



Prediction on the Performance Parameters of a Variable Compression Ratio (VCR) Dual Fuel Diesel-Producer Gas CI Engine: An Experimental and Theoretical Approach

A. Jemila Percy¹ · M. Edwin¹

Received: 14 June 2022 / Accepted: 24 November 2022 / Published online: 9 December 2022
© King Fahd University of Petroleum & Minerals 2022

Abstract

In recent years, biomass fuelled engines have gathered major interest due to rapid depletion and rising price of conventional fuels. Biomass gasification has a better conversion efficiency compared to other conversion techniques. Also, Producer gas can be used directly in diesel engines without any modifications. In this study, the performance parameters of a variable compression ratio CI engine fuelled with diesel-producer gas combination derived from rice husk, coconut shell, and rubber shell have been experimentally and theoretically investigated. During experimentation, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption and biomass consumption (BMC) are obtained by varying compression ratio and brake power (BP). A new theoretical model based on the finite-time thermodynamics is developed and validated with experimental results. The experimental results show that rubber shell powered DF engine showed the maximum diesel savings of 48%. It is also observed that, among the three selected feedstock, the rubber shell-based dual fuel engine had the highest BTE of 19.80% followed by the coconut shell and rice husk as 19.44% and 19.13%, respectively. Similarly lowest BMC of 3.53 kg/h was observed for rubber shell driven engine. In addition, the rubber shell derived producer gas had a lower BSFC of 0.64 kg/kWh on dual fuel mode than rice husk and coconut shell. It is also predicted that the optimum BTE and diesel savings as 19.18% and 48% are obtained at the compression ratio and BP of 18 and 2.56 kW, respectively.

Keywords Biomass gasification · Producer gas · Dual fuel · Engine performance · Finite time thermodynamics

Abbreviations

VCR Variable compression ratio
CR Compression ratio
CI Compression ignition
PG Producer gas
IC Internal combustion
SI Spark ignition
BTE Brake thermal efficiency
BSFC Brake specific fuel consumption
BSEC Brake specific energy consumption
BMC Biomass consumption
BP Brake power

FTT Finite time thermodynamics
FC Fuel consumption
DS Diesel savings
HC Hydro carbon
CO Carbon monoxide
NO Nitrous oxide
CV Calorific value of fuel
3D Three dimensional
CFD Computational fluid dynamics
AAC Available area under cultivation
AY Average yield
RPR Residue to product ratio
GRP Gross residue potential
BTDC Before top dead centre
HP Horse power
PT Platinum resistance thermometer
SEC Specific energy consumption
BM Biomass

✉ M. Edwin
edwinme1980@gmail.com

¹ Department of Mechanical Engineering, University College of Engineering, Nagercoil, Anna University Constituent College, Nagercoil, Tamil Nadu, India



List of symbols

CR	Compression ratio
d, D	Diameter, m
C	Specific heat, kJ/kg
m	Mass flow rate, kg/s
Q	Heat, kJ
N	Speed, rpm
V	Voltage
I	Current
H	Calorific value of fuel
q	Error or uncertainty
E	Engine capacity, kW
L	Load, kW
B	Blend percentage of PG, %
X	Regression coefficients
P	Effective power, kW
T	Temperature, K
Z	Friction constant, kPa
V	Volume, m ³

Subscripts

d	Diesel
pg	Producer gas
t	Total
st	Stoichiometric
t	Total
f	Fuel
e	Electrical
th	Thermal
ef	Effective
m, n	Carbon and hydrogen%
p	Pressure
v	Volume
in	Input
out	Output
a	Air
l	Loss

Greek symbols

Φ	Equivalence ratio
η	Efficiency

1 Introduction

Global energy demand is increasing rapidly due to the growing population and booming economy. About 992 million people in the world still do not have access to electricity. In

India around 18% of people dwelling in rural areas are still not electrified [1]. Rural electrification is a challenging task because of the remoteness of the villages from the grid, the lower population in rural areas, and the cost of transmission and maintenance cost required for power grid extension [2]. Rural electrification depends mainly on conventional fuels, which contribute most to global warming and pollution. Due to rapid the depletion of fossil fuels, energy security is a suspicious threat to future generations. Therefore, renewable energy technologies can be used as an alternative to grid extension and are best suited for decentralised power generation, reducing atmospheric emissions [3–5].

Biomass is one among the renewable energy sources that can help to fill the gap between energy production and energy demand [6, 7]. Biomass gasification is a thermochemical process that converts solid feedstock into usable gases [8]. The main advantage of gaseous fuels is their higher combustion efficiency (70–80%) and higher heat release rate. In addition, it is easy to control and adjust the rate of energy output and can be used for various power sources [9]. The formation of tar, which is difficult to purify and reduces the output of H₂, is the main challenge in the gasification process [10, 11]. The most common locally available biomass materials such as wood and non woody agricultural residues such as coconut shells, rubber seed kernels and coir pith can be gasified in a gasifier to producer gas that can be utilised for heat and power applications [12]. From the findings from the existing literature, appropriate examinations on the parametric analysis of the various types of biomass resources utilised in the gasification process of the gasifiers may significantly increase the system's performance in terms of calorific value and cold gas efficiency depending on the type of feedstock, equivalence ratio, flow rate, and gasifying agents [13]. Experimental studies carried out using a 15MW_e downdraft gasifier reported that the coir pith shows poor performance, whereas coconut shell shows maximum efficiency because of its higher combustible species concentration [14]. Due to the high carbon concentration in sugarcane bagasse, gasification of coconut shells proved superior to sugarcane bagasse. When coconut shells were employed as a producer gas, the tar concentration decreased from 4018 to 160 mg/Nm³ [15].

Due to fast depletion, high impacts of environmental pollution, and growing prices of conventional fuels, the use of alternative fuels in engines is an attractive research area [16, 17]. When compared to petrol, dual fuel (producer gas-fossil fuel) operation resulted in considerable reductions in HC, CO, and NO_x emissions. The findings of this study will be valuable for researchers working on the development of gasifiers and utilisation of producer gas as a supplemental fuel for SI and CI engine operations. The utilisation of biomass-derived producer gas fuelled I.C. engine can assist developed countries reduce their fossil fuel consumption [18]. Biodiesel, a liquid biofuel made from a variety of



biomass sources can be used in both single and dual fuel modes. However, gaseous biofuels such as producer gas and bio gas must be run on dual fuel mode since gaseous fuel will not ignite under the prevailing conditions of temperature and pressure inside the engine cylinder [19]. Hence a considerable amount of diesel has to be supplied as an ignition source for making the engine run on dual fuel mode. Retrofitting the existing SI engines for producer gas operation is not attractive because they suffer from a high-power derating of about 40–70%. Modification of existing diesel engine for producer gas operation is simple and also power derating is limited to 20–30% [20]. Therefore, dual fuel operation using producer gas in CI engines is an effective approach for diesel conservation.

Experiments on a gasifier engine system using coirpith and woodchips as feedstock were conducted to analyse the engine's performance characteristics at various producer gas flow rates and load conditions. At 70% load condition, the highest brake thermal efficiency (BTE) of 20% and 21% was obtained in dual fuel mode as coirpith and woodchips respectively. When compared to producer gas (PG) generated from coirpith, wood-generated producer gas had a higher calorific value and had a higher BTE. The amount of PG permitted into the engine cylinder increases as the load increases. Hence proper combustion does not take place due to the insufficient oxygen in the air-gas mixture which is the reason for decrease in BTE at higher loads [21]. Electrical power output and engine-generator efficiency for a multistage hybrid gasifier-engine system were on dual fuel operation. The results showed a maximum feasible electrical load of 11.5 kWe with a system efficiency of 15%, which was much lower than the system efficiency of 22.5% achieved during diesel mode operation. The lower calorific value of PG and the lower air fuel ratio for dual fuel operation were the reasons for the drop in efficiency [22]. Under different loading conditions, using producer gas as a supplemental fuel decreases BTE for all mixtures of diesel producer gas. When compared to diesel alone mode, it yielded adequate performance when 30% producer gas was used. The BTE diminishes as the percentage of producer gas increases. In dual-fuel mode, NO_x pollution for all types of fuel blends was observed to decrease than for sole diesel fuel engines [23]. Another study was conducted on a dual fuel engine using methyl ester rice bran oil and producer gas at different loads. It was discovered that methyl ester rice bran oil blended with producer gas gives higher brake thermal efficiency than diesel and producer gas mixture. The percentage of diesel substitution was determined by the load, the quality (CV) and quantity (flow rate) of producer gas. At 63% engine load, a maximum diesel savings of 78% was observed [24]. Pre-treating or preheating the biofuels can significantly affect the performance of the system. Experiments using preheated blends of refined rice bran oil and

PG revealed a reduction in BTE and SEC when compared to diesel only mode. A blend of refined rice bran oil preheated to 60 °C and mixed with diesel in the ratio of 1:1 operated at 84% engine load showed the highest BTE and lowest SEC compared to other blends. The SEC in dual fuel mode is comparatively higher than diesel only mode because when producer gas enters the cylinder at a higher temperature than ambient condition at the starting of compression stroke, it substantially increases the temperature inside the cylinder which results in higher energy input [25]. Compression ratio is one of the crucial process parameters of a dual fuel engine because the CR of engine varies with respect to engine design. Therefore, studies with various compression ratio engines must be carried out in order to assess its performance. The CR in VCR engines is usually made by adjusting the cylinder head, thus changing the swept volume. Sawdust and cotton stalks derived PG was employed for dual fuel operation. The engine's performance and emission characteristics were studied at CR 12–18, and the results revealed that as CR increased, the percentage of diesel fuel saving increased. This is because at higher CR, the temperature and pressure inside the engine cylinder increase, thus improving the combustion efficiency resulting in higher diesel replacement. However, at lower loads, due to the demand for a rich mixture, diesel replacement is lower [26].

From the review of existing literature, it is found that several experimental studies on a biomass gasifier-based power generation system have been reported. Only a limited theoretical studies have been identified. It is critical to theoretically model and analyse the system in order to identify the major governing factors so that the system may be validated and optimised for operation with improved efficiency. Theoretical modelling of downdraft fixed-bed reactors, using thermodynamic equilibrium model have been utilised to forecast the final composition of the production gas. Other studies employed models that combined chemical and thermodynamic equilibrium to forecast the final composition of the production gas and reaction temperature for certain reactor designs [27]. The dual fuel process in engines can be modelled in a number of ways. Zero-dimensional, multi-zone, and 3DCFD techniques are some of the modelling methodologies that have been published in the literatures to simulate dual fuel combustion [28, 29]. In practical engines the thermodynamic processes are never in equilibrium. Considering this keynote, non-equilibrium thermodynamics modelling called as Finite Time thermodynamics have been used for solving practical problems. The FTT model is simple for doing numerical computations and as they are more practical oriented, the results obtained are much realistic and reliable compared to other modelling approaches [30]. Many thermodynamic analyses, comparisons, and optimizations have been employed by design engineers to aid in the development of novel design concepts. In a study employing

Finite Time thermodynamics, the relationships between net power and efficiency for Diesel, Otto, and Dual cycles were determined theoretically by taking heat-transfer losses into account [30]. Previous literature provided a study to determine the characteristics of power and efficiency for otto, dual cycles considering the heat transfers and friction losses. In one of the preceding studies, losses arising from heat resistance and friction were determined and the performance of an irreversible diesel cycle was predicted [31].

Due to the menacing environmental impacts of conventional fuels, the world is mitigating towards renewable biofuels. Experimental evaluation on dual fuel engines using PG generated from various feedstock are available in numerous numbers in the literature. Theoretical investigation for dual fuel engine technology needs major attention as they help to identify the most influential and critical parameters in experimentation. However, only a few theoretical studies have been reported in the literature. In this regard, this study uses the finite time thermodynamics (FTT) model, developed for predicting the performance parameters of a variable compression ratio (VCR) CI engine fuelled with diesel-producer gas (PG) combination. The results of the theoretical model are compared with the experimental results in terms of Brake thermal efficiency at different compression ratio and load conditions for engine operated with PG generated all the feedstock. Using the proposed model, the impacts of engine load and compression ratio on engine performance were also studied. There is no study available that looks at the impact of engine load and CR on engine performance using PG generated from different biomass feedstock using experimentation and the finite time thermodynamics (FTT) model. This study will be useful for researchers and engine design engineers working in the field of gaseous biofuels to identify the most influential design factors for efficient operation.

2 Materials and Methods

A generalised flow chart for this research work has been presented in Fig. 1. This research involves three phases, namely identification of study area and the abundant biomass resources available within the study area, utilisation of the selected biomass for production of producer gas using biomass gasifiers for experimental evaluation of dual fuel engine, theoretical evaluation of the dual fuel engine using Finite time thermodynamics model, and Comparison of experimental and theoretical results.

2.1 Selection of Study Area and Available Biomass Resources

A research was conducted in a few remote villages in the southern region of India to efficiently utilise the existing

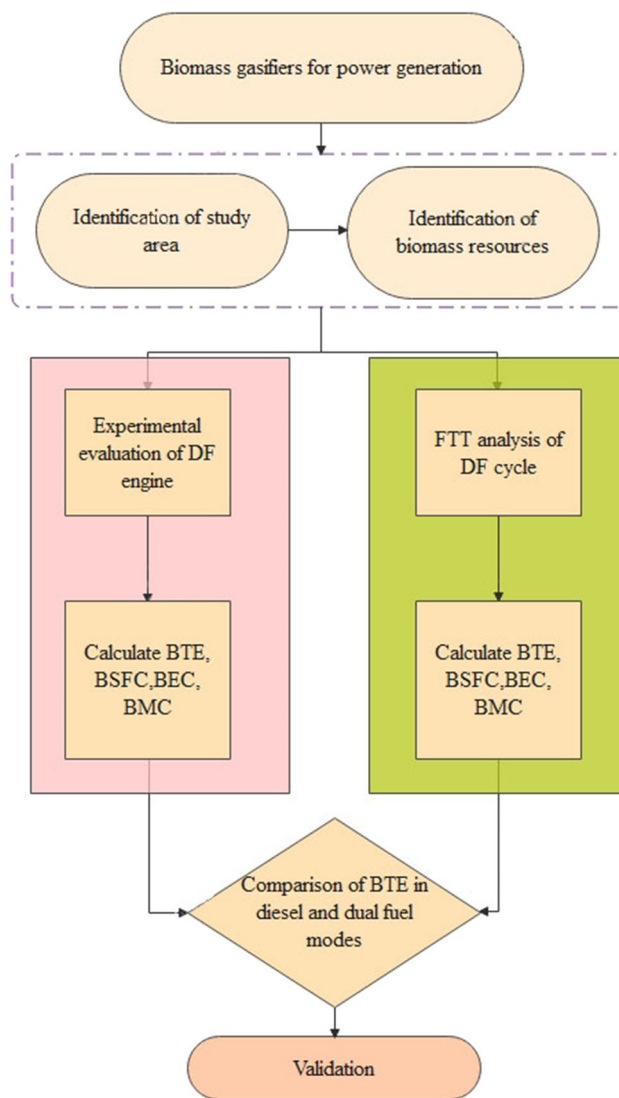


Fig. 1 General flow chart of this Research work

biomass energy resources in remote places. The study area is located along the south-west coast of Kanyakumari district, Tamil Nadu, India. The geographical coordinates extend from $77^{\circ} 9' 49.20''$ E to $77^{\circ} 34' 15.00''$ E longitude and $8^{\circ} 6' 32.60''$ N to $8^{\circ} 14' 15.30''$ N latitude [32, 33]. The survey emphasised on agricultural operations in the rural areas and crop plantations. Furthermore, the financial feasibility of technology and the impact of technology on rural areas were investigated using previous work provided by several researchers. Field surveys focusing on rural households and personal interviews were conducted in the villages to obtain data on the provision of renewable feed stocks, current energy usage, and so on. The database is being used in this research project to collect relevant information from the field of research [34, 35]. In the present study, production of agricultural biomass from all the major crops within the study area is identified. The major BM energy resources

noted in this study are, rice husk, coconut shell, and rubber shell. Gross residue potential (GRP) is the total amount of residue produced and is determined by using residue-to-product ratio (RPR). The energy potential of each of the biomass feedstock is calculated by using the following formula [36]

$$GRP = AAC \times AY \times RPR \tag{1}$$

AAC—Available area under cultivation (Ha), AY—Average yield (kg/ha), RPR—Residue to product ratio.

The important observations of the energy feed stock and their estimated Gross residue potential from the study are given in Table 1. The proximate and the ultimate analysis of the biomass feedstock were determined using the standard procedure at the Food Safety and Quality Testing Laboratory (Indian Institute of Food Processing Technology, Tanjavur, Tamil Nadu) and are given in Table 2.

2.2 Experimental Setup and Procedure

An experimental setup, as illustrated in Fig. 2a, has been designed and developed to carry out the investigation. It consists of a gasifier unit, diesel fuel tank, CI engine, and measurements apparatus. For the production of producer gas from the selected biomass feedstock (rice husk, coconut shell and rubber shell), a downdraft gasifier was used. The specifications of the downdraft biomass gasifier are presented in Table 3. The gasifier unit consists of downdraft gasifier where biomass feedstocks (rice husk, coconut shell and rubber shell) are fed into the top of the reactor maintained under controlled conditions. Air is supplied in limited amount by means of tyres provided on the sides of the gasifier for the gasification process to take place inside the chamber. The gas generated is passed through a scrubber and filter unit in-order to remove the impurities. The ultraclean gas obtained was stored in the of 10 m³ gas collection bag because the composition of producer gas (Table 4) may vary persistently due to pressure drop and lead to incomplete combustion and misfiring when it is directly fixed to the engine. Hence storage bags were used to maintain same gas composition throughout the operation. From the storage bags the producer gas was mixed with air in the intake pipe in T joint arrangement (90°) and sent into the engine cylinder.

The power generation unit consisted of a single cylinder, four stroke, multi-fuel, variable compression ratio engine of rated capacity 3.75 kW coupled to an eddy current dynamometer making the generator setup. The detailed specifications of the engine are presented in Table 5. A load cell was connected to the generator setup to provide the electrical resistance. The engine was made to run at a rated speed of 1500 rpm and diesel was injected by a diesel injector at 23° before top dead centre (BTDC) at an injection pressure of 230 bar. Being a variable compression ratio (VCR) diesel

Table 1 Observations of the energy feed stock and their estimated Gross residue potential from the study

Crop	Residue	Area (Ha) [37, 38]	Production (kg)	Avg yield rate (kg/ha)	Residue production ratio [39, 40]	Gross residue potential (kg)
Paddy	Husk	13,619	66,703,749	9814	1.5	213,850,985
Coconut	Shell	23,917	287,099,668	12,004	0.2	57,419,934
Rubber	shell	27,407	6,851,750	250	1	6,851,750

Table 2 Ultimate and proximate analysis of biomass feedstock used in the biomass gasifier

Sl. no	Component	Composition (%)		
		Rice husk	Coconut shell	Rubber shell
1	Carbon	22.8	50.22	56.65
2	Hydrogen	5.20	5.70	7.05
3	Nitrogen	0.47	1.5	2.55
4	Oxygen	34.61	43.37	33.55
5	Sulphur	0	0.1	0.2
6	Ash	21.24	0.71	0.15
7	Calorific value (MJ/kg)	14.69	20.5	25.7

Table 3 Specification of the downdraft biomass gasifier

Sl. no	Item	Description
1	Type	Downdraft Gasifier
2	Supplier	Ankur Scientific Energy Technologies Pvt Ltd
2	Rated capacity	150 kW _{th}
3	Rated gas flow	100 Nm ³ /h
4	Biomass consumption	Rice husk 40–50 kg/h
		Coconut shell 30–34 kg/h
		Rubber shell 25–32 kg/h
5	Typical conversion efficiency	75%

Table 4 Composition of producer gas

Sl. no	Component	Composition (%)		
		Rice Husk	Coconut shell	Rubber shell
1	CO	12	17.58	23.63
2	CO ₂	10.2	15.88	17.10
3	N ₂	43.1	40.67	35.82
4	H ₂	21.6	16.12	15.37
5	CH ₄	2.1	5.83	5.86
6	O ₂	1.05	3.02	1.41
7	CH ₄ (MJ/Nm ³)	4.28	6.61	7.3

engine, compression ratio of the engine is variable and can vary from 12 to 22. The engine was run at different engine loads, compression ratio, and blend ratio of producer gas, and the experimental measurements were recorded. The pictorial view of the experimental setup used in the experimentation is shown in Fig. 2b.

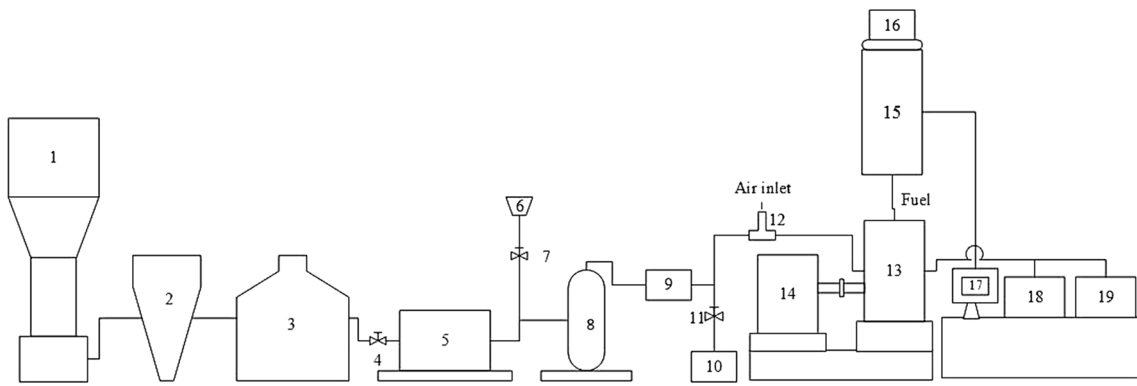
Table 5 Specification of the CI engine

Sl. no	Parameters	Specification
1	Type of the engine	Legion brothers, Single-cylinder, Multi fuel VCR
2	Nozzle opening pressure	205–230 bar
3	Rated power	5 HP (3.75 kW)
4	Speed	1450–1550 rpm
5	Cylinder Diameter(bore)	87 mm
6	Stroke length	110 mm
7	Compression ratio	12–22

The performance of the variable compression ratio (VCR)diesel engine is tested in two modes. (1) Diesel only mode and (2) Dual fuel (diesel- producer gas) mode. The performance of the engine is measured in terms of brake thermal efficiency, brake specific fuel consumption and brake specific energy consumption for diesel only mode and dual fuel (Diesel/Producer gas) mode.

As a prior preparation for experimentation, the identified biomass feedstock (Rice husk, coconut shell or rubber shell) is fed into the gasifier by a hooper provided on the top. Air is forced into the gasifier by means of a blower and the combustion of biomass is initiated by pouring a little quantity of diesel. Thus, the combustion process in gasifier takes place and the gas generated leaves the bottom of the gasifier. This gas generated is then passed through a coarse filter and scrubber unit to remove the impurities and dust particles. The ultra clean gas obtained is then cooled and passed through the filter unit consisting of a passive filter, fine filter and fabric filter. The filtered producer gas obtained is introduced into the engine cylinder by mixing with the intake air. Initially the engine is run on diesel only mode and then switched to dual fuel (diesel-producer gas) mode by adjusting the producer gas inlet valve. The experimental readings were carried out for various compression ratio and load by varying the knob in the eddy current dynamometer. Experiments were conducted





1. Downdraft Gasifier 2. Scrubber unit 3. Filter 4. Control valve 5. Blower 6. Flare 7. Control valve 8. Surge tank 9. Digital gas flow meter 10. Gas analyzer 11. Control valve 12. T joint 13. Engine 14. Dynamometer 15. Fuel tank 16. Manometer 17. Computer 18. Exhaust gas analyzer 19. Smoke meter

(a) Schematic representation of the experimental setup



(b) Pictorial view of the experimentation setup

Fig. 2 a Schematic representation of the experimental setup. b Pictorial view of the experimentation setup

in diesel only mode and dual fuel mode with varying braking power (0.5–3.5 kW) and compression ratio (12–18). At each brake power and compression ratio, three trials were carried out in order to avoid error.

2.2.1 Measurements of Performance Parameters

To evaluate the performance parameters, an eddy current dynamometer, a piezoelectric transducer and digital PT-100 type temperature sensor was calibrated and used in the computerised CI engine set up along with a digital data acquisition system. Brake power, brake thermal efficiency for only diesel mode, brake thermal efficiency of dual fuel (diesel-producer gas) mode, brake specific fuel consumption and brake specific energy consumption were measured during experimentation of the dual fuel CI engine setup.

The performance of the engine is evaluated by the relation between power developed, specific energy consumption, and specific fuel consumption at each operating condition within the effective speed and load range. An engine's fuel consumption is obtained by calculating the required time to consume a given volume of fuel. The mass of fuel was determined by multiplying the volumetric fuel consumption by the density of the fuel. For precise volumetric assessment of air measurement, an air box with orifice metre and manometer was utilised, and the mass flow rate was obtained. Temperature was measured using a digital PT-100 type temperature sensor.

Brake thermal efficiency (BTE) is the ratio of the available thermal energy in the fuel to the power delivered by the engine. In this experimentation, brake thermal efficiency (BTE, %) for diesel only mode and the dual fuel (diesel-producer gas) mode was determined as the following equations [41],

Brake thermal efficiency for diesel only mode (BTE_d, %),

$$\text{BTE}_d = \frac{\text{BP} \times 3600 \times 100}{m_d \times H_d} \quad (2)$$

where m_d is the mass flow rate of diesel in kg/h; H_d is the calorific value of diesel in kJ/kg; BP is the brake power, which is investigated by using eddy current dynamometer in kW and is expressed as [42],

$$\text{BP} = T \left(\frac{2\pi N}{60} \right) \times 10^{-3} = f(VI) \quad (3)$$

where N is the engine speed in rev/min, T is the Torque in Nm, V is the voltage and I is the current in amperes.

Brake thermal efficiency for dual fuel (diesel/producer gas) mode (BTE_{dual}, %) [41],

$$\text{BTE}_{\text{dual}} = \frac{\text{BP} \times 3600 \times 100}{\{m_d \times H_d\} + \{m_{\text{pg}} \times H_{\text{pg}}\}} \quad (4)$$

where m_{pg} is the mass flow rate of producer gas in kg/h; H_{pg} is the calorific value of producer gas in kJ/kg.

Brake specific fuel consumption (BSFC) is defined as the rate of fuel flow per unit power generation. It is a measure of the engine's efficiency in utilising the fuel supplied to produce work. The fuel consumption of an engine is calculated by using a glass pipette to determine the time taken to consume a particular volume of fuel. By multiplying volumetric fuel consumption by density, the mass of fuel was estimated. For efficient volumetric evaluation of air consumption, an air box with orifice metre and manometer was utilised, and the mass flow rate was obtained. This is one of the most crucial criteria when comparing the different fuel sources. Brake specific fuel consumption (BSFC, kg/kWh) is expressed as follows [41]:

$$\text{BSFC}_d = \frac{m_d}{\text{BP}} \quad (5)$$

$$\text{BSEC}_{\text{dual}} = \frac{m_d + m_{\text{PG}}}{\text{BP}} \quad (6)$$

where m_d , m_{PG} are the fuel consumption rates of diesel and producer gas and BP is the brake power in kW.

Brake specific energy consumption (BSEC) is another measure of engine performance which is more reliable than BSFC. The BSEC gives the effective utilisation of fuel in terms of energy. The BSEC for diesel only and dual fuel (diesel-producer gas) modes are calculated by the following equation [41],

$$\text{BSEC}_d = \frac{m_d \times H_d}{\text{BP}} \quad (7)$$

$$\text{BSEC}_{\text{dual}} = \frac{(m_d \times H_d) + (m_{\text{pg}} \times H_{\text{pg}})}{\text{BP}} \quad (8)$$

where BSEC_d is the brake specific energy consumption for diesel only mode in kJ/kWh; BSEC_{dual} is the brake specific energy consumption for dual fuel (diesel/producer gas) mode in kJ/kWh; m_d is the mass flow rate of diesel in kg/h; H_d is the calorific value of diesel in kJ/kg; m_{pg} is the mass flow rate of producer gas in kg/h; H_{pg} is the calorific value of producer gas in kJ/kg.

The use of producer gas with diesel reduced the consumption of diesel fuel. The percentage of diesel savings for experimentation is calculated using the given formula [43]

$$\%DS = \frac{m_{\text{diesel}} - m_{\text{dual}}}{m_{\text{diesel}}} \quad (9)$$

where m_{diesel} , m_{dual} are the diesel consumption rates in diesel only mode and dual fuel mode, respectively.

Table 6 Accuracies and uncertainties of the measurand measured in experimentation

Measurand	Accuracy (%)	Uncertainty (%)
Temperature, °C	± 5	± 0.5
Load kW	± 0.1	± 0.2
Engine speed, rpm	± 20	± 0.1
Time, sec	± 0.1	± 0.2
Manometer, mm	± 1	± 1
Flow meter, cc	± 0.1	± 1

2.2.2 Uncertainty Analysis

The error or uncertainty analysis in an experimental work quantifies the difference between measured and true value of a thermo physical quantity of a material. The uncertainty in the estimate of the true value provides a rational way of evaluating the significance of the scatter on repeated trials [44].

$$\Delta q = \sqrt{\left(\frac{\partial q}{\partial x_1} \cdot \Delta x_1\right)^2 + \left(\frac{\partial q}{\partial x_2} \cdot \Delta x_2\right)^2 + \left(\frac{\partial q}{\partial x_3} \cdot \Delta x_3\right)^2 + \dots} \tag{10}$$

$$q = \frac{\Delta q}{|q|} \times 100 \tag{11}$$

The Gaussian distribution was used to estimate the overall uncertainty of the experimentation by quantifying the observed quantities such as Temperature, load, engine speed, Time, manometer and flow meter from their respective uncertainties as given in Table 6. For the calculated parameters such as brake thermal efficiency, brake specific fuel consumption and brake specific energy consumption the overall uncertainty of ± 1.2% was observed which were assessed using Eqs. (10) and (11).

2.3 Theoretical Modelling

The dual fuel combustion technology uses two different fuels, a primary fuel and a secondary fuel. In this study, Producer gas the secondary fuel, is mixed with intake air, and this premixed mixture is introduced inside the engine cylinder. During the compression stroke, the temperature and pressure of the premixed mixture inside the engine cylinder increase. At the end of the compression a minor quantity of diesel (primary fuel) is injected in order to start the combustion. In the next process, auto ignition of the premixed mixture occurs as the attained temperature inside the cylinder is much higher than the self-ignition temperature of the premixed mixture. The dual fuel combustion of the premixed flame is a complex mechanism compared to the diesel combustion and almost

occurs in an uncontrolled manner due to the turbulence of the gaseous fuel and occurs for a longer period contributing to most of the energy input. The final process is the expansion process wherein the combusted mass is exhausted out of the engine cylinder. The processes taking place in dual fuel diesel engine are in relevance with dual cycle which is shown Fig. 3 has been considered for modelling. A novel Finite Time Thermodynamics (FTT) model for diesel engines running on diesel-producer gas combination has been made in this analysis [45] and numerically computed using MATLAB software.

In dual fuel mode the main parameter is diesel replacement which primarily depends upon the compression ratio, heating value of fuel, load percentage, and the capacity of the engine. From the conduct of experiments and reviewing the past literatures [46], an equation has been developed using multivariable regression analysis to calculate the percentage of diesel saving.

$$\%DS = ((X_1 \times CR) - (X_2 \times CV) - (X_3 \times L) - X_4) \times E \tag{12}$$

where X_1 , X_2 , X_3 , and X_4 are the regression coefficients obtained by multivariable regression and their values of X_1 ranges from 1.6 to 1.8, X_2 from 0.85 to 1.15, X_3 from 0.01 to 0.029, and X_4 from 10.22 to 25.26 respectively.

The effective efficiency (η_{ef}) and effective power (P_{ef}) of the dual fuel cycle is given by

$$\eta_{ef} = \frac{P_{ef}}{Q_f} \tag{13}$$

where Q_f is the total heat potential of the fuel in kJ/kg.

$$P_{ef} = Q_{in} - Q_{out} \tag{14}$$

where Q_{in} is the total heat added during constant volume heat addition (Q_{in1}) process (process 2–3) and constant pressure heat addition (Q_{in2}) process (process 3–4) and is given by

$$Q_{in} = Q_{in1} + Q_{in2} = m_t \left[\int_{T_2}^{T_3} C_v dT + \int_{T_3}^{T_4} C_p dT \right] \tag{15}$$

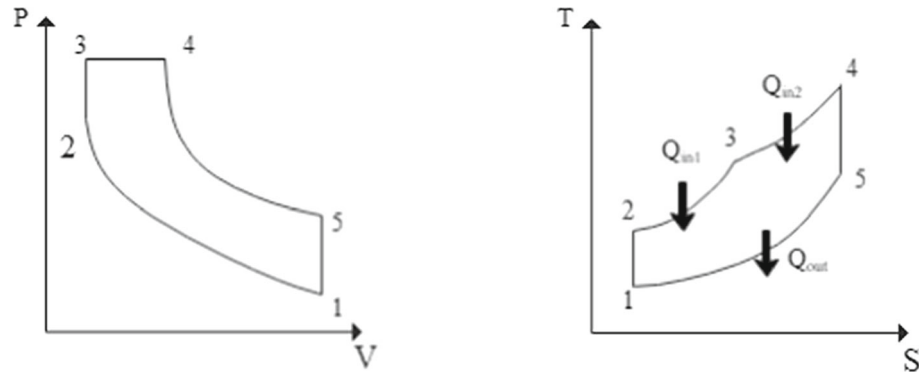
The total heat rejection from the cycle Q_{out} is given by

$$Q_{out} = m_t \left[\int_{T_1}^{T_5} C_v dT \right] \tag{16}$$

where m_t is the total mass flow rate of fuel and air entering into the engine cylinder in kg/s and is given by

$$m_t = m_a + m_f \tag{17}$$

Fig. 3 Thermodynamic cycle (P–V and T–S) of dual fuel engine



where m_a is the mass flow rate of air and m_f is the mass flow rate of fuel and is given by

$$m_f = m_d + m_{pg} \quad (18)$$

where m_d and m_{pg} are the mass flow rates of diesel and producer gas, respectively.

In most cycle models, the working fluid is assumed to behave as an ideal gas with constant specific heats. The specific heats at constant volume C_v and pressure C_p can be expressed as a function of Temperature as given as follows [47]:

$$\begin{aligned} C_p = & 2.506 \cdot 10^{-11} T^2 + 1.454 \cdot 10^{-7} T^{1.5} \\ & - 4.246 \cdot 10^{-7} T + 3.162 \cdot 10^{-5} T^{0.5} \\ & + 1.3301 - 1.512 \cdot 10^4 T^{-1.5} \\ & + 3.063 \cdot 10^5 T^{-2} - 2.21 \cdot 10^7 T^{-3} \end{aligned} \quad (19)$$

$$\begin{aligned} C_v = & 2.506 \cdot 10^{-11} T^2 + 1.454 \cdot 10^{-7} T^{1.5} \\ & - 4.246 \cdot 10^{-7} T + 3.162 \cdot 10^{-5} T^{0.5} \\ & + 1.0433 - 1.512 \cdot 10^4 T^{-1.5} \\ & + 3.063 \cdot 10^5 T^{-2} - 2.21 \cdot 10^7 T^{-3} \end{aligned} \quad (20)$$

Total heat potential of the fuel (Q_f) is the amount of heat released during the combustion of the fuel and is expressed as

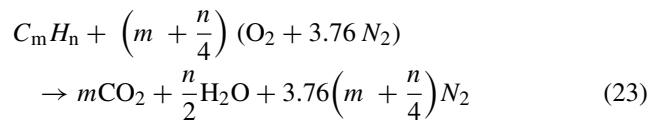
$$Q_f = m_d \times H_d + m_{pg} \times H_{pg} \quad (21)$$

where H_d and H_{pg} are the calorific values of diesel KJ/kg and producer gas KJ/Nm³, respectively.

The diesel saving of a dual fuel engine is calculated by variation in air fuel ratio of the fuel mixture. The equivalence ratio is given by

$$\Phi = \frac{m_f/m_a}{F_{st}} \quad (22)$$

where F_{st} is the stoichiometric air fuel ratio and is calculated using Eq. (23) [48]. By balancing the equation, the stoichiometric fuel air ratios for producer gas derived from rice husk, coconut shell and rubber shell was found as 1.26, 1.57 and 1.69, respectively.



The engine is assumed to run on constant speed mode at 1500 rpm, and the governing system was used to control the required power output. On only diesel mode of operation, generally, the amount of air drawn by the engine was in excess of stoichiometric requirement. When producer gas was introduced into the system, the amount of air drawn by the engine eventually decreased. Hence air–fuel ratio was reduced. The methodology for modelling study for a dual cycle powered diesel producer gas engine using Finite Time Thermodynamics is as shown in Fig. 4.

3 Results and Discussion

The performance of a 5 HP (3.75 kW) diesel engine was assessed using both the diesel and dual fuel mode. A 150 kW_{th} capacity downdraft gasifier was employed to generate producer gas for executing the engine performance trials in dual fuel mode. Three agro-residues, namely as rice husk, coconut shell, and rubber shell were utilised to evaluate the performance of the biomass gasifier operated dual fuel engine. Experiments were carried out with different brake power (0.5–3.75 kW) and compression ratios (12–18) in both diesel and dual fuel modes on the combustion of three chosen agro-residues and the results are presented below in detail.

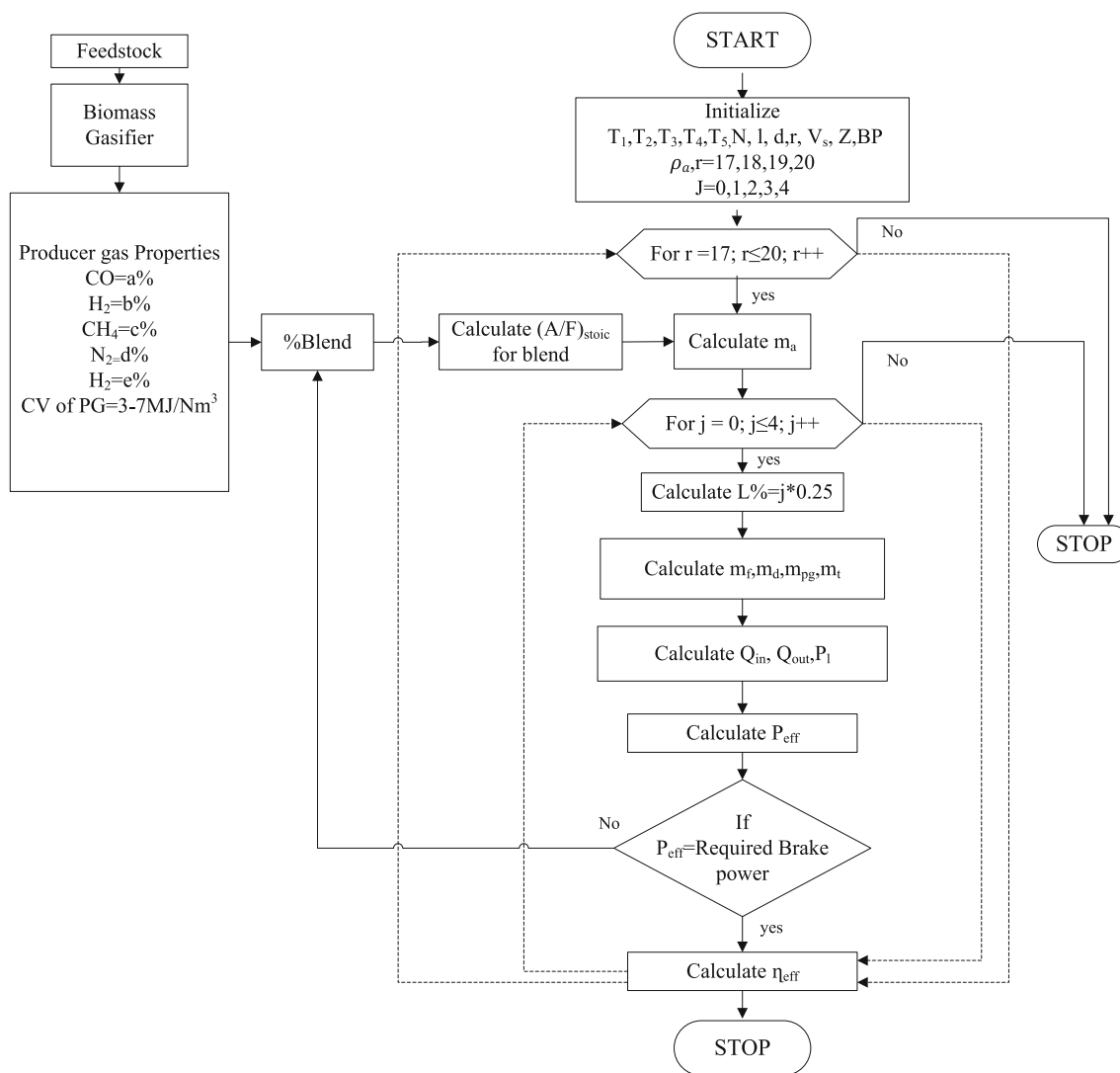


Fig. 4 Flow chart showing Finite Time Thermodynamic Modelling for a dual fuel engine

3.1 Effect on Brake Thermal Efficiency (BTE) with the Engine Load and CR

The variation of brake thermal efficiency of the engine operated with diesel only mode and dual fuel (diesel-producer gas) modes with respect to engine loads and various CR for the selected feedstocks are as shown in Figs. 5 and 6. It shows that the brake thermal efficiency increases with increase in engine load. A similar trend has been observed in the previous studies also [49]. It is found that the maximum brake thermal efficiency of diesel only mode was 24.28% at the engine load of 3.44 kW. Dual-fuel engines are always less efficient than the stand alone diesel fuelled engines. Because of the lower combustion rate caused by the low calorific value of producer gas, poor efficiency is observed at lower loads of dual fuel operation. Diesel also causes poor ignition and combustion of the lean air-gas mixture at these low loads. As a result, a

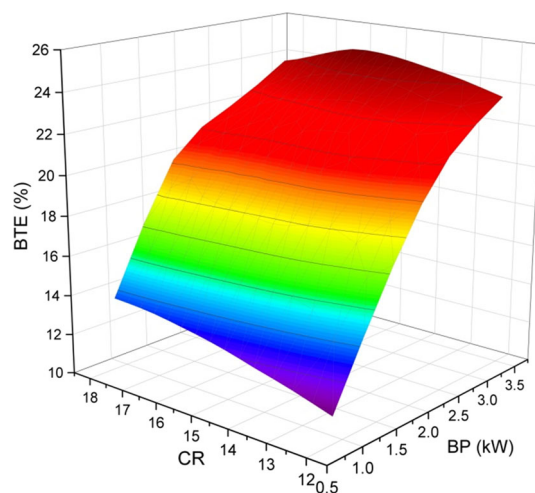


Fig. 5 Variations of BTE with CR and BP in diesel only mode

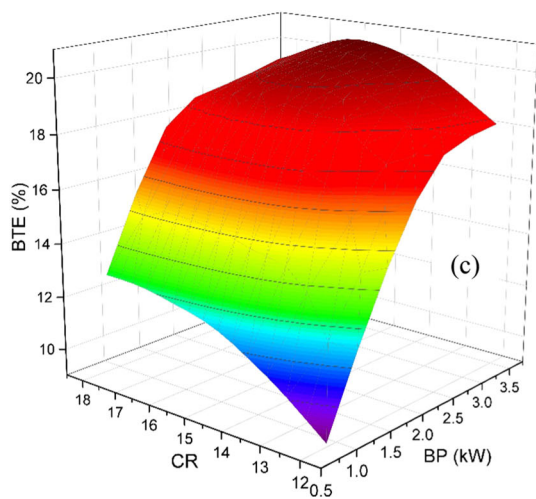
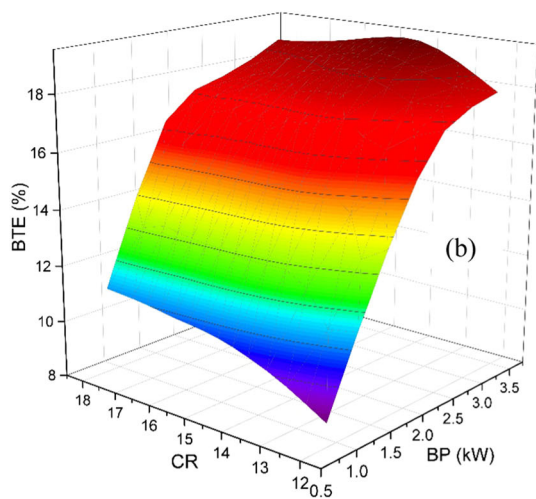
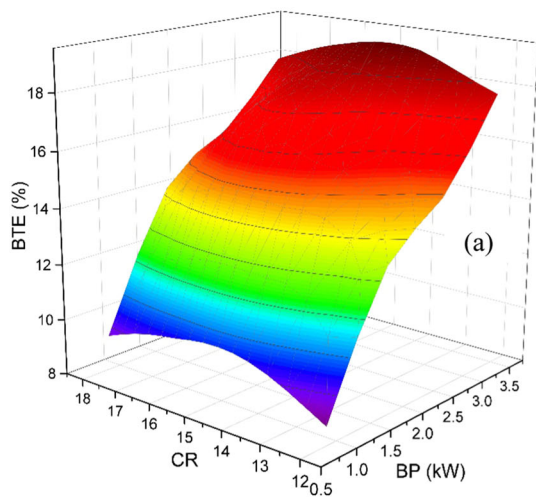


Fig. 6 Variations of BTE with CR and BP in dual fuel (diesel-producer gas) mode as **a** rice husk **b** coconut shell **c** rubber shell as a feedstock

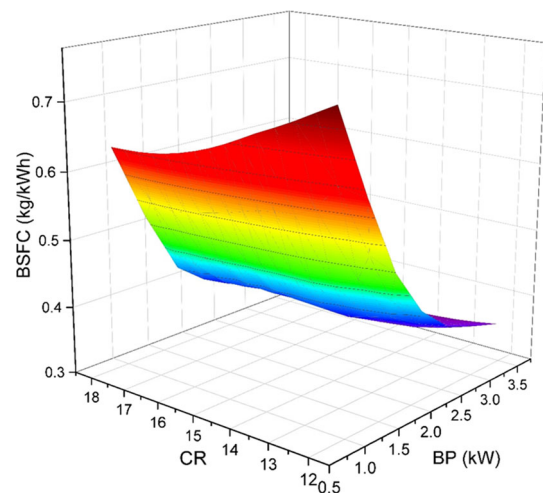


Fig. 7 Variations of BSFC with CR and BP in diesel only mode

small effect of producer gas on part-load efficiency has been detected. However, beyond 40% load, the brake thermal efficiency of dual fuel operation is improved. This is due to the greater amount of premixing of the fuel producer gas combination and the quicker combustion rate of the producer gas. The thermal efficiency of a diesel-fuelled engine is higher because more diesel implies more energy released, resulting in higher thermal efficiency. The efficiency of the engine improves as the calorific value of the producer gas rises. It is also observed that the BTE of rice husk was 19.13% at CR 16 and 3.44 kW load. Similarly, at CR14 and 3.44 kW, the BTE of 19.44% was recorded for coconut shell. Rubber shell had the highest BTE of 19.80% at CR16 and 2.56 kW. Based on the trends, Rubber shell feed stock has a highest BTE than other feed stocks because the calorific value of producer gas is greater.

3.2 Effect on Brake Specific Fuel Consumption (BSFC) with the Engine Load and CR

The BSFC value is a measure of efficiency of the fuel and it indicates how efficiently the engine converts supplied fuel into useful work. The variation of brake specific fuel consumption of the engine operated with diesel only mode and dual fuel (diesel-producer gas) modes with respect to engine loads and various CR for the selected feedstocks are as shown in Figs. 7 and 8. Equations (5) and (6) are used to compute brake specific fuel consumption in diesel and dual fuel modes. It is noticed that BSFC is lower at higher loads and increasing at lower loads. For all CR, the lowest BSFC (0.33 kg/kWh) is obtained at the maximum load (3.44 kW) and the highest BSFC (3.44 kW) is obtained at CR16 for diesel only mode. At CR12 and 3.44 kW, ricehusk had a minimum BSFC of 0.67 kg/kWh. Coconut shell yielded 0.66 kg/kWh at CR 12 and 3.44 kW, whereas rubber yielded

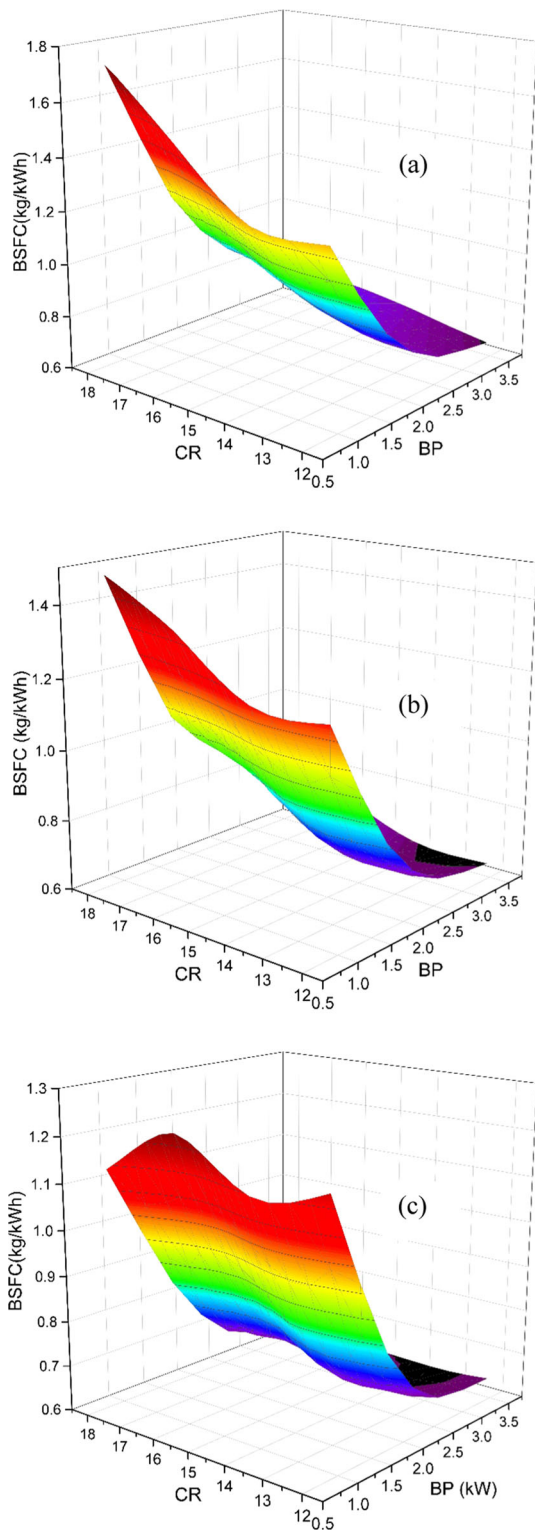


Fig. 8 Variations of BSFC with CR and BP in dual fuel (diesel-producer gas) mode as **a** rice husk **b** coconut shell **c** rubber shell as a feedstock

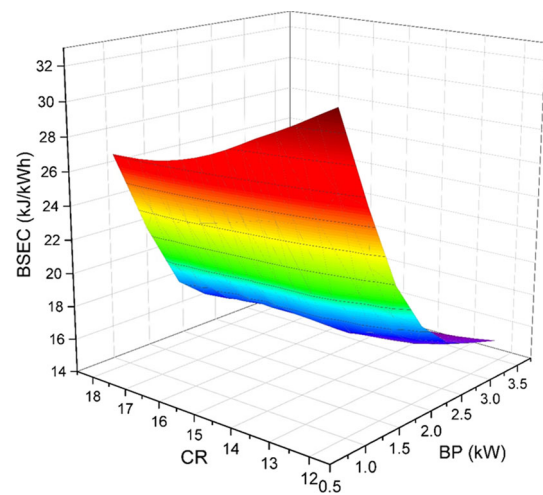


Fig. 9 Variations of BSEC with CR and BP in diesel only mode

0.64 kg/kWh at CR 18 and 3.44 kW. The findings revealed that the calorific value of producer gas from various feedstocks influenced the BSFC of the engine. This is because with higher loads, more fuel is injected into the cylinder, resulting in better combustion and effective usage of the fuel consumed. According to the results, rubber shell based producer gas had a lower BSFC on dual fuel mode than rice husk and coconut shell, indicating that rubber shell derived PG is efficiently utilised for producing the required power. The BSFC decreases when the calorific value of the fuel decreases, since a decrease in the calorific value of a fuel leads in an increase in the engine’s fuel consumption.

3.3 Effect on Brake Specific Energy Consumption (BSEC) with the Engine Load and CR

The variation of brake specific energy consumption of the engine operated with diesel only mode and dual fuel (diesel-producer gas) modes with respect to the engine loads and various CR for the selected feedstocks are as shown in Figs. 9 and 10. For diesel only mode and dual fuel (diesel-producer gas) modes, the BSEC shows an opposite trend to BTE. The lower the BTE gives the lower the BSEC. Equations (7) and (8) were used to determine the BSEC. The maximum BSEC of 32.12 kJ/kWh was recorded at 0.86 kW for diesel only mode, and as load increases, the BSEC declines to 15.44 kJ/kWh at 3.44 kW and CR 16. The lowest BSEC was 15.05 kJ/kWh for rice husk and 15.26 kJ/kWh for coconut shell at CR14 and 3.44 kW, respectively. At CR 18 and 2.56 kW, a lower BSEC of 12.19 kJ/kWh was recorded for rubber shell. Because the calorific value of the air gas mixture is lower at greater loads and the fuel consumption of producer gas is higher, the BSEC is lower. At lower loads, incomplete combustion predominates, resulting in a rise in the BSEC of the engine.

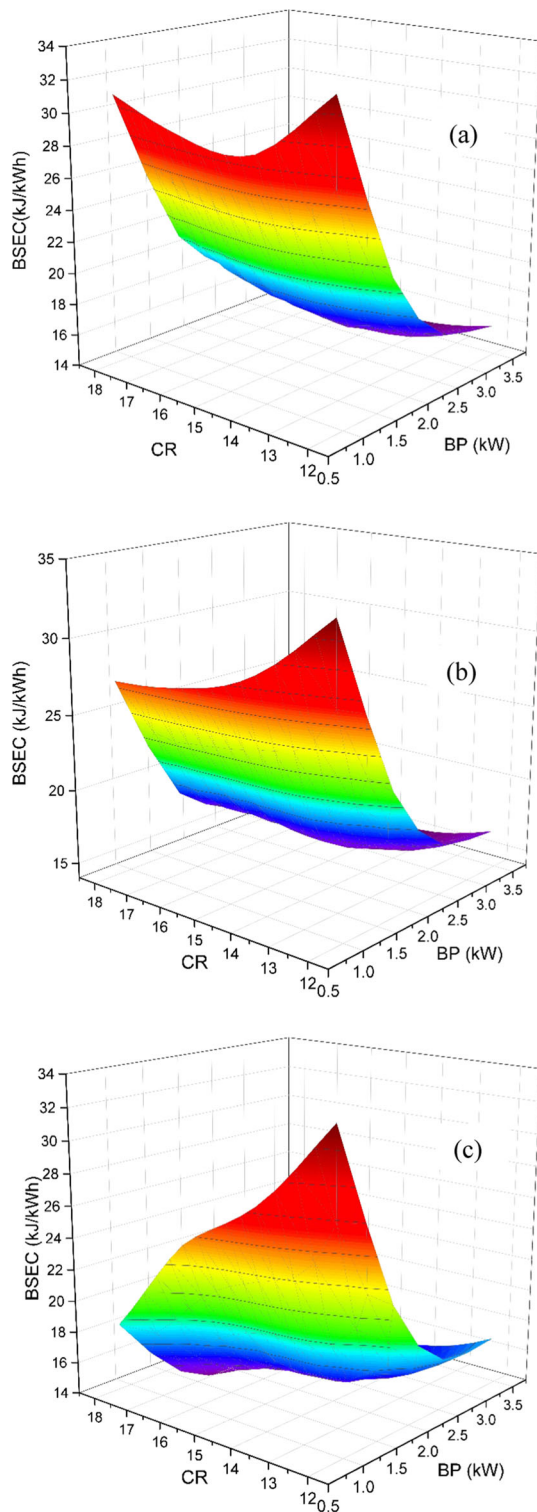


Fig. 10 Variations of BSEC with CR and BP in dual fuel (diesel-producer gas) mode as **a** rice husk **b** coconut shell **c** rubber shell as a feedstock

3.4 Variations of Biomass Consumption with the Engine Load and CR

Before a prototype can be developed for real-time applications, it is critical to calculate the biomass consumption rate for any biomass power producing system. As a result, the biomass consumption rate must be determined under various operating conditions. The efficiency of the gasifier system was chosen at 75% [50]. In this investigation, and the BM consumption rates for the rice husk, coconut shell and rubber shell feedstocks were calculated and represented as shown in Fig. 11. The figure showed that the BM consumption rate increased with load for all the feedstocks. For ricehusk biomass the BMC increases with increase in load and maximum biomass consumption of 4.56 kg/h is observed at 3.44 kW. This is because of the higher loads, more fuel is used to provide the required power, resulting in an increase in producer gas consumption. The BM consumption reduces as the CR ratio increases, and the lowest value of BMC is found at CR16 and 3.44 kW. The BMC grows upwards to 4.37 kW at CR 18. This rise in BMC usage to 4.37 kW shows that BMC is reliant on the engine's BTE. The BTE is slightly decreased at CR 18, resulting in an increase in BMC. The BSEC is greater for all feedstocks. Rubber shell and coconut shell both showed similar patterns. The BMC for rubber shell is 3.53 kg/h at CR18 and 3.44 kW, whereas the BMC for coconut shell is 3.80 kg/h. This is because as the CV of producer gas rises, the amount of fuel required to generate the required power drops.

A generalised equation for the optimal percentage of diesel savings has been derived from the data reduction of experimental readings using multivariable regression analysis, as shown in Eq. (12). Using this optimal value of diesel savings, the optimal solution of BTE, CR, and BP can be examined, and this value is used as blend (per cent of PG) for theoretical analysis. Table 7 shows the optimum values of percentage of diesel savings, brake thermal efficiency, CR and BP.

According to the experimental results, the maximum BTE for biomass generated from rice husk is 19.13% at CR16 and 3.44 kW, while the % of DS value is only 7%. At CR14 and 0.86 kW, the maximum % of DS is 11.6%, but the equivalent efficiency is 9.98%. At CR18 and 2.56 kW, an optimal value of BTE 17.91% and DS 11.2% is obtained. At CR14 and 3.44 kW, a maximum BTE of 19.44% is attained for coconut shell biomass, while the corresponding DS value is only 13%. At CR18 and 1.72 kW, the maximum diesel savings is 27.14%, while the efficiency is just 16.95%. At CR 18 and 2.56 kW, there is a 17.54% improvement in diesel savings. At CR16 and 2.56 kW, a maximum BTE of 19.80% is achieved from rubber shell-based biomass, while the corresponding DS value is only 38%. At CR18 and 0.86 kW, the maximum DS value is 58.18%, however the efficiency is

Table 7 Optimum values of diesel savings, brake thermal efficiency, CR and BP

Feedstock		BTE %	CR	BP kW	%DS
Rice husk	Max BTE	19.13	16	3.44	7
	Max DS	9.98	14	0.86	11.6
	Optimum	17.91	18	2.56	11.2
Coconut shell	Max BTE	19.44	14	3.44	13.3
	Max DS	16.95	18	1.72	27.14
	Optimum	17.54	18	2.56	24
Rubber shell	Max BTE	19.80	16	2.56	38
	Max DS	12.57	18	0.86	58.18
	Optimum	19.18	18	2.56	48

Table 8 Comparison of Experimental results with existing literature

Fuel source	Calorific Value of PG MJ/Nm ³	Engine Capacity kW	DS %	BTE %	BSFC kg/kWh	BSEC MJ/kWh	Reference
Diesel + Walnut shell	7.3	3.5	58.18	21.61	0.665	–	[46]
Diesel + Woodchips + corn cobs	4–6	3.5	44.44	27	0.24	–	[51]
Diesel + Coconut shell PG	6.6	3.5	80	22	1.59	17.89	[52]
Diesel + Rice husk PG	4.28	3.5	11	19.3	0.67	15.26	
Diesel + Coconut shell PG	6.61	3.5	28	19.44	0.66	15.05	Present study
Diesel + Rubber shell PG	7.3	3.5	46	19.8	0.64	12.19	

12.5%. The optimal value is found at CR18, load 2.56 kW, and DS 48%, with a BTE of 21.68%. It was observed that the % of DS increased with calorific value of producer gas and CR allowed in to the engine cylinder. This is due to the fact that when the CR is high, more fuel (Diesel and PG) is admitted into the engine cylinder. Diesel and producer gas must supply the same amount of heat to create the required amount of electricity. Since producer gas obtained from rubber shells has a higher calorific value than producer gas derived from other feedstocks, it has a higher diesel replacement rate.

From the experimental results obtained it is found that the optimum values are found at 2.56 kW, which is obtained at the contributions for 48% for rubber shell based PG, 24% Coconut shell based PG, 11.2% for Rice husk based PG and this is taken as optimum value for further calculations. The values obtained are in similar range to those found in previous literature and are presented in Table 8. The BTE is computed and shown for theoretical and experimental for this optimal load (2.56 kW) and blend conditions (48% for rubber shell based PG, 24% Coconut shell based PG, 11.2% for Rice husk based PG) as shown in Fig. 12. It is evident from the plot that the theoretical model is closely in relevance to the experimental data. Figure 12 shows that as the compression ratio is increased, the BTE progressively rises and finally decreases. The fall in BTE at greater CR is due to a reduction in engine cylinder capacity, which leads to incomplete combustion and

hence a reduction in efficiency. Also, due to incomplete combustion, the heat energy released by combustion is lower at greater loads, contributing to a drop in efficiency.

4 Conclusions

The experimental and theoretical performance parameters of a variable compression ratio (VCR) CI engine fuelled with a diesel-producer gas (PG) combination obtained from rice husk, coconut shell, and rubber shell gasification were investigated in this work. Both the diesel and dual fuel modes were used to evaluate the performance of a 5 HP (3.75 kW) diesel engine. To provide producer gas for the engine performance measurements in dual fuel mode, a downdraft gasifier with a capacity of 150 kW_{th} was used. Experimental results have been used to verify a novel theoretical model based on finite-time thermodynamics (FTT). Based on the performance of the VCR engine fuelled with a diesel-producer gas combination of three chosen agro-residues the following conclusions are drawn.

- The maximum brake thermal efficiency of the diesel only mode was observed to be 24.28% at 3.44 kW engine load, which is greater than the dual fuel engine since more diesel implies more energy released, resulting in higher thermal efficiency.



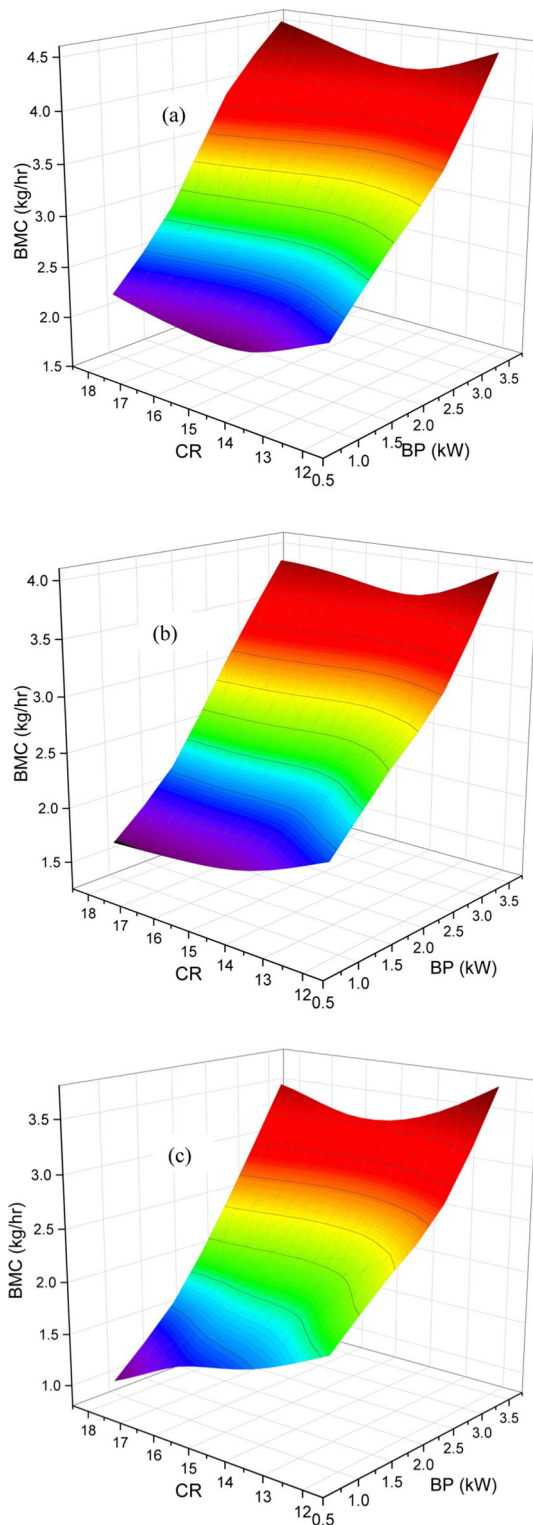


Fig. 11 Variations of BMC with CR and BP in dual fuel (diesel/producer gas) mode as **a** rice husk **b** coconut shell **c** rubber shell as a feedstock

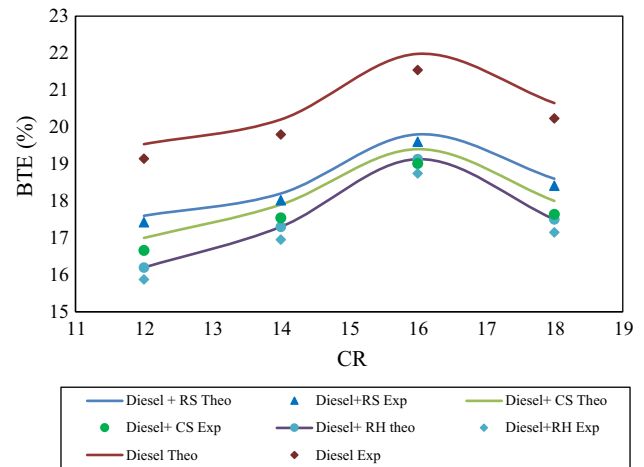


Fig. 12 Experimental and theoretical comparison of brake thermal efficiency with compression ratio

- The rubber shell-fueled dual fuel (DF) engine had the highest brake thermal efficiency of 19.80%, compared to 19.13% and 19.44% for rice husk and coconut shell-fueled DF engines, respectively. Since rubber shell has a higher calorific value than rice husk and coconut shell, which leads to the higher efficiency.
- The study found that the BSFC of the engine was influenced by the calorific value of producer gas from various biomass feedstocks. The experimental results revealed that the rubber shell-derived producer gas had a lower BSFC (0.64 kg/kWh) in dual fuel mode than rice husk (0.67 kg/kWh) and coconut shell (0.66 kg/kWh), this implying that rubber shell-derived PG is effectively used to provide the required energy.
- It is revealed that the rubber shell-derived producer gas had a lower BSEC of 12.19 kJ/kWh in dual fuel mode than rice husk and coconut shell as 15.05 kJ/kWh and 15.26 kJ/kWh respectively.
- Rubber shell has a BMC of 3.53 kg/h at CR18 and 3.44 kW, while coconut shell has a BMC of 3.80 kg/h and the rice husk has a BMC of 4.56 kg/h. This is because the amount of fuel required for generating the required power decreases as the heating value of producer gas rises.
- The optimum values are found at 2.56 kW of engine load, which is obtained at contributions of 48% for rubber shell based PG, 24% for Coconut shell based PG, and 11.2% for Rice husk based PG, according to the experimental results.
- In this work, experimental results have been used to validate a new theoretical model based on finite-time thermodynamics (FTT). It is evident that the theoretical model is closely relevance to the experimental data.
- It was concluded that the rubber shell derived producer gas fuelled dual fuel engine showed better BTE and diesel savings compared with the ricehusk and coconut shell based biomass fuel.

The findings from this research will be helpful for researchers and engine design engineers working in the field of biofuel powered dual fuel engines. The FTT model will help researchers to get reliable results for predicting the performance of the engine without doing experimentation on PG diesel-based dual fuel engines. As renewable biofuel technology is a promising area, this research has a lot of scope to be extended further by varying operating parameters like injection timing, using PG from a new source of biomass, pre-treating the biofuels, etc.

Author contribution AJP: Investigation, Data curation, Software, Methodology, Formal analysis, Validation. ME: Supervision, Investigation, Methodology, Resources, Conceptualization, Formal analysis, Writing—review and editing.

Funding The authors have no relevant financial or non-financial interests to disclose.

Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

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

References

- Malakar, Y.: Evaluating the role of rural electrification in expanding people's capabilities in India. *Energy Policy* **114**, 492–498 (2018). <https://doi.org/10.1016/j.enpol.2017.12.047>
- Ayaburi, J.; Bazilian, M.; Kincer, J.; Moss, T.: Measuring “Reasonably Reliable” access to electricity services. *Electr. J.* (2020). <https://doi.org/10.1016/j.tej.2020.106828>
- Schäfer, M.; Kebir, N.; Neumann, K.: Research needs for meeting the challenge of decentralized energy supply in developing countries. *Energy Sustain. Dev.* **15**, 324–329 (2011). <https://doi.org/10.1016/j.esd.2011.07.001>
- Edwin, M.; Nair, M.S.; Sekhar, S.J.: Techno-economic modeling of stand-alone and hybrid renewable energy systems for thermal applications in isolated areas. *Renew. Energy Syst. Model. Optim. Control.* (2021). <https://doi.org/10.1016/B978-0-12-820004-9.00013-9>
- Edwin, M.; Sekhar, S.J.: Thermal performance of milk chilling units in remote villages working with the combination of biomass, biogas and solar energies. *Energy* **91**, 842–851 (2015). <https://doi.org/10.1016/j.energy.2015.08.103>
- Das, S.; Kashyap, D.; Kalita, P.; Kulkarni, V.; Itaya, Y.: Clean gaseous fuel application in diesel engine: A sustainable option for rural electrification in India. *Renew. Sustain. Energy Rev.* (2020). <https://doi.org/10.1016/j.rser.2019.109485>
- Sikarwar, V.S.; Zhao, M.; Fennell, P.S.; Shah, N.; Anthony, E.J.: Progress in biofuel production from gasification. *Prog. Energy Combust. Sci.* **61**, 189–248 (2017). <https://doi.org/10.1016/j.pecs.2017.04.001>
- Jemila Percy, A.; Edwin, M.: Techno-economic studies on the variable compression ratio dual fuel diesel-producer gas CI engine utilizing different biomass feedstocks. *Environ. Progress Sustain. Energy* (2022). <https://doi.org/10.1002/ep.14024>
- Nabi, M.N.; Rahman, M.M.; Akhter, M.S.: Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions. *Appl. Therm. Eng.* **29**, 2265–2270 (2009). <https://doi.org/10.1016/j.applthermaleng.2008.11.009>
- Sridhar, G.; Sridhar, H.V.; Dasappa, S.; Paul, P.J.; Rajan, N.K.S.; Mukunda, H.S.: Development of producer gas engines. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **219**, 423–438 (2005). <https://doi.org/10.1243/095440705X6596>
- Mishra, S.; Upadhyay, R.K.: Review on biomass gasification: gasifiers, gasifying mediums, and operational parameters. *Mater. Sci. Energy Technol.* **4**, 329–340 (2021). <https://doi.org/10.1016/j.mset.2021.08.009>
- Jemila Percy, A.; Edwin, M.: Studies on the performance and emission characteristics of a dual fuel VCR engine using producer gas as secondary fuel: An optimization approach using response surface methodology. *Energy* **263**, 1265685 (2023). <https://doi.org/10.1016/j.energy.2022.125685>
- Banapurmath, N.R.; Tewari, P.G.; Hosmath, R.S.: Experimental investigations of a four-stroke single cylinder direct injection diesel engine operated on dual fuel mode with producer gas as inducted fuel and Honge oil and its methyl ester (HOME) as injected fuels. *Renew. Energy* **33**, 2007–2018 (2008). <https://doi.org/10.1016/j.renene.2007.11.017>
- Suryawanshi, S.J.; Shewale, V.C.; Thakare, R.S.; Yarasu, R.B.: Parametric study of different biomass feedstocks used for gasification process of gasifier—a literature review. *Biomass Convers. Biorefinery* (2021). <https://doi.org/10.1007/s13399-021-01805-2>
- Lal, S.; Mohapatra, S.K.: The effect of compression ratio on the performance and emission characteristics of a dual fuel diesel engine using biomass derived producer gas. *Appl. Therm. Eng.* **119**, 63–72 (2017). <https://doi.org/10.1016/j.applthermaleng.2017.03.038>
- Afzal, A.; Soudagar, M.E.M.; Belhocine, A.; Kareemullah, M.; Hossain, N.; Alshahrani, S.; Saleel, C.A.; Subbiah, R.; Qureshi, F.; Mujtaba, M.A.: Thermal performance of compression ignition engine using high content biodiesels: a comparative study with diesel fuel. *Sustain* **13**, 7688 (2021). <https://doi.org/10.3390/SU13147688>
- Edwin, M.; Nair, M.S.; Joseph Sekhar, S.: A comprehensive review for power production and economic feasibility on hybrid energy systems for remote communities. *Int. J. Ambient Energy* **43**, 1456–1468 (2022). <https://doi.org/10.1080/01430750.2020.1712252>
- Ruiz, J.A.; Juárez, M.C.; Morales, M.P.; Muñoz, P.; Mendivil, M.A.: Biomass gasification for electricity generation: review of current technology barriers. *Renew. Sustain. Energy Rev.* **18**, 174–183 (2013). <https://doi.org/10.1016/j.rser.2012.10.021>
- Tarabet, L.; Loubar, K.; Lounici, M.S.; Khiari, K.; Belmrabet, T.; Tazerout, M.: Experimental investigation of di diesel engine operating with eucalyptus biodiesel/natural gas under dual fuel mode. *Fuel* **133**, 129–138 (2014). <https://doi.org/10.1016/j.fuel.2014.05.008>
- Thangaiyan, A.K.; Mohamed Ibrahim, M.M.: Production of producer gas and its use as the supplementary fuel for SI engine. *Biomass Convers. Biorefinery* (2021). <https://doi.org/10.1007/s13399-021-01542-6>
- Ramadhass, A.S.; Jayaraj, S.; Muraleedharan, C.: Power generation using coir-pith and wood derived producer gas in diesel engines. *Fuel Process. Technol.* **87**, 849–853 (2006). <https://doi.org/10.1016/J.FUPROC.2005.06.003>
- Bhattacharya, S.C.; Hla, S.S.; Pham, H.-L.: A study on a multi-stage hybrid gasifier-engine system. *Biomass Bioenergy* **21**(6), 445–460 (2001)
- BenoWincy, W.; Edwin, M.; Joseph Sekhar, S.: Optimization of process parameters to implement biomass gasifier for drying high



- moisture paddy in reversible flatbed dryer. *Energy* **249**, 123771 (2022). <https://doi.org/10.1016/j.energy.2022.123771>
24. Singh, R.N.; Singh, S.P.; Pathak, B.S.: Extent of replacement of methyl ester of rice bran oil by producer gas in CI engine. *Int. J. Energy Res.* **31**, 1545–1555 (2007). <https://doi.org/10.1002/er.1311>
 25. Singh, R.N.; Singh, S.P.; Pathak, B.S.: Investigations on operation of CI engine using producer gas and rice bran oil in mixed fuel mode. *Renew. Energy.* **32**, 1565–1580 (2007). <https://doi.org/10.1016/j.renene.2006.06.013>
 26. Malik, A.; Mohapatra, S.K.: Power generation using cotton stalk-derived producer gas in diesel engines. *Energy Sources Part A Recovery Util. Environ. Eff.* **38**, 2816–2822 (2016). <https://doi.org/10.1080/15567036.2015.1111957>
 27. Patra, T.K.; Sheth, P.N.: Biomass gasification models for downdraft gasifier: a state-of-the-art review. *Renew. Sustain. Energy Rev.* **50**, 583–593 (2015). <https://doi.org/10.1016/j.rser.2015.05.012>
 28. De Robbio, R.; Cameretti, M.C.; Tuccillo, R.: Ignition and combustion modelling in a dual fuel diesel engine. *Propuls. Power Res.* **9**, 116–131 (2020). <https://doi.org/10.1016/j.jprr.2020.02.001>
 29. Valera, H.; Kumar, D.; Singh, A.P.; Agarwal, A.K.: Modelling aspects for adaptation of alternative fuels in IC engines. *Energy Environ. Sustain.* (2020). https://doi.org/10.1007/978-981-15-0335-1_2
 30. Ge, Y.; Chen, L.; Sun, F.; Wu, C.: Thermodynamic simulation of performance of an Otto cycle with heat transfer and variable specific heats of working fluid. *Int. J. Therm. Sci.* **44**, 506–511 (2005). <https://doi.org/10.1016/j.ijthermalsci.2004.10.001>
 31. Ge, Y.; Chen, L.; Sun, F.: Finite-time thermodynamic modeling and analysis for an irreversible Dual cycle. *Math. Comput. Model.* **50**, 101–108 (2009). <https://doi.org/10.1016/j.mcm.2009.04.009>
 32. Chrisben Sam, S.; Gurugnanam, B.: End point rate analysis and estimation along the southwest coast of Kanyakumari, Tamil Nadu, using geospatial techniques. *Int. J. Environ. Sci. Technol.* (2022). <https://doi.org/10.1007/S13762-022-04374-7>
 33. Sam, C.; Gurugnanam, B.: Coastal transgression and regression from 1980 to 2020 and shoreline forecasting for 2030 and 2040, using DSAS along the southern coastal tip of Peninsular India. *Geod. Geodyn.* **13**, 585–594 (2022). <https://doi.org/10.1016/J.GEOG.2022.04.004>
 34. Edwin, M.; Joseph Sekhar, S.: Techno-economic studies on hybrid energy based cooling system for milk preservation in isolated regions. *Energy Convers. Manag.* **86**, 1023–1030 (2014). <https://doi.org/10.1016/j.enconman.2014.06.075>
 35. Edwin, M.; Joseph Sekhar, S.: Thermo-economic assessment of hybrid renewable energy based cooling system for food preservation in hilly terrain. *Renew. Energy* **87**, 493–500 (2016). <https://doi.org/10.1016/j.renene.2015.10.056>
 36. Deep Singh, A.; Gajera, B.; Sarma, A.K.: Appraising the availability of biomass residues in India and their bioenergy potential. *Waste Manag.* **152**, 38–47 (2022). <https://doi.org/10.1016/J.WASMAN.2022.08.001>
 37. Shanmugapriya, E.V.; Samhitha, S.V.; Geetha, P.: A case study on the landuse pattern of Kanyakumari district using Gis. *IOSR J. Appl. Geol. Geophys.* **04**, 36–41 (2016). <https://doi.org/10.9790/0990-0404023641>
 38. Vignesh, K.S.; Anandakumar, I.; Ranjan, R.; Borah, D.: Flood vulnerability assessment using an integrated approach of multi-criteria decision-making model and geospatial techniques. *Model. Earth Syst. Environ.* **7**, 767–781 (2021). <https://doi.org/10.1007/s40808-020-00997-2>
 39. Mboumboue, E.; Njomo, D.: Biomass resources assessment and bioenergy generation for a clean and sustainable development in Cameroon. *Biomass Bioenergy* **118**, 16–23 (2018). <https://doi.org/10.1016/J.BIOMBIOE.2018.08.002>
 40. Ciria, P.; Barro, R.: *Biomass Resource Assessment*. Elsevier, Amsterdam (2016) <https://doi.org/10.1016/B978-1-78242-366-9.00003-4>
 41. Prabhu, A.V.; Avinash, A.; Brindhadevi, K.; Pugazhendhi, A.: Performance and emission evaluation of dual fuel CI engine using preheated biogas-air mixture. *Sci. Total Environ.* (2021). <https://doi.org/10.1016/j.scitotenv.2020.142389>
 42. Razmi-Ishak, M.; Abu-Bakar, A.R.; Belhocine, A.; Mohd-Taib, J.; Wan-Omar, W.Z.: Brake torque analysis of fully mechanical parking brake system: Theoretical and experimental approach. *Ing. Investig. Technol.* **19**, 37–49 (2018). <https://doi.org/10.22201/FL.25940732E.2018.19N1.004>
 43. Ramos Da Costa, Y.J.; Barbosa De Lima, A.G.; BezerraFilho, C.R.; De Araujo Lima, L.: Energetic and exergetic analyses of a dual-fuel diesel engine. *Renew. Sustain. Energy Rev.* **16**, 4651–4660 (2012). <https://doi.org/10.1016/j.rser.2012.04.013>
 44. Hiremath, S.S.; Khandal, S.V.; Banapurmath, N.R.; Math, V.B.; Gaitonde, V.N.: Comparative analysis of performance of dual fuel (DF) and homogeneous charge compression ignition (HCCI) engines fuelled with honne oil methyl ester (HOME) and compressed natural gas (CNG). *Fuel* **196**, 134–143 (2017). <https://doi.org/10.1016/j.fuel.2017.01.089>
 45. Gonca, G.; Dobrucali, E.: Theoretical and experimental study on the performance of a diesel engine fueled with diesel-biodiesel blends. *Renew. Energy.* **93**, 658–666 (2016). <https://doi.org/10.1016/j.renene.2016.03.037>
 46. Sharma, M.; Kaushal, R.: Performance and emission analysis of a dual fuel variable compression ratio (VCR) CI engine utilizing producer gas derived from walnut shells. *Energy* (2020). <https://doi.org/10.1016/j.energy.2019.116725>
 47. Zhao, Y.; Chen, J.: Performance analysis of an irreversible Miller heat engine and its optimum criteria *Applied. Therm. Eng.* **27**, 2051–2058 (2007). <https://doi.org/10.1016/j.applthermaleng.2006.12.002>
 48. Vallero, D.A.: *Thermal reactions*. In: *Air Pollution Calculations*, pp. 207–218. Elsevier, Amsterdam (2019). <https://doi.org/10.1016/b978-0-12-814934-8.00009-0>
 49. Sharma, M.; Kaushal, R.: Performance and exhaust emission analysis of a variable compression ratio (VCR) dual fuel CI engine fuelled with producer gas generated from pistachio shells. *Fuel* (2021). <https://doi.org/10.1016/j.fuel.2020.118924>
 50. Leibbrandt, N.H.; Aboyade, A.O.; Knoetze, J.H.; Görgens, J.F.: Process efficiency of biofuel production via gasification and Fischer-Tropsch synthesis. *Fuel* **109**, 484–492 (2013). <https://doi.org/10.1016/j.fuel.2013.03.013>
 51. Singh, J.; Singh, S.; Mohapatra, S.K.: Production of syngas from agricultural residue as a renewable fuel and its sustainable use in dual-fuel compression ignition engine to investigate performance, emission, and noise characteristics. *Energy Sources Part A Recover. Util. Environ. Eff.* **42**, 41–55 (2020). <https://doi.org/10.1080/15567036.2019.1587053>
 52. Prasad, G.A.; Murugan, P.C.; Wincy, W.B.; Sekhar, S.J.: Response surface methodology to predict the performance and emission characteristics of gas-diesel engine working on producer gases of non-uniform calorific values. *Energy* (2021). <https://doi.org/10.1016/J.ENERGY.2021.121225>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.