Comparative effect of biogas and biodiesel on performance and emission of diesel engine: a review

Sanjay D. Mali

Gujarat Technological University,
Gujarat, India
and
Mechanical Engineering Department GEC,
Gandhinagar, India
Email: malisanjay28@gmail.com

Pinkesh R. Shah

Mechanical Engineering Department GP,
Ahmedabad, India
Email: pinkeshrshah@gmail.com

Divyang R. Shah

Mechanical Engineering Department GEC,
Dahod, India
Email: drshah27872@gmail.com

Dinesh D. Mevada*

Mechanical Engineering Department GEC,
Gandhinagar, India
Email: dinesh.mevada@gecg28.ac.in
*Corresponding author

Abstract: The rate of usage of fossil fuels is a major problem that must be addressed in terms of future views on global overall energy demand due to its finite nature and environmental issues. Numerous experiments were conducted to investigate the performance and emissions of an IC engine running on alternative fuel often with additives, and compare with performance of conventional fuel. The results of the investigation show that using alternatives fuel improves brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) while simultaneously increasing pollutant concentrations. As an alternative fuel, biodiesel and biogas appear to be a credible alternative candidate for conventional fuel. In this review article comparison of conventional fuel with combined use of biodiesel and biogas has been carried out. Effect on various performance parameters like BTE, BSFC and emission parameter carbon monoxide, carbon dioxide and nitrogen oxide has been compared with conventional fuel. In comparison to diesel, mixing 20% biodiesel with biogas produces the best results without modifying the engine, while also having a good impact on pollutants.

Keywords: compression ignition engine; CIE; biodiesel; biogas; compressed natural gas; CNG.

Reference to this paper should be made as follows: Mali, S.D., Shah, P.R., Shah, D.R. and Mevada, D.D. (2023) 'Comparative effect of biogas and biodiesel on performance and emission of diesel engine: a review', *Int. J. Design Engineering*, Vol. 12, No. 1, pp.69–85.

Biographical notes: Sanjay D. Mali is currently a research scholar in Gujarat Technological University Ahmedabad, Gujarat and also working as an Assistant Professor in Government Engineering College, Gandhinagar, Gujarat, India. He has total teaching experience of more than eight years. His subjects of interests are power plant engineering, basic of mechanical engineering, thermodynamics, etc.

Pinkesh R. Shah is currently working as a Lecturer in Government Polytechnic, Kheda, Gujarat, India. He has total teaching experience of more than 20 years. His subjects of interests are fluid mechanics, thermal engineering, etc.

Divyang R. Shah is currently working as an Associate Professor in Government Engineering College, Dahod Gujarat, India. He has total teaching experience of more than 25 years. He has subject of interest are in field of thermal, energy, fluid mechanics, power plant, etc.

Dinesh D. Mevada is currently working as an Assistant Professor in Government Engineering College, Gandhinagar, Gujarat, India. He has total teaching experience of more than ten years. He has publishes more than 11 papers in different international journal like Scopus, WOS, UGC care, etc.

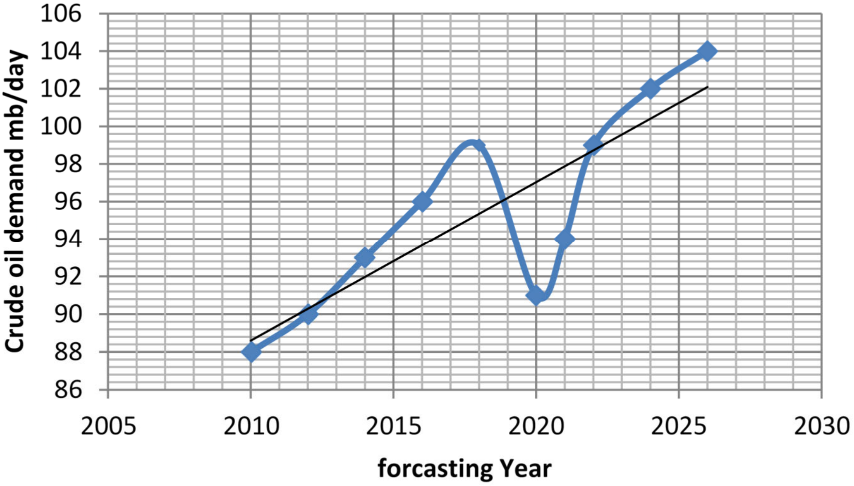
1 Introduction

The exhaustion of old energy sources and greenhouse gas emissions are two major challenges that dominate the first two decades of the contemporary epoch. The world has paid a high price for the fuel crisis in terms of human lives, the economy, and world peace. The second most significant source of global health hazards is emissions. Coal and oil are well known for being unsustainable owing to diminishing availability and for contributing to pollution. Global energy demand is increasing at a pace of two percentages per year, according to a report by the International Energy Agency (IEA), resulting in a catastrophic energy catastrophe. The US Energy Information Administration (EIA) predicts a 50% increase in global energy use between 2018 and 2050 in its newly issued International Energy Outlook 2019 Reference scenario (IEA, 2021; Miglani, 2019; Government of India, 2021). In India, the transportation industry consumes 18% of the country's total energy. This equates to 94 million tons of energy comparable to oil (MTOE). If present energy consumption trends continue, India will require an estimated 200 MTOE of energy supply per year by 2030 to meet the needs of this sector. This demand is now met primarily by imported crude oil, making this industry subject to swings in global crude oil prices. In addition, the industry emits 142 million tons of CO_2 each year, with road transport accounting for 123 million tons of the total (Yusri et al., 2018). Due to growing industrialisation and modernisation of the world has resulted in a significant increase in demand for petroleum products. Economic expansion in developing countries has resulted in a huge increase in energy demand. India's energy demand is increasing at a 6.5% annual rate. Imports cover over 80% of the country's crude oil requirements. As a result, the country's energy security has become a key worry (Chen et al., 2019). The supply of petroleum-based fuels is scarce. Internal Combustion engines are the principal source of power generation for the human race. The power supplied by IC engines is used in a variety of industries, including transportation, locomotives, irrigation, construction, maritime, defense, and telecommunications. Researchers are looking at alternative fuels that are less polluting and perform comparably to present fuels due to the depletion of traditional energy supplies, increased demand for fossil fuels, and rising greenhouse gas emissions. Because of their efficiency, diesel engines that run on fossil fuels are frequently utilised as the principal instrument for power generation in most all development areas. To mitigate the burden on the environment, modern technology and research are aiming to reduce dependency on fossil fuel. Massive engines and power generators, on the other hand, are not yet ready to run on batteries since they require large batteries and power storage (Chen et al., 2019; Rosha et al., 2018; Bora and Saha, 2016b). Furthermore, because the transition from combustion to electric engines is still taking shape and maturing, any premature transition to electric vehicles will have serious ramifications for the sustainability basis, i.e. social, economic, and ecological stability. As a result, the public and private sectors have decided to use CI engines that run on a blend of B10 biodiesel and B90 diesel in commercial vehicles. The majority of studies showed that a biodiesel/diesel blend of B20 could be used in a CI engine without any modifications (Bora and Saha, 2015, 2016a; Bora et al., 2014; Midhun Prasad and Murugavelh, 2020; Sundar and Udayakumar, 2020). Pure biodiesel as a fuel in a diesel engine is not suitable for engine, according to the literature review (Yusri et al., 2018; Chen et al., 2019; Rosha et al., 2018; Hegab et al., 2017). To greatly minimise diesel usage, any biodiesel with properties similar to diesel can be combined with another biodiesel. As a result, the amount of money required to import petroleum products will be reduced, which will promote the country's economic growth. There is a large concentration of finite reserves in certain places of the world, As a result, countries lacking these reserves have currency challenges, which are compounded by crude oil imports, Figure 1 show futuristic demand of crude oil in million barrels per day (Chen et al., 2019; Channappagoudra, 2020).

Due to COVID-19 in 2020-21 demand of oil decreasing but forecast graph predicts that it will increase at very rapidly (IEA, 2021). Figure 2 depicts segment-by-segment vehicle growth in percentage for India from 2012 to 2018, demonstrating how rapidly car demand is growing and impacting demand for fuel and vice versa. Petroleum consumption by these vehicles are one of the main cause of climate change and depleting resources of crude so, it is necessary to concentrate on saving environment as well as significant amount of natural available resources.

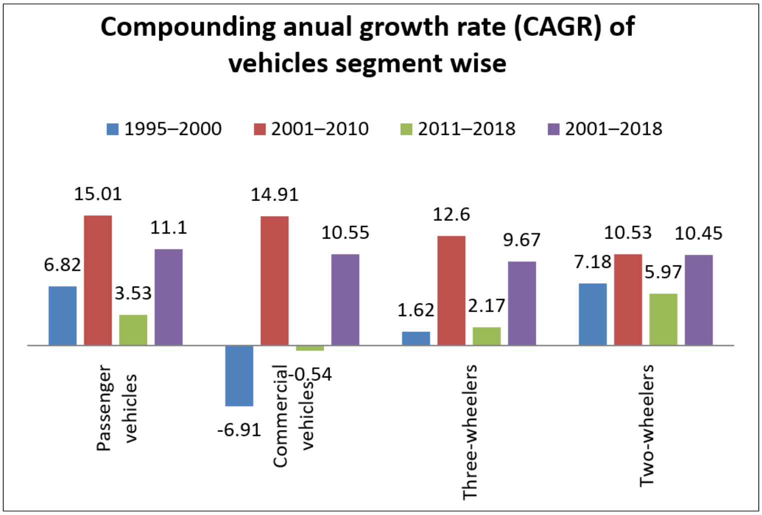
Researcher have put their effort on mainly to reduce pollution emitting by automobiles and exploring new bio diesel but still lot of opportunity remaining in the research field of biogas and blending of biogas and biodiesel. Biogas is made by breaking down organic matter in the absence of oxygen utilising bacteria to break down the components into intermediates like alcohols and fatty acids, which are then transformed to methane, carbon dioxide, and water (Niklesh Reddy et al., 2022; Patil et al., 2018; Rahman and Ramesh, 2019; Suresh et al., 2021). Biogas is a commonly accessible and efficient energy source that can be synthesised anaerobic environment from organic feedstock (Wang et al., 2019; Yaşar, 2020). Biogas has a huge potential in the next half century due to increased waste generation and the implementation of infrastructure to improve rubbish collection efficiency (Yaşar, 2020; Verma et al., 2017; Tutak et al., 2017). It has been observed by research that if any country move toward sustainable development its first step to look after automobile alternative fuels and for that they must think about blending of fuel like biodiesel blending or biogas blending.

Figure 1 Oil demand forecast, 2010–2026, pre-pandemic and in oil 2021 (see online version for colours)



Source: IEA (2021)

Figure 2 Segment-wise estimates CAGR of India up to 2018 (see online version for colours)



Source: Miglani (2019)

According to the research availability of various resources, biogas potential in next 30 year might range from Between 310 to 655 billion m3/year (IEA, 2021; Government of India, 2021). Government of India also focus on rural development and biogas have potential to achieve goal of being sustainable development tool for rural India. Government legislation and excellent findings from researcher trials have encouraged outlining their work (Das, 2020; Gopinath et al., 2020; Hosamani and Katti, 2018). The primary goals of this review paper are to analyse how different types of biodiesel and biogas affect IC engine performance, emission, and combustion characteristics. A secondary goal is to simplify the research process for new researchers by supplying the most recent cumulative survey in the area of alternative fuel for IC engines.

2 Biodiesel and biogas: as an alternative fuel

Biodiesel with Biogas is a far more efficient, long-lasting, and environmentally friendly fuel that works best in specifically designed IC engines that take use of its peculiar properties. Methane enrichment or hydrogen addition can be applied to enhance flame quality (Hegab et al., 2017; Lal and Mohapatra, 2017; Rahman and Ramesh, 2019). The use of such bio-fuels in blends with petroleum-based liquid fuels does not necessitate any major changes in supply and distribution infrastructure. The utility of diesel engines has expanded dramatically in recent decades, and biodiesel has been found as a viable alternative to conventional diesel. Tree base oils such as Jatropha, Karanja, cotton, palm, coconut, rapeseed, cotton, sunflower, soybean, peanut, and others are used to make biodiesel have great potential to supply stock of raw material for biodiesel (Kumar and Saluja, 2020). Various biodiesel and their fuel properties effect on performance and emission characteristics of engines. As India has variety of resources available for biodiesel and biogas those need to explore, some of them describe as Table 1.

From Table 1 Jatropha and Rice bran have great potential to supply feedstock of raw material for biodiesel also remaining feedstock can fulfil requirement of blend to diesel so significant amount of diesel can be saved. Besides Biodiesel and biogas combined used for diesel engine also gives satisfactory results on performance as well as emission (Yaşar, 2020). Biogas produces from live manure have lower amount of hydrogen sulphide and specifically cow dung have minimum amount of hydrogen sulphide so, possibility of damaging equipment minimised.

Raw biogas have lower amount of methane content 55% to 60% due to other incombustible matter like CO_2, SO_2, H_2S, these can be improved via various bio gas purification techniques like water scrubbing, adsorption (physical and chemical), cryogenic separation, membrane technology, biological upgrading and in-situ techniques (Yaşar, 2020; Lal and Mohapatra, 2017).

In order to comprehend the characteristics of combustion and anticipate the cylinder pressure, Aklouche et al. created predictive modelling of thermodynamic single zone of the engine in dual-fuel mode that runs with various gaseous fuel and biodiesel. A computer-controlled mixer was used to power a CI engine running in DF with two major gaseous fuels. A single-cylinder, air-cooled, 4-stroke, direct-injection engine with a fixed injection advance of pilot fuel at 13°CA before TDC is intended to run at varying speeds between 0 and 2,500 rpm and produce 4.5 kW at 1,500 rpm (Barik and Murugan, 2014).

Table 1 Different biodiesel and their thermo-chemical properties

Oils or fats	*Tire (C)*	*MIU (wt.%)*	*Density (Kg/m^3)*	*Kinematic viscosity at 40°C (mm^2/s)*	*Cetane no. (C)*	*High heating value (MJ/kg)*	*Flash point (C)*	*Saponification value*	*Iodine value*
Canola	-	0.85	911.5	34.72	37.6	39.7	246	189.8	-
Soyabean	22–27	0.77	913.8	28.87	37.9	39.6	254	195.3	128–143
Sunflower	16–20	0.65	916.1	35.84	37.1	39.6	274	193.14	125–140
Palm	42–45	0.03	918	44.79	42	267	208.63	48–58	
Peanut	26–32	-	902.6	39.6	41.8	39.8	271	191.5	84–100
Corn	14–21	1.67	909.5	30.75	37.6	39.5	277	183.06	103–128
Rice bran	24–28	2.73	918.5	36.68	56.3	-	-	201.27	90–108
Sesame	21–24	-	913.3	36	41.8	39.4	260	196.5	103–116
Cottonseed	32–38	-	914.8	33.5	-	39.4	234	198.5	103–115
Jatropha	31	0.16	940	33.9	34	38.65	225	200.8	82–98
Neem	35–36	2.16	918.5	50.3	-	-	-	209.66	65–80
Karnja	30–31	0.72	936.5	43.61	39	-	-	188.5	81–90
Mahua	23–31	960	24.5	-	36	232	190.5	58–70	-
Linseed	19–21	0.64	923.6	25.75	34.6	39.3	241	187.63	-
Coconut	20–24	2.74	918	27.26	-	-	-	267.56	7.5–10.5
Castor	3	0.41	955	251.2	42.3	37.4	-	191.08	83–86
Tabocco	16–18	-	917.5	27.7	-	-	-	191.5	125–154
beeftallow	-	0.84	-	45.34	-	-	-	198	-
Yellow grease	41	0.68	-	131.1	-	-	-	198.36	-

Source: Yaşar (2020)

Table 2 Different biogas feedstock and their biogas yield

Average maximum biogas production from difference feed stocks			
SI. no.	*Feed stock*	*Litre/kg of dry matter*	*% methane content*
1	Straw powder	930	46
	Maize straw	800	46
3	Poultry manure	440	65
4	Dry leaf	450	44
5	Sugar cane trash	750	45
6	Dung	350*	60

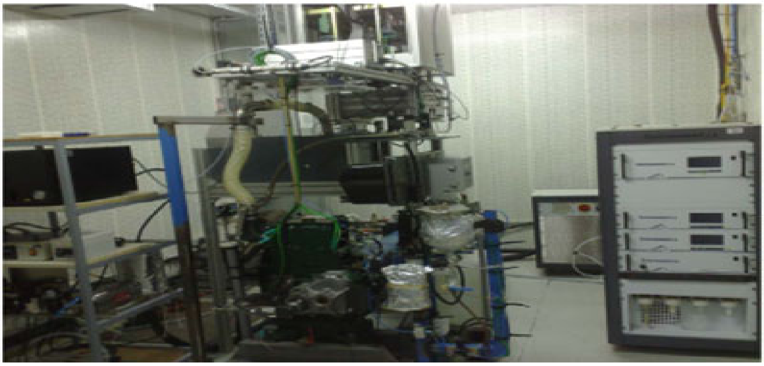
Source: Rosha et al. (2018) and Yaşar (2020)

Table 3 Different biogas and methane content

Combustible content of different gas	*MJ/kg*	*MJ/m^3*
Methane	50	35.9
Purified biogas	45	32.3
Raw biogas	30	21.5
Butane	45.7	118.5
Propane	46.4	90.9
Methanol	19.9	15.9
Ethanol	26.9	21.4

Source: Yaşar (2020) and Noel et al. (2016)

Figure 3 Experimental setup scheme (see online version for colours)

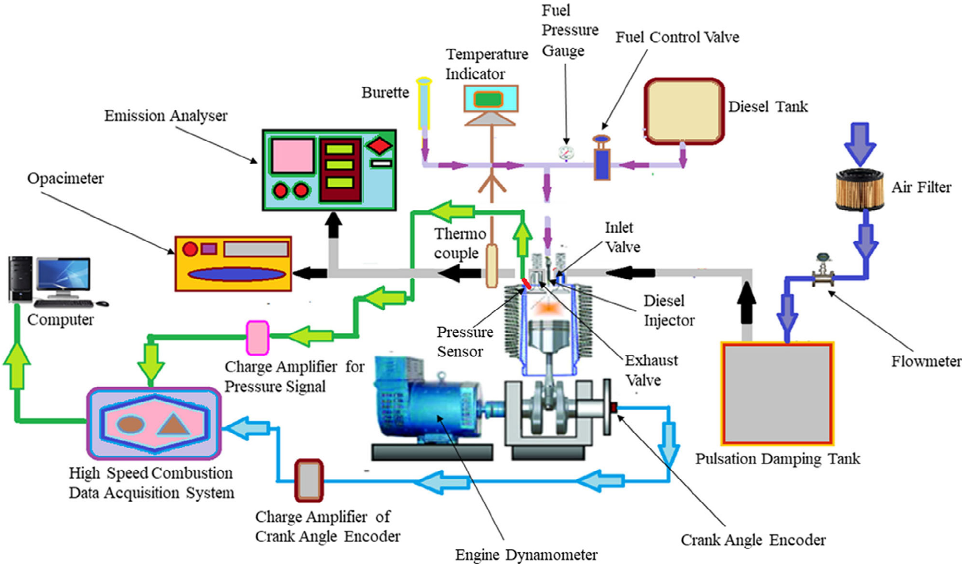


Source: Aklouche et al. (2018)

In order to conduct the studies, Ashok et al. created ‘Thermol-D’ additives and connected a single cylinder, four-stroke diesel engine to an eddy current dynamometer for loading.

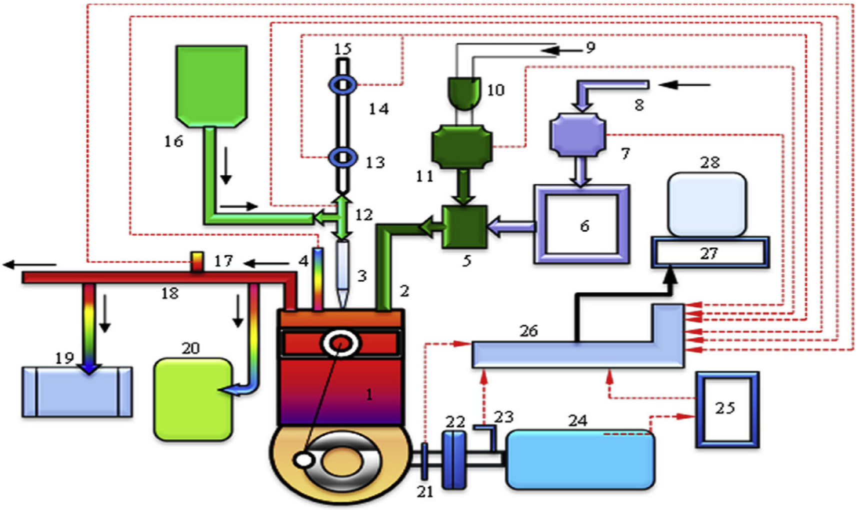
For testing performance and emission characteristics, Debabrata Barik et al. used a direct injection (DI) diesel engine with a rated output of 4.4 kW at 1,500 rpm and a compression ratio of 17.5:1. Engine parameters have been established with injection timing ranging from 21.5 CA bTDC to 27.5 CA bTDC in steps of 1.5 CA for various blends of bio diesel.

Figure 4 The experimental engine arrangement is shown schematically (see online version for colours)



Source: Ashok et al. (2020)

Figure 5 A diagram illustrating the experimental setup (see online version for colours)

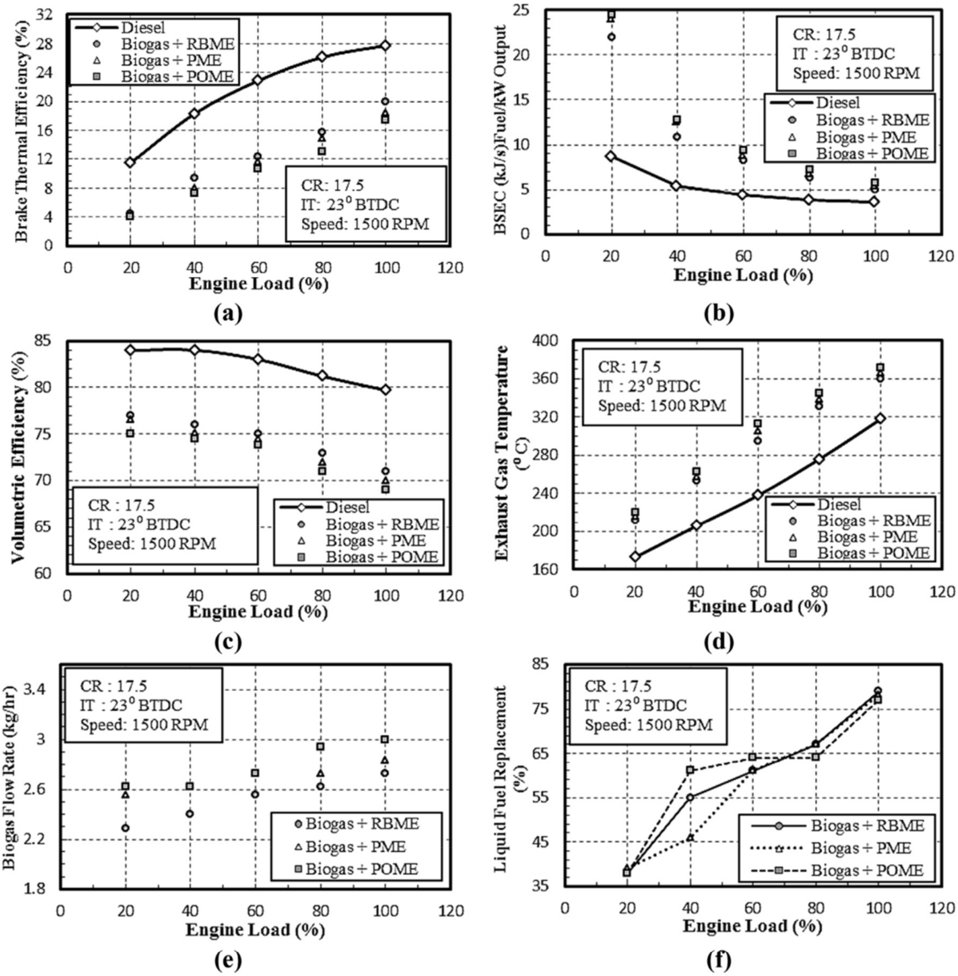


Notes: 1: engine; 2: intake manifold; 3: fuel injector; 4: pressure transducer; 5: biogas-air mixing kit; 6: air box; 7: air flow metre; 8: air intake; 9: biogas intake; 10: biogas filter; 11: biogas flow metre; 12: solenoid valve; 13: low fuel level optical sensor; 14: high fuel level optical sensor; 15: burette; 16: fuel tank; 17: Exhaust gas sensor; 18: exhaust manifold; 19: smoke metre; 20: exhaust gas analyser; 21: crank angle encoder; 22: coupling; 23: speed sensor; 24: dynamometer; 25: resistive load cell; 26: Control panel; 27: data acquisition system; 28: computer

Source: Barik et al. (2017)

Figure 6 point of the study was to see if biodiesel as rice bran oil methyl ester, Pongamia oil methyl ester, and palm oil methyl ester might be used as pilot fuel for a biogas-powered dual-fuel diesel engine. At 100% load, the findings of this pilot fuel research showed that rice bran methyl ester (RBME) biogas produced a maximum efficiency of 19.97%, compared to 18.4% and 17.4% for palm oil methyl ester (PME)-biogas and Pongamia oil methyl ester (POME)-biogas, respectively. The highest liquid fuel replacement for RBME-biogas, PME-biogas, and POME-biogas is found to be 79%, 78%, and 77%, respectively, for the identical loading situation and mode (Bora and Saha, 2015).

Figure 6 Biogas and biodiesel effect on engine performance



(a) (b)

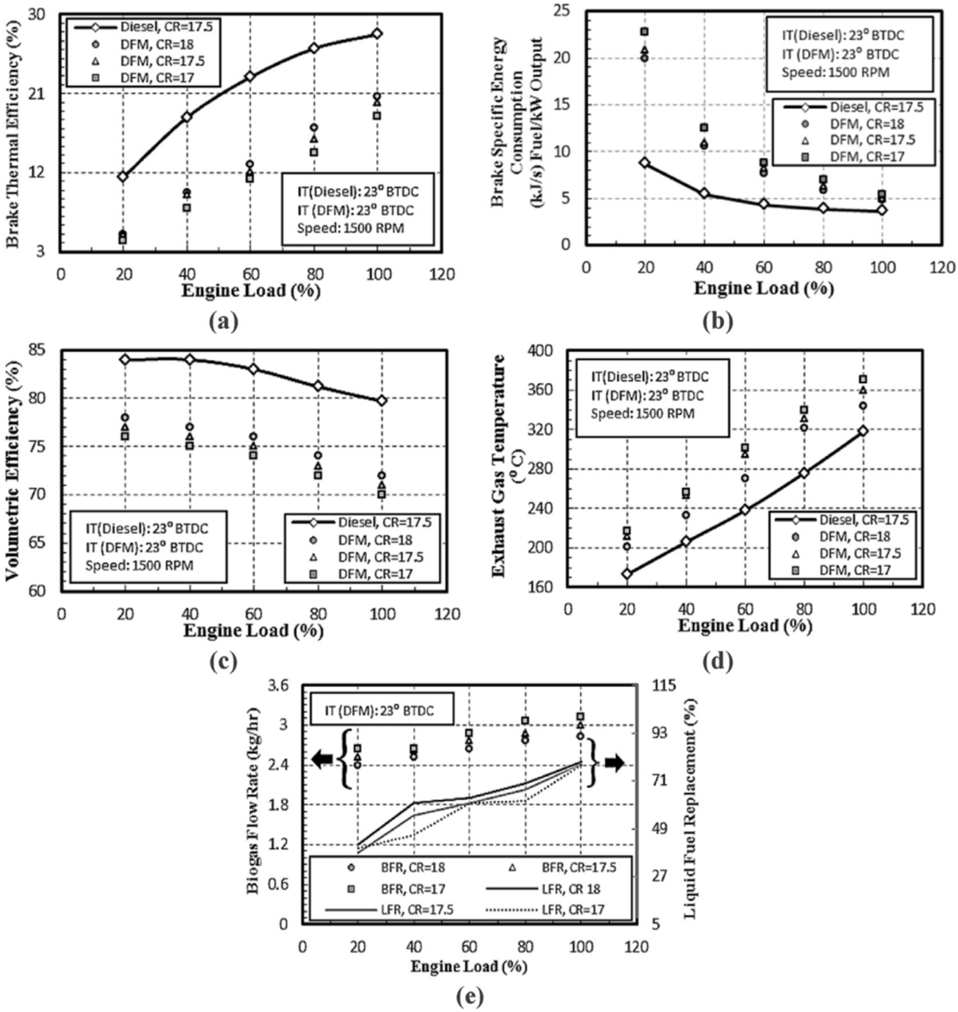
(c) (d)

(e) (f)

Source: Bora and Saha (2015)

Bhaskor J. Bora et al. have also investigated for RBME and raw biogas fuel with different compression ratio and check the effect on performance and emission characteristic of engine. The results of Figure 7 were carried out in a VCR diesel engine with a single cylinder, DI, NA, and water cooling. At a typical ignition timing (IT) of 23 BTDC, the CR was varied from 17 to 18. Under DFM, the brake thermal efficiencies (BTEs) were found to be 20.27%, 19.97%, and 18.39% at CRs of 18, 17.5, and 17, respectively, at 100% loading conditions, compared to 27.76% in diesel mode (Bora and Saha, 2015; Bora et al., 2014).

Figure 7 Biogas and biodiesel effect on engine performance



Source: Bora et al. (2014, 2016a)

The largest pilot fuel savings realised under the same loading scenario were 80%, 79%, and 78.26% with CRs of 18, 17.5, and 17, respectively. On average, the adjustment in compression ratio from 17 to 18 under DFM reduces CO and HC emissions by 17.67% and 17.18%, respectively. It has been found that effect of various changes in engine parameters while operating with biodiesel and biogas gives improved results in performance of engine as well as emission characteristics of engine. While Engine runs with biogas significant quantities of convention fuel saved without effect performance (Bora et al., 2014; Bora and Saha, 2016a). Mahua methyl ester has been tested by Anmol Singh Kshatriya et al. in a single-cylinder, four-stroke, CI engine that is built to run on dual fuel. Engine performance, emissions, and combustion parameters are assessed using Mahua biodiesel with biogas and compared to those that use only diesel fuel (Kshatriya et al., 2022). During the trial, it was noted that B20 performs better while raising BTH by up to 5% and simultaneously reducing CO_2 emissions (Kshatriya et al., 2022). The amount of pollution and liquid fuel use are reduced when biogas and biodiesel are blended. Focus is being placed on watching various particular matters with changing engine parameters and using various alternative fuels because compression ignition engines (CIEs) generate dangerous particular things that are very hazardous for the environment as well as human health (Rana et al., 2022). The morphology, nanostructure, and chemical composition of diesel particles are affected when alternative fuels are utilised, it is increasing the oxidative reactivity of PM. The physical and chemical features of PM were found to be simultaneously influenced by engine operating parameters (Rana et al., 2022). For a single cylinder, four-stroke 'CI engine' with a capacity of 2.2 kW at 1,500 rpm and built to run in dual fuel mode, the emission of pollution from diesel engines utilising biogas and biodiesel has been investigated and compared with base fuel. In comparison to diesel, it has been seen that this flow offers higher performance and lower emissions, with average increases in brake specific fuel consumption (BSFC), CO, and CO_2 of 11.81, 1.05, and 12.8%, respectively, and decreases in BTE, HC, and NOx (Leykun and Mekonen, 2022). The biogas energy contribution was 39.6% and 16.59%, respectively, with the diesel replacement ratio varying from 19.56 to 7.61% at zero engine load and 80% engine load (Leykun and Mekonen, 2022). Simmondsia chinensis oil that has been blended with B10, B20, and B30 has been tested on a single cylinder, four-stroke diesel engine at CR 18 and 25 bTDC (Subramanian et al., 2022). The comparison of experimental results with simulations using artificial neural networks shows that B30 provides the highest BTH while decreasing CO and HC emissions while increasing NOx emissions (Subramanian et al., 2022). To test the performance and emission characteristics of the VCR-DI CI engine, low density ethanol and diesel fuels were used. Trials for the experiment are run at four different CRs and for various engine loads. It was shown that all blend samples showed a considerable drop in BTE when the CR was raised from 15.5 to 18.5.All fuel mixes show significant fluctuations in smoke emission, with E0DF100 producing the maximum amount — 2.17 BSN (Bharat stage emission standards) — at CR 15.5, and E20DF80 producing the lowest amount — 1.2 BSN — at CR 18.5 (Dasore et al., 2022; Mevada et al., 2019, 2020, 2021; Panchal et al., 2020).

Table 4 Biogas and biodiesel mixture effect on engine performance and emission

Fuels	*Engine specification*	*Effects on engine performance*		*Effects on engine emission*				
		BTH	*BSFC*	*CO*	*CO_2*	*NO*	*HC*	*SMOKE*
Diesel with natural gas (NG) and bogas (Aklouche et al., 2018)	Single cylinder four stroke DI engine with 4.5 kW, 1,500 rpm	Positive	Negative	Negative	Negative	Positive	Negative	Positive
Thermol-D additive with diesel and calophyllumInophyllum biodiesel CI engine (Ashok et al., 2020)	Single cylinder four stroke diesel engine with 4.5k W, 1,500 rpm	Positive	Negative	Negative	Negative	Negative	Negative	Positive
Diesel with biogas dual fuel mode at 0.9kg/h gas flow rate (Barik and Murugan, 2014)	Single cylinder four stroke diesel engine with 4.4 kW, 1,500 rpm	Positive	Negative	Negative	Negative	Negative	Positive	-
Diesel with Karanja methyl ester-biogas dual fuel (Barik et al., 2017)	Single cylinder four stroke diesel engine with 4.5 kW, 1,500 rpm	Positive	Positive	Negative	Negative	Positive	Positive	Positive
Diesel with Rice-brain and biogas (Bora and Saha, 2016b)	Single cylinder four stroke diesel engine with 3.5 kW, 1,500 rpm	Positive	Negative	Negative	Negative	Positive	Negative	Negative
Diesel with hydrogen gas dual fuel mode (Castro et al., 2019)	Multi cylinder marine four stroke diesel engine with 58 kW, up to 4,500 rpm	Negative	Negative	Negative	Negative	Positive	Negative	Positive
Diesel and biodiesel with Hydrogen gas using GR (Chaichan, 2018)	Four cylinder four stroke diesel engine with 1,500 rpm	Negative	Negative	Negative	Negative	Positive	Negative	-
Diesel with CNG and biogas (Chandra et al., 2011)	Single cylinder four stroke diesel engine with 4.9 kW, 1,500 rpm	Negative	Positive	No effect	No effect	No effect	Negative	Positive
Diesel with diary scum biodiesel and biogas (Channappagoudra, 2020)	Single cylinder four stroke diesel engine with 3.5 kW, 1,500 rpm	Positive	Not counted	Negative	Negative	Negative	-	-
Diesel with diary scum biodiesel and biogas (Channappagoudra et al., 2020)	Single cylinder four stroke diesel engine with 3.5 kW, 1,500 rpm	Positive	Negative	Negative	Not counted	Positive	Negative	-
Diesel with nano particles-biodiesel (Ghanbari et al., 2017)	Six cylinder four stroke diesel engine with 82 kW, 2,300 rpm	Positive	Negative	Negative	Positive	Positive	Positive	Positive
Diesel with producer gas and Cooking oil and timber base biodiesel (Gopalakrishnan and Karthick, 2020)	Single cylinder four stroke diesel engine with 3.5 kW, 1,500 rpm	Positive	Negative	Negative	Not counted	Not counted	Positive	-
Diesel with lemon grass oil (LGO) and H2 gas (Hariharan et al., 2020)	Single cylinder four stroke diesel engine with 5 bph, 1,500 rpm	Positive	Negative	Negative	Negative	Positive	Positive	Positive
Diesel with Rice bran biodiesel and biogas (Bora and Saha, 2015, 2016; Bora et al., 2014)	Single cylinder four stroke diesel engine with 3.5 kW, 1,500 rpm	Positive	Negative	Positive	Negative	Negative	Positive	-

3 Conclusions

Many researchers have commented on ongoing research initiatives that concentrate on harnessing renewable resources to replace conventional fuels. The current review looks at how a CI engine can be utilised to power rural electrification using renewable fuels (biogas and Biodiesel). Some of the significant findings from the literature review are listed below.

- Blending of biogas significantly degrades the performance of the dual fuel CI engine but environmental emissions are reported to improve.
- In all load circumstances, increasing the fuel density improved the BSFC.
- When compared to diesel mode, incomplete combustion during DF operation resulted in higher HC and CO emissions.
- IC engine performance declined while NOx emission significantly decreased, and vice versa.
- The Ministry of Indian government is encouraging different projects that boost biomass and biodiesel power generation.

References

Aklouche, F.Z., Loubar, K., Bentebbiche, A., Awad, S. and Tazerout, M. (2018) 'Predictive model of the diesel engine operating in dual-fuel mode fuelled with different gaseous fuels', *Fuel*, May, Vol. 220, pp.599–606, doi: 10.1016/j.fuel.2018.02.053.

Ashok, B. et al. (2020) 'Multi-functional fuel additive as a combustion catalyst for diesel and biodiesel in CI engine characteristics', *Fuel*, October, Vol. 278, p.118250, doi: 10.1016/j.fuel.2020.118250.

Barik, D. and Murugan, S. (2014) 'Investigation on combustion performance and emission characteristics of a DI (direct injection) diesel engine fueled with biogas–diesel in dual fuel mode', *Energy*, August, Vol. 72, pp.760–771, doi: 10.1016/j.energy.2014.05.106.

Barik, D., Murugan, S., Sivaram, N.M., Baburaj, E. and Shanmuga Sundaram, P. (2017) 'Experimental investigation on the behavior of a direct injection diesel engine fueled with Karanja methyl ester-biogas dual fuel at different injection timings', *Energy*, January, Vol. 118, pp.127–138, doi: 10.1016/j.energy.2016.12.025.

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

Bora, B.J. and Saha, U.K. (2016a) 'Experimental evaluation of a rice bran biodiesel – biogas run dual fuel diesel engine at varying compression ratios', *Renewable Energy*, Vol. 87, pp.782–790, March, doi: 10.1016/j.renene.2015.11.002.

Bora, B.J. and Saha, U.K. (2016b) 'Optimisation of injection timing and compression ratio of a raw biogas powered dual fuel diesel engine', *Applied Thermal Engineering*, January, Vol. 92, pp.111–121, doi: 10.1016/j.applthermaleng.2015.08.111.

Bora, B.J., Saha, U.K., Chatterjee, S. and Veer, V. (2014) 'Effect of compression ratio on performance, combustion and emission characteristics of a dual fuel diesel engine run on raw biogas', *Energy Conversion and Management*, November, Vol. 87, pp.1000–1009, doi: 10.1016/j.enconman.2014.07.080.

Castro, N., Toledo, M. and Amador, G. (2019) 'An experimental investigation of the performance and emissions of a hydrogen-diesel dual fuel compression ignition internal combustion engine', *Applied Thermal Engineering*, June, Vol. 156, pp.660–667, doi: 10.1016/j.applthermaleng.2019.04.078.

Chaichan, M.T. (2018) 'Performance and emission characteristics of CIE using hydrogen, biodiesel, and massive EGR', *International Journal of Hydrogen Energy*, March, Vol. 43, No. 10, Art. no. 10, doi: 10.1016/j.ijhydene.2017.09.072.

Chandra, R., Vijay, V.K., Subbarao, P.M.V. and Khura, T.K. (2011) 'Performance evaluation of a constant speed IC engine on CNG, methane enriched biogas and biogas', *Applied Energy*, November, Vol. 88, No. 11, Art. no. 11, doi: 10.1016/j.apenergy.2011.04.032.

Channappagoudra, M. (2020) 'Comparative study of baseline and modified engine performance operated with dairy scum biodiesel and Bio-CNG', *Renewable Energy*, May, Vol. 151, pp.604–618, doi: 10.1016/j.renene.2019.11.062.

Channappagoudra, M., Ramesh, K. and Manavendra, G. (2020) 'Effect of injection timing on modified direct injection diesel engine performance operated with dairy scum biodiesel and Bio-CNG', *Renewable Energy*, March, Vol. 147, pp.1019–1032, doi: 10.1016/j.renene.2019.09.070.

Chen, H., He, J. and Zhong, X. (2019) 'Engine combustion and emission fuelled with natural gas: a review', *Journal of the Energy Institute*, August, Vol. 92, No. 4, pp.1123–1136, doi: 10.1016/j.joei.2018.06.005.

Das, S. (2020) 'The national policy of biofuels of India – a perspective', *Energy Policy*, August, Vol. 143, p.111595, doi: 10.1016/j.enpol.2020.111595.

Dasore, A., Rajak, U., Panchal, M., Reddy, V.N., Verma, T.N. and Chaurasiya, P.K. (2022) 'Prediction of overall characteristics of a dual fuel CI engine working on low-density ethanol and diesel blends at varying compression ratios', *Arab. J. Sci. Eng.*, doi: 10.1007/s13369-022-06625-8.

Ghanbari, M., Najafi, G., Ghobadian, B., Yusaf, T., Carlucci, A.P. and Kiani, M.K.D. (2017) 'Performance and emission characteristics of a CI engine using nano particles additives in biodiesel-diesel blends and modeling with GP approach', *Fuel*, August, Vol. 202, pp.699–716, doi: 10.1016/j.fuel.2017.04.117.

Gopalakrishnan, S. and Karthick, R. (2020) 'Impact OF fuel injection pressure in diesel fuelled engine using biodiesel, flammable and non-flammable gas in mixed fuel mode', *Materials Today: Proceedings*, Vol. 21, pp.811–816, doi: 10.1016/j.matpr.2019.07.250.

Gopinath, S., Devan, P.K., Mohan, C., Krishna Rao, L.R., Lokesh Kumar, P. and Vara Prasad, S. (2020) 'A review on influence of injection timing and injection pressure on DI diesel engine fuelled with low viscous fuel', *Materials Today: Proceedings*, Vol. 33, pp.280–286, doi: 10.1016/j.matpr.2020.04.070.

Government of India (2021) *Bureau of Energy Efficiency (BEE)* [online] https://beeindia.gov.in/.

Hariharan, N., Senthil, V., Krishnamoorthi, M. and Karthic, S.V. (2020) 'Application of artificial neural network and response surface methodology for predicting and optimizing dual-fuel CI engine characteristics using hydrogen and bio fuel with water injection', *Fuel*, June, Vol. 270, p.117576, doi: 10.1016/j.fuel.2020.117576.

Hegab, A., La Rocca, A. and Shayler, P. (2017) 'Towards keeping diesel fuel supply and demand in balance: dual-fuelling of diesel engines with natural gas', *Renewable and Sustainable Energy Reviews*, April, Vol. 70, pp.666–697, doi: 10.1016/j.rser.2016.11.249.

Hosamani, B.R. and Katti, V.V. (2018) 'Experimental analysis of combustion characteristics of CI DI VCR engine using mixture of two biodiesel blend with diesel', *Engineering Science and Technology, An International Journal*, August, Vol. 21, No. 4, pp.769–777, doi: 10.1016/j.jestch.2018.05.015.

International Energy Agency (IEA) (2021) *Oil Demand Forecast, 2010–2026, Pre-Pandemic and in Oil 2021* [online] https://www.iea.org/data-and-statistics/charts/oil-demand-forecast-2010-2026-pre-pandemic-and-in-oil-2021.

Kshatriya, A.S. et al. (2022) 'Investigations into the combined effect of Mahua biodiesel blends and biogas in a dual fuel engine', *Energies*, Vol. 15, No. 6, pp.1–15, doi: 10.3390/en15062057.

Kumar, V. and Saluja, R.K. (2020) 'The effect of operating parameters on performance and emissions of DI diesel engine fuelled with Jatropha biodiesel', *Fuel*, October, Vol. 278, p.118256, doi: 10.1016/j.fuel.2020.118256.

Lal, S. and Mohapatra, S.K. (2017) 'The effect of compression ratio on the performance and emission characteristics of a dual fuel diesel engine using biomass derived producer gas', *Applied Thermal Engineering*, June, Vol. 119, pp.63–72, doi: 10.1016/j.applthermaleng.2017.03.038.

Leykun, M.G. and Mekonen, M.W. (2022) 'Investigation of the performance and emission characteristics of diesel engine fueled with biogas-diesel dual fuel', *Fuels*, Vol. 3, No. 1, pp.15–30, doi: 10.3390/fuels3010002.

Mevada, D. et al. (2019) 'Applications of evacuated tubes collector to harness the solar energy: a review', *Int. J. Ambient Energy*, pp.1–18, doi: 10.1080/01430750.2019.1636886.

Mevada, D. et al. (2020) 'Effect of fin configuration parameters on performance of solar still: a review', *Groundw. Sustain. Dev.*, September 2019, Vol. 10, Scopus Indexed, doi: 10.1016/j.gsd.2019.100289.

Mevada, D., Panchal, H. and Sadasivuni, K.K. (2021) 'Investigation on evacuated tubes coupled solar still with condenser and fins: experimental, exergo-economic and exergo-environment analysis', *Case Stud. Therm. Eng.*, June, Vol. 27, p.101217, doi:10.1016/j.csite.2021.101217.

Midhun Prasad, K. and Murugavelh, S. (2020) 'Experimental investigation and kinetics of tomato peel pyrolysis: performance, combustion and emission characteristics of bio-oil blends in diesel engine', *Journal of Cleaner Production*, May, Vol. 254, p.120115, doi: 10.1016/j.jclepro.2020.120115.

Miglani, S. (2019) 'The growth of the Indian automobile industry: analysis of the roles of government policy and other enabling factors', in Liu, K-C. and Racherla, U.S. (Eds.): *Innovation, Economic Development, and Intellectual Property in India and China: Comparing Six Economic Sectors*, pp.439–463, Springer Singapore, Singapore, doi: 10.1007/978-981-13-8102-7_19.

Miglani, S. (2019) 'The growth of the Indian automobile industry: analysis of the roles of government policy and other enabling factors', in Liu, K.C. and Racherla, U. (Eds.): *Innovation, Economic Development, and Intellectual Property in India and China*, ARCIALA Series on Intellectual Assets and Law in Asia, Springer, Singapore, https://doi.org/10.1007/978-981-13-8102-7_19.

Niklesh Reddy, P., Khayum, N., Paruvada, S.K., Killol, A. and Murugan, S. (2022) 'Experimental study on combustion characteristics of a CI engine runs on a renewable fuel', *International Journal of Ambient Energy*, December, Vol. 43, No. 1, pp.2003–2018, doi: 10.1080/01430750.2020.1722743.

Noel, D., Ramesh Mamilla, V., Bharat Kumar, Y. and Trinath, V. (2016) 'Performance on CI engine fuelled Honge biodiesel blended with diesel', *Materials Today: Proceedings*, Vol. 3, No. 10, pp.3626–3631, doi: 10.1016/j.matpr.2016.11.005.

Panchal, H., Mevada, D. and Sadasivuni, K.K. (2020) 'Recent advancements in condensers to enhance the performance of solar still: a review', *Heat Transf.*, Vol. 49, No. 6, pp.3758–3778, doi: 10.1002/htj.21799.

Patil, A.R., Desai, A.D., Madavi, A.D., Kamble, S.A., Navale, S.B. and Dhutmal, V.U. (2018) 'Comparative study on effect of biodiesel on CI engine performance and emission characteristics', *Materials Today: Proceedings*, Vol. 5, No. 2, pp.3556–3562, doi: 10.1016/j.matpr.2017.11.604.

Rahman, K.A. and Ramesh, A. (2019) 'Studies on the effects of methane fraction and injection strategies in a biogas diesel common rail dual fuel engine', *Fuel*, January, Vol. 236, pp.147–165, doi: 10.1016/j.fuel.2018.08.091.

Rahman, K.A. and Ramesh, A. (2019) ‘Studies on the effects of methane fraction and injection strategies in a biogas diesel common rail dual fuel engine’, *Fuel*, January, Vol. 236, pp.147–165, doi: 10.1016/j.fuel.2018.08.091.

Rana, S., Saxena, M.R. and Maurya, R.K. (2022) ‘A review on morphology, nanostructure, chemical composition, and number concentration of diesel particulate emissions’, *Environ. Sci. Pollut. Res.*, Vol. 29, No. 11, pp.15432–15489, doi: 10.1007/s11356-021-15999-5.

Rosha, P., Dhir, A. and Mohapatra, S.K. (2018) ‘Influence of gaseous fuel induction on the various engine characteristics of a dual fuel compression ignition engine: a review’, *Renewable and Sustainable Energy Reviews*, February, Vol. 82, pp.3333–3349, doi: 10.1016/j.rser.2017.10.055.

Rosha, P., Dhir, A. and Mohapatra, S.K. (2018) ‘Influence of gaseous fuel induction on the various engine characteristics of a dual fuel compression ignition engine: a review’, *Renewable and Sustainable Energy Reviews*, February, Vol. 82, pp.3333–3349, doi: 10.1016/j.rser.2017.10.055.

Subramanian, K., Paramasivam, S.A., Dillikannan, D., Muthu, M. and Yadav Sanjeevi, P.R. (2022) ‘Prediction of thermal performance and exhaust emissions of a diesel engine fuelled with Simmondsia Chinensis oil methyl ester using ANN’, *Int. J. Ambient Energy*, July, pp.1–14, doi: 10.1080/01430750.2022.2103184.

Sundar, K. and Udayakumar, R. (2020) ‘Comparative evaluation of the performance of rice bran and cotton seed biodiesel blends in VCR diesel engine’, *Energy Reports*, February, Vol. 6, pp.795–801, doi: 10.1016/j.egyr.2019.12.005.

Suresh, K.V., Fernandes, P. and Raju, K. (2021) ‘Effect of injection pressure on performance and emission of diesel engine with blends of Honge-Rice bran bio diesel’, *Materials Today: Proceedings*, Vol. 35, pp.489–493, doi: 10.1016/j.matpr.2020.03.071.

Tutak, W., Jamrozik, A., Pyrc, M. and Sobiepański, M. (2017) ‘A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine’, *Applied Thermal Engineering*, May, Vol. 117, pp.155–163, doi: 10.1016/j.applthermaleng.2017.02.029.

Vélez Godiño, J.A., Jiménez-Espadafor Aguilar, F.J. and García, M.T. (2018) ‘Simulation of HCCI combustion in air-cooled off-road engines fuelled with diesel and biodiesel’, *Journal of the Energy Institute*, August, Vol. 91, No. 4, pp.549–562, doi: 10.1016/j.joei.2017.04.002.

Verma, S., Das, L.M. and Kaushik, S.C. (2017) ‘Effects of varying composition of biogas on performance and emission characteristics of compression ignition engine using exergy analysis’, *Energy Conversion and Management*, April, Vol. 138, pp.346–359, doi: 10.1016/j.enconman.2017.01.066.

Wang, X., Sun, B. and Luo, Q. (2019) ‘Energy and exergy analysis of a turbocharged hydrogen internal combustion engine’, *International Journal of Hydrogen Energy*, February, Vol. 44, No. 11, pp.5551–5563, doi: 10.1016/j.ijhydene.2018.10.047.

Yaşar, F. (2020) ‘Comparison of fuel properties of biodiesel fuels produced from different oils to determine the most suitable feedstock type’, *Fuel*, March, Vol. 264, p.116817, doi: 10.1016/j.fuel.2019.116817.

Yusri, I.M., Abdul Majeed, A.P.P., Mamat, R., Ghazali, M.F., Awad, O.I. and Azmi, W.H. (2018) ‘A review on the application of response surface method and artificial neural network in engine performance and exhaust emissions characteristics in alternative fuel’, *Renewable and Sustainable Energy Reviews*, July, Vol. 90, pp.665–686, doi: 10.1016/j.rser.2018.03.095.

Nomenclature

A/F	Air/fuel ratio	BPR	Biogas premix ratio, %
HC	Hydrocarbon, g/kWh	BSFC	Brake specific fuel consumption, kg/kWh
ID	Ignition delay	NO_x	Oxides of nitrogen, g/kWh
BDC	Bottom dead centre	NH3	Ammonia
BDFM	Biodiesel dual fuel mode	NO	Nitric oxide, g/kWh
LHV	Lower heating value, MJ/kg	BTE	Brake thermal efficiency, %
BG	Biogas	SI	SPARK IGNITION
MFB	Mass fraction burned	DI	DIRECT IGNITION
KME	Karanja methyl ester	CI	Compression ignition
BTE	Brake thermal efficiency, %	CO	Carbon monoxide, g/kWh
BDFM	Biodiesel dual fuel mode	PM	Particulate matter
LHV	Lower heating value, MJ/kg	CNG	Compressed natural gas
MFB	Mass fraction burned	TDC	Top dead centre
BMEP	Brake mean effective pressure, bar	H_2S	Hydrogen sulphide
N_2O	Nitrous oxide	EGT	Exhaust gas temperature, ˚C
DFM	Dual fuel mode	DFM	Dual fuel mode
IC	Internal combustion	CI	Compression ignition
ATDC	After Top dead centre	CO_2	Carbon dioxide
BFR	Biogas flow rate	CR	Compression ratio
BMEP	Brake mean effective pressure (bar)	CO	Carbon monoxides
BP	Brake power (kW)	CNG	Compressed natural gas
BSEC	Brake specific energy consumption (kJ/s/kW)	ID	Ignition delay
BSFC	Brake specific fuel consumption (kg/s/kW)	IT	Injection timing (degree)
BTE	Brake thermal efficiency	LHV	Lower heating value of biogas (MJ/kg)
bTDC	Before top dead centre	LPG	Liquefied petroleum gas
bBDC	Before bottom dead centre		