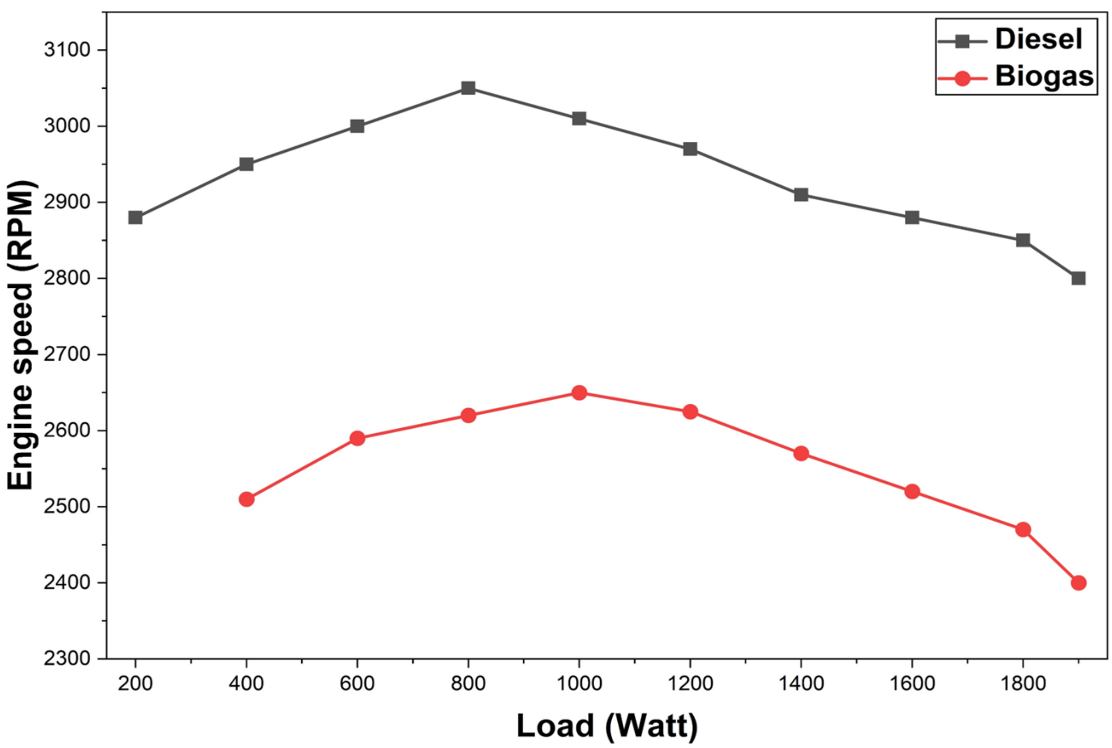


**Fig. 5** Graphical analysis of load against engine speed in the generator

### 3.6 Variation of Engine Torque with Loading

The variation in engine torque under different loading conditions for diesel and biogas operation is presented in Figure 6. The results clearly demonstrate that diesel consistently produced higher torque than biogas across all load ranges. This is primarily due to diesel's higher calorific value and energy density, which ensure efficient combustion and greater pressure generation inside the cylinder, thereby transmitting more force to the piston. At the minimum load of 200 W, the diesel generator produced a torque of around 1.2 N·m, whereas the biogas-fuelled generator delivered only 0.4 N·m, reflecting a reduction of approximately 66.6% with biogas. As the load increased, both fuels exhibited a nearly linear rise in torque, though diesel maintained a clear advantage. For instance, at 1000 W, diesel achieved 3.1 N·m, compared to 2.0 N·m for biogas, corresponding to about 35.5% lower torque [24].

At the maximum load of 1900 W, the diesel engine developed a torque of approximately 6.0 N·m, while the biogas engine reached 4.5 N·m, showing a reduction of nearly 25%. Although the relative performance gap narrows at higher loads, biogas torque values remained consistently lower throughout the test range.

The reduced torque output of biogas-fuelled engines is largely explained by its lower methane concentration and the presence of inert gases such as $CO_2$, which dilute the air–fuel mixture. This dilution lowers flame propagation speed, slows combustion, and reduces peak pressure in the cylinder, thereby limiting torque production. Diesel, by contrast, benefits from faster ignition, higher combustion efficiency, and stable pressure development, allowing it to deliver stronger torque under all load conditions [24]. Overall, the findings indicate that diesel operation resulted in 20–65% higher torque compared to biogas, depending on load. While biogas offers clear sustainability and environmental advantages, its use in engines requires optimization strategies such as methane enrichment, $CO_2$ removal, or engine modifications (e.g., higher compression ratio) to improve combustion quality and narrow the performance gap with diesel [25].

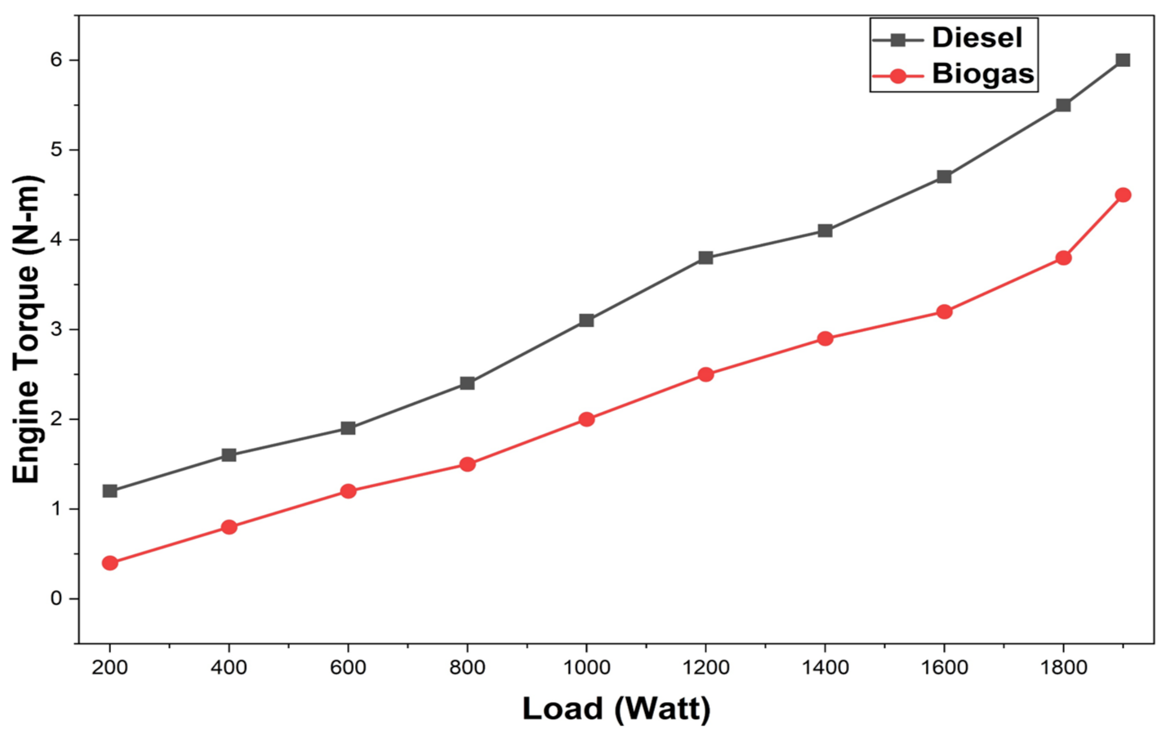


**Fig. 6** Engine torque variation with load up to maximum capacity

### 3.7 Brake Thermal Efficiency Performance at Varying Loads

The variation of brake thermal efficiency (BTE) with load for diesel and biogas operation is presented in Figure 7. Across the entire load spectrum (200–1900 W), diesel consistently demonstrated higher thermal efficiency compared to biogas. Both fuels, however, showed a clear upward trend in BTE with increasing load, reaching their respective peak values at the maximum load of 1900 W. At this point, diesel attained a BTE of about 35.5%, whereas biogas achieved approximately 24%. Several factors account for the superior efficiency of diesel:

- Fuel Calorific Value: Diesel possesses a significantly higher calorific value (42–45 MJ/kg) relative to biogas (20–24 MJ/m³). As a result, diesel combustion releases more energy per unit of fuel, directly translating into higher conversion efficiency under identical engine conditions [26].

- Combustion Characteristics: Diesel, being a liquid fuel with a high cetane number, ensures better atomization, rapid ignition, and near-complete combustion within the cylinder. In contrast, biogas, composed mainly of $CH_4$ and $CO_2$, has a lower energy density and slower flame propagation speed. The presence of $CO_2$ dilutes the combustible mixture, leading to incomplete combustion and consequently lower efficiency [27].

- Effect of Load: At low load levels, a considerable portion of the input energy is lost to friction, cooling, and other parasitic losses, resulting in lower efficiency. For instance, at 200 W, diesel recorded a BTE of roughly 6%, whereas biogas achieved only 2.5%, showing a performance gap of about 57%. As the load increased, a larger fraction of the fuel energy was converted into useful work, thereby improving efficiency for both fuels. At the highest load (1900 W), diesel still outperformed biogas, though the relative difference narrowed to about 11.5% [28].

The observed trends confirm that while both fuels benefit from increased loading, diesel maintains a clear advantage in thermal efficiency due to its intrinsic chemical and physical properties. Biogas performance improved significantly with load, yet it could not reach diesel's efficiency levels [29].

Overall, the results highlight that diesel remains more efficient for power generation applications, but biogas efficiency can be improved through fuel enrichment (e.g., methane concentration enhancement), $CO_2$ removal, or engine modifications tailored for gaseous fuels. These improvements could enable biogas to operate closer to diesel efficiency levels while maintaining its sustainability and environmental benefits [30-31].

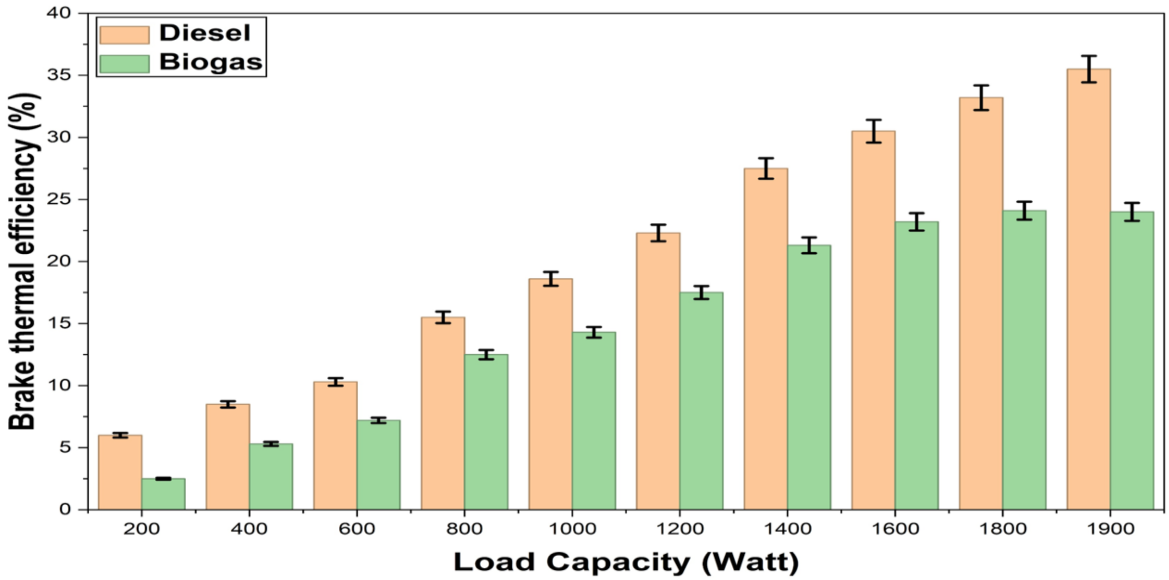


**Fig. 7** Variation of brake thermal efficiency with load represented in a bar graph

### 3.8 Comparison of running cost analysis

The cost analysis of biogas and gasoline (Diesel) was done for 10 Kg biogas and 10 Liters of gasoline fuel. The total running time of load capacity of 1900 Watt on a 3 KVA generator for 10 kg biogas was 555 minutes and 10 Liter gasoline fuel was 701 minutes respectively as discussed in section 4.3. The total production cost of 10 kg biogas is discussed below [32-33]:

### A. Raw material cost for biogas generation

For generation of 10 kg biogas was needed approximately 150 kg of biogas. The total production cost of biogas generation is shown in Table 4.

**Table 4.** Raw material cost for 10 kg production of biogas

| Type of waste | Cost per kg in rupees | Quantity of waste in kg | Total cost |
|---|---|---|---|
| Animal manure | 1 rupees / kg | 52.5 kg | 52.5 rupees |
| Food and vegetable waste | 1 rupees / kg | 52.5 kg | 52.5 rupees |
| Sugarcane bagasse waste | 1.2 rupees / kg | 45 kg | 54.0 rupees |
| **Total cost** | | **150 kg** | **159.00 rupees** |

### B. Water for digestion

Biogas production typically requires water for dilution. The total ratio of 2:1 (water to feedstock by weight). Total cost of 300 Liter of water was approximately 15 rupees.

**C. Labour and energy cost**

Small-scale systems require minimal labour; 0.5-1 hours/day for feedstock input and maintenance. Total labour cost for 10 kg biogas was approximately 65 rupees. The power for pumps, agitators, and monitoring equipment is required in biogas plant. Estimated electricity consumption: ~1 kWh/day for small-scale systems and the cost: 10 rupees / kWh. Allocated energy cost for 10 kg is 20 rupees.

**D. Capital costs**

The total cost of biogas system was approx. 4000000 rupees (small-scale digesters, excluding subsidies) and daily average output approx. 6 kg biogas/day (varies). The average lifespan of biogas system is 13 years with consistent use.

Total production of biogas in 1 year, 6* 365= 2190 kg

Production of biogas in 13-year, 2190*13=28470 kg

Cost per kg of biogas, Total cost/ Total production of biogas

400000/28470=14 (rupees/kg)

Total cost of 10 kg of biogas, 14*10 = 140 rupees

**E. Maintenance Costs**

The routine checks, repairs, and cleaning cost is average 6000 rupees / year. The total cost of per kg of biogas was

6000/1825= 3.22 rupees/kg

Total cost of 10 kg biogas, 10*3.22 = 32.25 rupees

**F. Total Cost for 10 kg Biogas**

Summing all cost

Total Cost = Raw Material cost + Water for digestion + Labour and energy cost + Capital Cost + Maintenance cost

Total cost of 10 kg biogas = 159+15+85+140+32.25= 431.25 rupees

The cost of 1 Liter gasoline (Diesel) is around 94 rupees in Rewa Madhya Pradesh India, then total cost of 10 Liter gasoline fuel was

94*10=940 rupees

The cost analysis of both the fuels is shown in Table 5. It was analysed that the running cost of biogas was 41.8 % cheaper than the gasoline fuel [29].

**Table 5** comparison of running cost of biogas and gasoline fuel

| Type of fuel | Quantity | Total cost | Running time | Running cost/minutes |
|---|---|---|---|---|
| Biogas | 10 kg | 431.25 rupees | 555 minutes | 0.78 rupees/minute |
| Diesel | 10 Liters | 940 rupees | 701 minutes | 1.34 rupees/minute |

Cost Efficiency of biogas is significantly cheaper per unit running cost than gasoline (Diesel) [34]. Environmental impact of biogas has a smaller carbon footprint and is renewable, making it more environmentally friendly. Biogas is more suitable for generators and heating applications in rural areas or sustainable systems, while diesel is preferred for high-density energy needs (e.g., vehicles) [35].

**4. Conclusions**

The biogas has been done generated successfully by using various fuels (animal waste, food waste and sugarcane bagasse waste at different mixture ratio) and compared with the gasoline (diesel) fuels. The following conclusions have been drawn from current study:

➢ Biogas was successfully produced from animal waste, food waste, and sugarcane bagasse at different mixture ratios and compared with diesel.

➢ The carbon-to-nitrogen (C: N) ratio is critical for microbial activity and methane production. Mixture M-3 (~25–28:1) provided optimal digestion, metabolism, and methane yield.

➢ Methane content increased from 58.3% (M-1) to 64.1% (M-3), with calorific value reaching 24,100 kJ/m³, indicating enhanced gas quality through optimized feedstock blending.

➢ M-3 achieved the highest biogas yield (~12% higher than M-2 and ~26% higher than M-1). Post-purification, biogas contained ~95% methane, density 0.66 kg/m³, and octane number ~120, suitable for generator use.

➢ Diesel showed better voltage stability (225–204 V) compared to biogas (215–170 V) under varying loads due to higher energy density.

➢ Diesel achieved higher engine speed and torque; biogas performance was 20–65% lower depending on load, limited by slower flame propagation and $CO_2$ dilution.

➢ Maximum brake thermal efficiency (BTE) of diesel was ~35.5%, while biogas reached ~24%; efficiency gap narrowed at higher loads but diesel remained superior.

➢ Running cost of biogas (0.78 rupees/min) was ~42% lower than diesel (1.34 rupees/min), offering significant operational savings despite lower performance.

- Biogas is renewable, carbon-neutral, and environmentally friendly, presenting a viable alternative for sustainable energy, especially in rural or decentralized systems.

- Overall, optimized biogas mixtures, particularly M-3, can serve as cost-effective and sustainable generator fuel with minor engine modifications and proper purification.

In summary, although diesel provides higher engine performance because of its greater calorific value and combustion efficiency, carefully optimized biogas mixtures particularly M-3 represent a practical, economical, and eco-friendly option for power generation. With proper purification, enrichment, and minor adjustments to the engine, biogas can play a significant role in sustainable energy production and reduce dependence on fossil fuels.

**Statements & Declarations**

**Funding** The research work has not been funded from anywhere.

**Competing Interests: -** The authors have no relevant financial or non-financial interests to disclose.

**Ethics Approval**: - This research work is original and has not been submitted elsewhere in any journal for publication.

**Consent to Participate**: - Not Applicable.

**Consent for Publication**: All authors agree to publish this article.

**Availability of data and materials**: All data are available in the manuscript.

**Authors' Contributions Abhay Varma:** Investigation, Writing – original draft, Writing – review & editing.

**Pushpraj Singh**: Writing–review, conceptualisation, & editing, Supervision.

**Abhay Agrawal**: Writing–original draft, Review & editing, Supervision.

**Rajkumar Singh**: Writing–review, conceptualization, & editing, Supervision.

**Prashant Singh Chauhan**: Writing–original draft, Review & editing, Supervision.

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