Chapter 2

LITERATURE REVIEW
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The main purpose of this literature review is to provide background information on the issues to be considered in this research and to emphasize the relevance of the present study. An intensive literature survey has been carried out from available sources on the utilization of different alternative fuels such as vegetable oil and its blends, bio-diesel and its blends in diesel engine, mainly with specific emphasis on various gaseous fuels irrespective of pilot fuels in dual fuel mode as well as turbocharged mode of diesel engine. This chapter contains in brief an up-to-date account of research activities in the area of dual fuel operation of diesel engine using various gaseous fuels with pilot fuels including the diesel engine operated in single mode as well as turbo charged mode. Numerous studies have been carried out by many researchers to investigate the effect of the type of alternative fuels as well as turbocharger on the emission parameters like carbon monoxide (CO), hydrocarbon (HC), carbon dioxide (CO₂), oxide of nitrogen (NOₓ), smoke and particulate matter (PM), and performance parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), exhaust gas temperature (EGT) and combustion parameters like heat release rate, pressure rise rate and ignition delay period etc of dual-fuel engine. These experiments are conducted by the researchers in different test engines of various gaseous fuels with pilot fuels. This chapter includes reviews of available research report on:

- Effect of vegetable oil and its blends
- Effect of bio-diesel and its blends
- Effect of biogas with pilot fuels
- Effect of hydrogen with pilot fuels
- Effect of natural gas with pilot fuels
- Effect of LPG with pilot fuels
- Effect of producer gas with pilot fuels
- Effect of turbocharger

At the end of this chapter a summary of the literature survey is presented and an efforts have been made to identify the knowledge gaps in the earlier investigation and address them in the development of the test rig built for the present study
2.1 Effect of vegetable oil and its blends

Agarwal and Das [54] stated that the higher viscosity of plant oil creates some engine problems like poor fuel atomization which leads to poor engine performance, ring sticking, injector pump failure and injector deposit etc.

Wang et al. [55] conducted experiment using vegetable oil blends with diesel and reported lower NOx and a small change in CO emission compared to diesel.

Senthil kumar et al. [56] carried out experiment using Jatropha oil-diesel blend and reported that EGT, HC, smoke and CO emissions are higher than mineral diesel.

Agarwal and Rajamanoharan [57] conducted experiments using preheated and blended Karanja oil in diesel engine. It was observed that during the engine operation on Karanja oil both in preheated and blended form, the performance and emission parameters were found to be similar with fossil diesel for lower concentrations of blend. Whereas, for higher concentrations of blend, performance and emissions were observed to be marginally lower.

Deshpande [58] used blends of linseed oil and diesel to run the CI engine. Minimum smoke and maximum brake thermal efficiency were noted in this study.

Mbarawa Makame [59] studied the performance, emission and economic evaluation of the clove stem oil (CSO)–diesel blended fuels as alternative fuels for diesel engine. Engine tests found that performance parameters of the CSO–diesel blended fuels do not differ greatly from those of the pure diesel fuel. Slight power losses, combined with an increase in fuel consumption, were experienced with the CSO–diesel blended fuels. A remarkable reduction in the exhaust smoke emissions can be achieved when operating on the CSO–diesel blended fuels.

Bajpai et al. [60] studied the effect of preheated and blended Karanja oil and found that a fuel blend of 10% Karanja oil showed higher brake thermal efficiency at a 60% load. The overall emission characteristics were found to best for the case of 10% Karanja oil blend.

2.2 Effect of bio-diesel and its blends

Nazar et al. [61] analyzed the performance of coconut oil in diesel engine in biodiesel and neat mode. It was reported that neat coconut oil and its methyl ester can be directly used in
diesel engines without any modifications. Engine performance with coconut oil methyl ester was better than with neat coconut oil. At full load, brake thermal efficiency with pure coconut oil was 32% and for its methyl ester it was 33.2% which was lower than diesel of 34%. The HC and CO levels were found higher with coconut oil and its ester as compared to diesel. Neat coconut oil and its ester results in lower NO emissions in comparison to its ester and diesel. Drastic reduction in smoke level was found with coconut oil and its methyl ester in comparison to diesel. Particulate emission was also found to be lower for coconut oil and its methyl ester. Peak pressure and maximum rate of pressure rise were very close to diesel for methyl ester of coconut oil.

**Alltiparmak et al. [62]** examined the effect of blends of tall oil biodiesel with diesel fuel as substitute fuels for diesel. It was found that the performance parameters such as power output and engine torque with tall oil biodiesel-diesel blends increased up to 5.9% and 6.1% respectively. It was also observed that CO emissions decreased to 38.9% and NOx emissions increased up to 30% with this fuel blends. The variation of smoke opacity was insignificant.

**Malhotra et al. [63]** conducted experiments taking Karanja and Jatropha bio-diesel in diesel engine with and without catalytic converter. It was reported that Bio-diesel blending in diesel helps to improve the physico-chemical properties such as cetane number, lubricity, flash point and sulphur content. Blends of biodiesel in diesel had shown significant benefits in terms of emissions particularly those of CO and Particulate matter. Use of catalytic converter found to be helpful in reduction of CO emissions in a diesel vehicle. The use of biodiesel which has in-built oxygen further helps in improving the efficiency of catalytic converter; there by further reduction of CO. Use of diesel oxygenated catalyst reduced particulate material in a diesel vehicle.

**Usta [64]** conducted an experiment to study the performance and emissions characteristics of a turbocharged indirect injection diesel engine using tobacco seed oil methyl ester under full and partial load conditions. The findings obtained indicated that the addition of tobacco seed oil methyl ester to the diesel fuel decreased CO and SO2 emissions except NOx emission which is of slightly higher value. However, it was also observed that with the addition of tobacco seed oil methyl ester, the power output and the efficiency increased slightly.
Nabi et al. [65] investigated the exhaust emissions and combustion characteristics using neat diesel oil and diesel–biodiesel blends. From the investigation it was found that diesel-bio-
diesel blends showed lower carbon monoxide (CO) and smoke emissions but higher oxides of nitrogen ($NO_x$) emission as compared to conventional diesel fuel. However, when EGR was applied, $NO_x$ emission with diesel–biodiesel blends was slightly reduced as compared to diesel.

Centinkaya et al. [66] conducted experiments with objective to reduce the production cost of Biodiesel using low cost feedstock such as waste oils, used cooking oil and animal fats. They investigated the road performance of diesel engine fuelled with used cooking oil biodiesel in winter season for 7500 km road tests in urban and long distance traffic. The results were compared with base line diesel. The results showed that the performance parameters like engine torque and brake power using used cooking oil bio-diesel were 3–5% less than those of base line diesel. The exhaust gas temperature of engine at every engine speed of biodiesel was less than that of base line diesel. The variation of injection pressures in both fuels was insignificant.

Puhan et al. [67] examined the effect of Mahua oil methyl ester (MOME) as a substitute fuel for diesel. They found that MOME shows similar characteristics as that of diesel. A small amount of power loss, and an increase in fuel consumption was experienced with Mahua oil methyl ester. Similarly, the CO, $NO_x$ and HC emissions were very less for MOME compared to diesel. Finally, they suggested that the MOME is a suitable alternative fuel for diesel in a diesel engine.

Dincer [68] reported that use of biodiesel in diesel engine shows lower emission parameters such as CO, $CO_2$, ozone-forming hydrocarbon and particulate matter and higher $NO_x$ emission compared to fossil diesel.

2.3 Effect of biogas with pilot fuels

Duc and Wattanavichien [69] conducted an experiment to investigate the effect of biogas-
diesel dual-fuel operation on performance, emission and long term use of an IDI diesel engine. The study revealed that there was no variation of the engine performance at all test speeds. The HC, CO emission and specific energy consumption in dual-fuel mode were
higher compared to diesel mode. From the study, it has been observed that with long term use of the engine in dual-fuel mode, there was a destruction of piston crown due to high thermal load. They suggest that this problem can be solved for long term use by little variation in engine parameters. Similar results were also reported by Tippayawong et al. [70] on DI diesel engine on dual-fuel mode. They suggested that the long term use of dual-fuel engine is feasible after periodic maintenance and service of the engine.

Luijten and Kerkhof [71] examined the effect of pure Jatropha oil with bio-gas on performance of a 12 kW DG set on dual-fuel mode for rural electrification. It has been reported that the engine was able to produces electricity using pure Jatropha oil with biogas without need of transesterificatio and any engine modification.

Cacua et al. [72] examined the effect of enriched air on the performance of a diesel-biogas dual-fuel DG set engine. They found that there was an improvement in thermal efficiency with enriched oxygen at all loads ranges. However, at 40% of the load, it was increased up to 28%. The cylinder peak pressure was higher for 25% and 27% oxygen enrichment compared to the case of atmospheric air for all loads. The main pollutants of the exhaust gas of dual diesel-biogas engines were methane and carbon monoxide. At 40% of full load and 25% O\textsubscript{2}, carbon monoxide decrease by 19.5% regarding to atmospheric air (21% O\textsubscript{2}). Methane emissions were decreased 35% for 27% O\textsubscript{2} for all loads. Similarly, at 50% of full load, carbon monoxide emissions increase up to 11% and 7.5% by adding 22% and 25% oxygen respectively.

Yoon and Lee [73] performed an experiment to study the combustion, performance and emissions characteristics of a four-cylinder IDI diesel engine fuelled with diesel and biodiesel in single mode and with biogas in dual-fuel mode. The result showed that the total BSFC in dual-fuel mode for both fuels under low load condition (20% and 40%) was higher compared to single mode operation. On the other hand, at higher engine loads (over 80%), the total BSFC in dual-fuel combustions increases significantly. The variation of BTE is the reverse case of variation of BSFC of the engine. The exhaust gas temperature was slightly lower value for dual-fuel combustions compared to single-fuel mode. Similar results were obtained in case of NO\textsubscript{x} emission. Moreover, soot emissions in case of dual-fuel mode were lower than that of single mode at all test conditions. The ignition delays of dual-fuel mode for both fuels were longer than single mode operations. In dual-fuel combustion, the peak pressure and heat
release rate for biogas–biodiesel dual-fuel operation were slightly lower than those of biogas–diesel combustion at 20% engine load. But at 60% engine load, these values were higher. The concentrations of HC and CO emissions were significantly higher for the dual-fuel mode with both pilot fuels than those for the single mode operation under all test conditions.

Bedoya et al. [74] test the effect of mixing system and pilot fuel quality on performance of diesel–biogas dual-fuel engine. In their study, they compared the performance of engine using a naturally aspirated mixing of gas-air system and diesel as pilot fuel (SM1) with a supercharged mixing gas-air system and biodiesel as pilot fuel (SM2). They found that there was an improvement of 8% brake thermal efficiency in SM2 system compared to SM1 system. The exhaust gas temperature decreases due to improvement in thermal efficiency for SM2 system. Overall volumetric efficiency was reduced by 6% using SM2 compared to SM1 system. The peak cylinder pressure and heat release rate for SM2 system was higher than that of SM1 system. It was also reported that CO and methane emission for SM2 system under part load as well full load condition were less compared to SM1 system.

2.4 Effect of hydrogen with pilot fuels

Liu et al. [75] investigate the effect of addition of hydrogen on NOx emission of heavy duty dual-fuel diesel engine under different load conditions. It was reported that the addition of H2 into to the engine increases the emissions of NO2. The maximum NO2 emissions obtained in the H2-diesel dual-fuel engine were three to five times those for normal diesel operation. When operated at 10% load, the maximum NO2/NOx ratio of 60% was observed with the addition of 4% H2. When operated at 70% load, the maximum NO2/NOx ratio of 10% was observed with the addition of 2% H2.

Saravanan et al. [76] examined the effect of hydrogen on performance of dual-fuel engine using diesel and diethyl ether (DEE) as pilot fuels under varying load conditions. The study revealed that at 75% load, the brake thermal efficiency of hydrogen-DEE was found to be 29.3% and hydrogen with diesel was 26.23% in dual-fuel mode compared to 21.6% normal diesel operation. Similarly, at 25% load, the specific energy consumption (SEC) of hydrogen-DEE and hydrogen-diesel dual-fuel operation was 60% and 24% lower respectively, compared to base line diesel. At 75% load, the peak pressure, heat release rate and cylinder
pressure of hydrogen-diesel dual-fuel were higher than diesel mode. Whereas, the above parameters were lower values in case of hydrogen-DEE dual-fuel compared to diesel. The NO\textsubscript{x} emission in case of hydrogen-diesel and hydrogen-DEE dual operation was found to be higher values and lower values compared to base line diesel. Smoke and CO\textsubscript{2} emissions at 75\% load were lower for hydrogen dual-fuel operation compared to diesel mode. The CO and HC emissions were higher for hydrogen-DEE dual compared to hydrogen-diesel dual and base line diesel at 75\% load.

Korakianitis et al. [77] demonstrated the effect of hydrogen with diesel and RME as pilot fuels on the performance of dual-fuel engine over existing diesel engine under two different speed conditions of 750 and 1000 rpm. They found that hydrogen dual-fuel with both pilot fuels gives higher peak combustion pressure compared to diesel operation at both speeds. RME pilot fuel produces similar combustion, emission and thermal efficiency trends to diesel pilot fuel for both single-fuels as well as dual-fuel operating modes. During hydrogen dual-fuel operation, there was a reduction in volumetric efficiency, where reductions of about 2\% and 4\% were recorded at 750 rpm and 1000 rpm respectively. The increases in NO\textsubscript{x} emissions in both modes of operation were observed to be similar amount for both pilot fuels at both speeds. Smoke, HC and CO levels were comparable with normal diesel engine operation. Hydrogen dual-fuelling produces lower CO\textsubscript{2} levels than normal CI engine operation with both pilot fuels.

Korakianitis et al. [78] in an another experiment, used neat RME, and 5\% and 10\% emulsified RME as pilot fuels with hydrogen in dual fuel mode of a four-stroke 1.5 L single-cylinder Gardner 1L2 engine. They examined the effect of above pilot fuels with hydrogen in dual-fuel mode and neat RME in normal diesel engine operation on the performance of the above engine at two different speed conditions i.e., 750 rpm and 1000 rpm. They reported that during hydrogen dual-fuel operation at 750 rpm, the thermal efficiency levels were slightly lowered compared to normal CI engine operation at full load condition. This is contrary to the general trends in the literature [79]. Hydrogen dual-fuel operation with the above pilot fuels reduces SFC compared to normal CI engine operation at all test ranges. This trend does not correlate with the trends in the literature. Hydrogen dual-fuel operation with the neat pilot fuel increases NO\textsubscript{x} emissions compared to normal CI engine operation by about 50\% at both
speeds. However, the 10% emulsion produces lower NO\textsubscript{x} compared to the 5% emulsion. Overall NO\textsubscript{x} emission reduces with emulsified biodiesel in dual-fuel mode compared to normal diesel engine operation. Dual-fuel operation with hydrogen generates HC emission very similar trends compared to normal CI engine operation at both speeds. Similarly, dual-fuel operation of all pilot fuels with hydrogen produces CO emission fairly similar trends to normal diesel engine operation at both speeds. During dual-fuel operation of all the pilot fuels, with increase load, a significant reduction in CO\textsubscript{2} emissions were found (roughly 40% compared with normal CI engine operation). However, the emulsified pilot fuels do not affect the CO\textsubscript{2} emission substantially. Smoke emissions at 750 rpm during hydrogen dual-fuel operation reduce compared to normal CI engine operation. Whereas, at 1000 rpm it was comparable with normal CI engine operation.

Geo et al. [80] conducted an experiment on a dual-fuel diesel engine fuelled with rubber seed oil (RSO), rubber seed oil methyl ester (RSOME) and diesel with hydrogen under different load conditions. They reported that in single mode operation of all test fuels, the brake thermal efficiency for RSO is lower followed by RSOME than diesel at all load conditions. The exhaust gas temperature was high for RSO and RSOME compared with diesel in single mode operation. Again, EGT increases with induction of hydrogen in dual-fuel mode. The study also revealed that NO\textsubscript{x} emission for RSO and RSOME was less compared to diesel. The HC and CO levels were at all loads with the induction of hydrogen for all injected fuels, but the values with RSO are higher than other fuels. Smoke emission in dual-fuel mode is less compared to single mode for all test fuels. Whereas, this value for RSO was lower as compared to RSOME and diesel with hydrogen in dual-fuel mode. The ignition delay increases for all the fuels with hydrogen induction. The combustion duration decreases with hydrogen at all loads.

2.5 Effect of natural gas with pilot fuels

Papagiannakis and Hountal [81] carried out an experimental study regarding the effect of natural gas percentage on performance and emissions of a DI dual-fuel diesel engine. The study showed that dual-fuel operation results higher ignition delays, lower peak cylinder pressure compared to normal diesel operation at all test. Combustion duration under dual-fuel operation was generally longer compared to normal diesel operation at all load conditions. It
was found that the BSFC for dual-fuel engine was higher value compared to normal diesel operation. The level of NO concentration under dual-fuel operation was lower compared to normal diesel operation. Under dual-fuel operation the CO and HC emissions were generally higher compared to normal diesel operation. At part load as the natural gas mass ratio increases, soot concentration decreases sharply. The same results mentioned above are also reported by Papagiannakis and Hountal [82]. Finally, they suggested that dual-fuel combustion using natural gas is a promising technique for controlling both NO and soot emissions on existing DI diesel engines. The penalty in BSFC is compensated by the lower price of natural gas. The disadvantages regarding BSFC, HC and CO can be possibly reduced by applying modifications in engine tuning i.e., injection timing of the pilot diesel fuel.

Korakianitis et al. [77] examined the effect of diesel and rapeseed methyl ester (RME) as pilot fuels with natural gas and hydrogen as primary fuels on performance of dual-fuel engine over existing diesel engine. The two gaseous fuels were tested separately with this two pilot fuels in dual-fuel engine under two different speeds i.e. (750 rpm and 1000 rpm), and its effects on performance of the engine are discussed separately in their respective sections. At both speeds during natural gas dual-fuel operation with both pilot fuels, thermal efficiency levels were comparable with diesel in single mode operation throughout the load ranges. The volumetric efficiency was reduced during dual-fuel operation with both tested fuels compared to diesel and RME normal operations. Higher values of HC and CO emissions were recorded compared to normal CI engine operation at low and intermediate engine loads. At full load condition for both speeds, specific NOx emissions were found to be higher levels compared to normal diesel operation. At both speeds, there was no significant variation in the smoke levels with load for either fuelling mode and with both pilot fuels tested. Concerning the effect of two pilot fuels in dual fuel mode, it was reported that RME pilot fuel produces similar emission and thermal efficiency trends to diesel pilot fuel for both single-fuel and dual-fuel operating modes. They stated that methyl esters are suitable diesel alternate fuel for both normal and dual-fuel operation. Finally, they suggested that natural gas can be used in dual-fuel mode diesel engine successfully.

Selim et al. [83] conducted an experiment using diesel and Jojoba methyl ester (JME) as pilot fuels and CNG/LPG as primary fuels to improve the performance of a variable compression
ratio dual-fuel engine over existing diesel engine. The two gaseous fuels were tested separately with this two pilot fuels and its effect on the performance of dual-fuel engine were presented in their respective sections. During compressed natural gas (CNG) dual-fuel operation, it was observed that pressure rise rate was highest for dual-fuel engine running on diesel/CNG, followed by JME/CNG and minimum for pure diesel case. Higher cetane number of JME can reduce the ignition delay period of the fuel compared to diesel. The brake power and brake-specific fuel consumption were almost comparable for all fuels used except for lower compression ratios. The carbon monoxide and HC emissions were highest for JME/CNG case compared to diesel/CNG case. It was also observed that with increase in engine speed, CO and HC emissions were decreased. Regarding the effect of knocking phenomena in dual-fuel engine, it was observed that using JME against diesel as a pilot fuel, made the engine to knock later at high compression ratio. Also, the pressure rise rate was lower for JME at all loads.

Papagiannakis et al. [84] investigated the effects of the total air–fuel ratio on the efficiency and pollutant emissions of a high speed dual-fuel diesel engine under different engine speeds. It was reported that the increase of diesel fuel supplementary ratio, results to a lower brake thermal efficiency, exhaust gas temperature and total heat release rate compared to normal diesel operation. At low and intermediate load conditions and for all engine speeds, the increase of the gaseous fuel concentration results to a decrease of the specific NO emissions. The effect was more pronounced at low load where the reduction of the specific NO emission was up to 60%. Dual-fuel operation leads to a significant reduction of soot emissions. The increase of diesel fuel supplementary ratio increases the concentration of the carbon monoxide emissions. This effect becomes more evident at low and intermediate loads in comparison to the one observed at high load. Furthermore, dual-fuel operation generates higher unburned hydrocarbon emissions compared to the ones observed under normal diesel operation. At part load, this specific difference was higher, while at high engine load and low air–fuel ratios, a slight decrease was observed.

2.6 Effect of LPG with pilot fuels
Selim et al. [83] examined the effect of LPG as primary fuel with diesel and (JME) as injected fuels on performance of variable compression ratio dual-fuel engine over normal
diesel engine. The effect of pressure rise rate for all modes of operation depends upon engine speed, compression ratio, quantity of pilot fuel, torque and pilot fuel injection timing. It was observed that with increase in engine speed as well as quantity of pilot fuel, the pressure rise rate generally decreases but increases with increases in engine compression ratio. Again, with increase in torque, pressure rise rate increases. Moreover, the pressure rise rate was highest for dual-fuel engine running on diesel/LPG followed by JME/LPG and minimum for pure diesel case. The JME fuel has the lower ignition delay period compared to diesel. It was also presented that brake power and brake specific fuel consumption under the above mentioned parameters were comparable for all test fuels. Again it was found that the CO emission under above mentioned parameters was higher for JME/LPG case compared to diesel/LPG. Similar trend was noticed for HC. The CO and HC emission was decreased when the engine speed was increased. Also, they were reduced as the mass of pilot fuel was increased. The use of LPG at high compression ratio and high amount of the gas increases the possibility of gas knocking.

Lata and Misra [85] performed an experiment to analyze the ignition delay period of a 4-cylinders turbocharged dual-fuel diesel gen-set using hydrogen and liquefied petroleum gas (LPG) as secondary fuels under different load and diesel substitutions. On the basis of temperature, pressure, oxygen concentration and polytropic index, the ignition delay period has been estimated under different engine load conditions. It was found that the ignition delay period reduces at higher load and concentration of the gaseous fuel mixture. Furthermore, it was observed that ignition delay of LPG-diesel dual-fuel case was higher than hydrogen–diesel-dual fuel case.

Lata et al. [86] investigated the effect of hydrogen, LPG and mixture of LPG and hydrogen as secondary fuels on efficiency and exhaust emission of a 4-cylinder, turbocharged and intercooled 62.5 kW diesel gen-set in dual-fuel mode. The experiments were performed under four different test conditions of the engine as follows:

In case I: engine runs on pure diesel only. In case II: engine runs on hydrogen as primary fuel and diesel as injected fuel. In case III: engine runs on LPG as primary fuel and diesel as injected fuel and in case IV: engine runs on diesel as injected fuel and LPG + hydrogen as primary fuel. The study showed that at 10% load conditions and for 30% primary fuel
substitution in cases II and III, the indicated thermal efficiencies was found to be 17.3% and 20.16% respectively, as compared to 23.48% of case I operation. Similarly, at 40% load, the thermal efficiency for the cases II and III was found to be 29.4% and 27.84% respectively, as compared to 32.1% of case I operation. It was also noted that at 80% load, the thermal efficiency for case II and case III was higher as compared to diesel mode. It was also found that 40% mixture of LPG + hydrogen in the ratio 70:30 increases the brake thermal efficiency by 22% and 27% at 40% and 80% load conditions respectively as compared to diesel mode only. Similarly, it was observed that dual-fuel operation produces less NOx compared to diesel operation only. Smoke emission in all dual-fuel operation under all load conditions reduced as compared to diesel operation. However, the CO emissions for all dual-fuel modes at all load conditions are higher than diesel case. At 10% load condition, the HC emissions in cases II, III and IV were found to be 6.86 g/kWh, 5.9 g/kWh and 6.94 g/kWh respectively as compared to 1.72 g/kWh of diesel operation. At 80% load condition, cases II, III and IV show maximum HC emission of 5.64 g/kWh, 4.57 g/kWh and 1.07 g/kWh, respectively as compared to 1.8 g/kWh of case I operation. At higher load, case IV shows lower HC than diesel case.

Lata and Misra [87] developed a theoretical model to predict pressure, net heat release rate, average gas temperature and brake thermal efficiency for dual-fuel diesel engine fuelled with hydrogen, LPG and mixture of LPG and hydrogen as primary fuels and compared this result with the experimental result. The experiments were conducted on 4 cylinder turbocharged, intercooled with 62.5 kW gen-set diesel engine to measure brake thermal efficiency at different load conditions, pressure and net heat release rate with respect to crank angle. The predicted brake thermal efficiency was found to be 3-4% less than the experimentally measured brake thermal efficiency. The predicted maximum pressure rise and net heat release rate were observed to be 6-7% less than experimental results.

2.7 Effect of producer gas with pilot fuels

Ramadhas et al. [88] examined the effect of coir-pith producer gas with diesel and rubber seed oil on the performance and emission parameters of a naturally aspirated dual-fuel engine operated at an engine speed of 1500 rpm. They observed that the dual fuel engine shows a lower performance compared to normal diesel operation. However, specific energy consumption of rubber seed oil-producer gas was higher than diesel-producer gas at all test
ranges of the engine. Again, it was observed that with increase in load EGT increases for all test fuels. The CO emission of dual-fuel mode for both test fuel was always much higher than that of diesel in all operating conditions. In comparison to diesel-producer gas dual operation, rubber seed oil-producer gas produces more CO emissions. Similarly, CO$_2$ emission increases with increase in load for all tested fuels. The above parameter was more in case of dual-fuel operation compared to normal diesel operation. However, the rubber seed oil-producer gas produces more CO$_2$ compared to diesel-producer gas at all test ranges. The smoke density of rubber seed oil and rubber seed oil-producer gas dual-fuel operation was more compared to diesel at all test conditions. It was also found that with increase in load smoke density increases for all test fuels.

Ramadash et al. [41] in another experiment on the same engine setup examined the effect of two different producer gases generated from wood chips and coir-pith with diesel in dual-fuel mode. They reported that BSEC in dual-fuel mode was higher than that of diesel mode at all load conditions. The minimum BSEC was achieved of about 70% load in the dual-fuel mode. It was also found that above 60% of full load, BSEC of diesel-coir-pith was more compared with diesel-wood producer gas dual-fuel mode. The variation of BTE is also reverse case variation of BSEC of the engine. It was also noted that at 70% load, the maximum brake thermal efficiency was of 19.9% using coir-pith and 21% using wood chips. The CO emission increases with increase in load for all tests modes, but higher in case of dual-fuel mode compared to diesel mode. CO$_2$ emission was more in dual-fuel mode of diesel-wood producer gas compared to that of diesel and diesel-coir-pith producer gas at all test ranges. Smoke emission increases with increase in load for all test fuels in both modes, but this value was more in case of diesel mode compared to dual-fuel mode operation. Finally, they suggest that producer gas dual-fuel engine can run efficiently up to 50-60% of maximum load, after that performance is inferior. Also higher diesel saving was achieved in dual-fuel mode operation of wood chips, compared to coir-pith. They also concluded that diesel replacement while using coir pith in the gasifier could be improved by briquetting.

Banapuratham and Tewari [89] carried out an experiment to compare the performance of a dual-fuel diesel engine fuelled with woody bio-mass producer gas as primary fuel along with diesel, Honge oil and Honge oil methyl ester (HOME) as pilot fuel with and without
carburetord mode. They stated that bio-derived gas and vegetable oil, when used in a dual-fuel mode with carburetor, resulted in better performance with reduced emissions. They also found that highest brake thermal efficiency was obtained as 24.25%, 22.25% and 23% with producer gas-diesel, producer gas-Hong oil and producer gas-HOME respectively. The EGT and NOx emissions were higher for Hong oil-producer gas in dual-fuel operation of with and without carburettor mode. They also reported that there was an improvement in NO level with all dual-fuel combinations when operated with carburetor, and the results obtained were as 130 ppm, 195 ppm and 175 ppm with diesel, Hong oil and HOME as pilot fuels respectively. It has been found that the CO, HC and smoke emissions with brake power were higher with Honge oil–producer gas dual-fuel operation.

Sing et al. [90] carried out experiments in a multi cylinder diesel gen-set in dual fuel mode using producer gas as a primary fuel with diesel and mixed fuel of refined rice bran oil (RRBO) with diesel as pilot fuels under different load conditions of engine. The study showed that blend used up to 75% RRBO with diesel does not produce any adverse effect on the engine. Generally, it was found that at all load conditions, with increase in percentage of rice bran oil in the blends, specific energy consumption increases and brake thermal efficiency decreases considerably. Again, it was found that with increase in percentage of RRBO in the blends, all the emission parameters reduced significantly at all test conditions except oxides of nitrogen (NO and NO2) which increases with increase in RRBO percentage. Similarly, the engine performance with mixed fuels mode was observed and reported that engine detonation occurred at higher load. It was also found that at 84% engine load, the mixed fuel mode in the ratio of 3:1 and producer gas operation, the emission parameters like HC, NO and NO2 reduced by 48.28%, 61.06% and 80.49% respectively. However, CO emission increased by 16.31% as compared to conventional diesel.

Roy et al. [91] conducted an experiment to compare the performance and emission study of a supercharged dual-fuel diesel engine driven by producer gas having variable hydrogen percentage with diesel. One type of producer gas contains 13.7% hydrogen and other contains 20% hydrogen. Tests were carried out under a constant injection pressure and injection quantity for various fuel–air equivalence ratios and injection timings. The study showed that producer gas having high H2-content produced improved combustion performance and
emissions parameters (except NO\textsubscript{x}) compared to producer gas having low H\textsubscript{2}-content under leaner conditions. However, the HC and CO emissions with producer gas having high H\textsubscript{2}-content were 10–25\% lower than low H\textsubscript{2}-content producer gas within the optimum fuel–air equivalence ratio range. It was also found that NO\textsubscript{x} emissions were higher side for high H\textsubscript{2}-content producer gas compared to low H\textsubscript{2}-content producer gas. They concluded that to reduce this higher value of NO\textsubscript{x} emissions, an EGR could be used.

Banapuramath et al. [92] performed a combustion study of a 4-stroke diesel engine operated in dual fuel mode using Honge oil, Neem and Rice bran oils with producer gas at different injection timing and injection pressure. The study showed that dual-fuel mode operation resulted in poor performance at all the loads when compared with single fuel mode at all injection timings tested. The maximum brake thermal efficiency for diesel, Honge, Rice Barn and Neem oils in single mode was found to be 31, 28, 27 and 26\% respectively. Whereas, the brake thermal efficiency of engine in dual-fuel mode with producer gas operated with all the injected fuels such as diesel, Honge, Rice Barn and Neem oils was found to be 24, 20, 19 and 17\% respectively. The magnitude of engine derating was in the order of 30\% in dual-fuel mode. Decreased smoke and NO\textsubscript{x} emissions were observed for dual-fuel mode for all the fuel combinations compared to single fuel operation. The CO and HC emissions were found to be more in dual-fuel mode compared to single mode operation.

In most of the literature, it was mentioned that power derating is the major problem with producer gas operation in a gas engine. A power drop of 40\% to 70\% can be expected as mentioned in literature [93, 94, 95]. In literature, it was also mentioned that diesel savings up to 70-90\% occurs in dual fuel operation using renewable alternative fuels [53, 26, 95].

Banapurmath et al. [96] developed two gas carburetors with 45° and 90° gas entries to enable effective mixing of air and producer gas. In their work, they reported that the maximum brake thermal efficiency was found to be 22.75\% when using carburetor with 90° gas entries in comparison with 20\% in carburetor with 45° gas entries.

Martinez et al. [97] presented a review articles regarding the improvement of producer gas quality in downdraft biomass gasifier and its application in internal combustion engine. They reported that producer gas quality can be changed by the effect of particle size, moisture
content and air/fuel equivalence ratio. Many investigators in their research work mentioned that maximum diesel savings occurs up to 71% \cite{92}, 64% \cite{98}, 72% \cite{41}, 75% \cite{99} using wood producer gas at optimum load condition.

**Das et al.** \cite{100} carried out an experiment on a single cylinder diesel engine in dual fuel mode using producer gas generated from selected agricultural residue such as wood chips, pigeon pea stalks and corn corbs. They noted that the average value of thermal efficiency on dual fuel mode operation was observed to be slightly lower than that of diesel mode. For the same amount of energy output, the specific diesel consumption was found to be 60 to 64 % less in dual fuel mode than that in diesel mode. The average diesel substitution of 62% was observed with wood chips, followed by corn cobs (63%) and pigeon pea stalks (62%).

**Panwar et al.** \cite{101} tested a 150 kWh capacity producer gas burner for thermal application. They reported that the maximum temperature (753 °C) was at the centre of the flame and the temperature beyond this point gradually reduces in radially outward direction. Again, the maximum flame temperature was achieved when the air to fuel (A/F) ratio was kept at 1.0. Furthermore, both NOx and CO decreases with increase in gas flow rate.

**Bargat et al.** \cite{102} conducted an experiment in a single cylinder dual fuel diesel engine using wood chips producer gas and blends of Jatropha bio-diesel. They reported that dual fuel mode operation the engine shows lower performance and higher smoke density compared to normal diesel operation at all load conditions. It is also noted that the best combination of fuel found to be diesel 75 % + Jatropha bio-diesel 25% + producer gas for rated speed of 1500 rpm. The brake thermal efficiency was found to be 26.08%. The higher EGT was found to be 427 °C.

**2.8 Effect of turbocharger**

**Sahin et al.** \cite{103} performed an experiment in an IDI turbocharged diesel engine using gasoline fumigation and found that smoke index is reduced to (25-30) % for (8-12) % gasoline fumigation.

**Rakopoulous et al.** \cite{104} carried out an experiment with a turbocharged diesel engine using blends of bio-diesel and n-butanol with diesel and compared it with the performance of diesel.
They concluded that smoke opacity increased by 40% for bio-diesel blend and decreased by 69% in case of n-butanol blend. Similarly, NO emission for both bio-fuel blends increased as compared to neat diesel fuel.

Shirk et al. [105] examined the effect of adding H₂ on the exhaust emissions of a four-cylinder turbocharged diesel engine and found that the substitution of 5% to 10% of diesel by hydrogen marginally decreased the NOₓ emission, but substantially increased the formation of NO₂ emission.

Liew et al. [106] investigated the effect of H₂ addition with EGR on exhaust emission for a heavy-duty variable geometry turbocharged diesel engine. They mentioned that the addition of H₂ reduced the emission of particulate matter (PM). However, the addition of small amount of H₂ substantially increased the NO₂ emission. Similarly, the addition of H₂ substantially reduced CO₂ emission due to the substitution of carbon rich diesel fuel with hydrogen. Furthermore, the addition of H₂ reduced the CO emission levels when the engine was operated at 10-50% load.

Zamboni and Capobianco [107] investigated the effect of low and high pressure exhaust gas recirculation (EGR) on pollutant emission of an automotive turbocharged diesel engine. They found that low pressure EGR circuit proved to be a potential enhancer of NOₓ emission.

Gharehghani et al. [108] conducted an experiment using a turbo- charged spark ignition engine and concluded that the maximum thermal efficiency was increased by 4% at 2500 rpm over a natural aspirated engine.

Salvatore et al. [109] carried out an experiment using bio-diesel of rapeseed oil in a Direct Injection (DI) turbocharged diesel engine. The result showed that at particular injection timing, bio-diesel increased the NOₓ emissions and decreased the HC and CO emission along with large reduction of smoke. They concluded that the NOₓ, HC and CO emissions of bio-diesel can be reduced by using an exhaust gas recirculation technology in the presence of an exhaust oxidizing catalyst.
Senator [110] investigated the performance and emission characteristics of a DI turbocharged
diesel engine fuelled with a blend of rapeseed bio-diesel with diesel. It has been stated that
performance is invariable with the variation of equivalence ratio. However, with the increase
in load (i.e. as the equivalence ratio decrease) the particulate matter and CO emission
increases sharply. However, at part load condition, NOx emission increased up to 20%
compared to that of conventional diesel. The analysis of the above result indicated that the
heat release rate must takes place in advance of top dead centre (TDC).

The details of research work based on dual fuel mode operation conducted by various
researcher using different test engines and test fuels are presented in Table 2.1.

**Table 2.1** Details of engine specification and test fuels used in experiments by various
researchers

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Test Engine Specification</th>
<th>Pilot fuel</th>
<th>Primary fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramdhash et al. [88]</td>
<td>Single cylinder four stroke, DI, naturally aspirated, 5.5kW ‘Canon’ make diesel engine</td>
<td>Diesel and rubber-seed oil.</td>
<td>Coir-pith producer gas</td>
</tr>
<tr>
<td>Ramdhash et al. [41]</td>
<td>-do-</td>
<td>Diesel</td>
<td>Wood and Coir-pith producer gas</td>
</tr>
<tr>
<td>Banapurmath and Tewari [89]</td>
<td>Single cylinder, four stroke, DI, 5.2kW naturally aspirated ‘Kirlosker’ make diesel engine</td>
<td>Diesel, HOME and Hong oil</td>
<td>Wood producer gas</td>
</tr>
<tr>
<td>Tippayawong et al. [70]</td>
<td>Single cylinder, four stroke, DI, 5.5kW, naturally aspirated ‘Mitsubishi DI-800, model diesel engine</td>
<td>Diesel</td>
<td>Biogas</td>
</tr>
<tr>
<td>Cacua et al. [72]</td>
<td>Lister Petter TR2, DI, 4- stroke, air cooled, 2- cylinders, 20 kW at 3000 rpm.</td>
<td>Diesel</td>
<td>Biogas</td>
</tr>
<tr>
<td>Yoon and Lee [73]</td>
<td>Four-stroke,4-cylinder, compression ratio:19, turbocharged, water cooled, diesel engine</td>
<td>Diesel, biodiesel</td>
<td>Biogas</td>
</tr>
<tr>
<td>Korakianitis et al. [77]</td>
<td>Four-stroke 1.5 l single-cylinder, compression ratio 13:1,Gardner 1L2 diesel engine</td>
<td>Diesel and RME</td>
<td>Hydrogen and natural gas</td>
</tr>
<tr>
<td>Selim et al. [37]</td>
<td>Ricardo E6, single cylinder, 4-stroke, naturally aspirated, IDI diesel engine variable compression, 3000 rpm.</td>
<td>Diesel and JME</td>
<td>CNG/LPG</td>
</tr>
<tr>
<td>Lata and Misra [85, 86, 87]</td>
<td>4- cylinders,4-stroke,DI turbocharged, intercooled with 62.5 kW gen-set diesel engine</td>
<td>Diesel</td>
<td>LPG/H2</td>
</tr>
</tbody>
</table>

37
Researchers | Test Engine Specification | Pilot fuel | Primary fuel
--- | --- | --- | ---
Liu et al. [75] | 1999 Cummins ISM370 model, 276 kW @2100 rpm, turbocharged, in-line 6-cylinder diesel engine | Diesel | Hydrogen
Saravanan et al. [76] | Kirloskar, AV1 make, single cylinder, 4- stroke, compression ignition, constant speed, vertical, water-cooled, direct injection, 3.7 kW. | Diesel and DEE | Hydrogen
Korakianitis et al. [78] | Four-stroke 1.5 l single-cylinder, compression ratio 13:1,Gardner 1L2 diesel engine | Diesel, RME and emulsified bio-diesel | Hydrogen
Geo et al. [80] | Kirloskar,TAF1, single cylinder, 4- stroke, 4.4 kW air cooled diesel engine | RSO, RSOME and Diesel | Hydrogen

The properties of various gaseous fuels used in the above research work is collected from the literatures and presented in Table 2.2

<table>
<thead>
<tr>
<th>Fuel</th>
<th>LPG</th>
<th>Hydrogen</th>
<th>NG</th>
<th>Biogas</th>
<th>Prod. Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (%)</td>
<td>C₃H₈: 62</td>
<td>H₂</td>
<td>CH₄:86.4-90</td>
<td>CH₄:60-70</td>
<td>CO:18-22</td>
</tr>
<tr>
<td></td>
<td>C₄H₁₀:37</td>
<td></td>
<td>C₂H₆:3.0-6.0</td>
<td>CO₂:30-40</td>
<td>H₂: 15-19</td>
</tr>
<tr>
<td></td>
<td>C₂H₆:1.08</td>
<td></td>
<td>C₃H₈:0.35-2.0</td>
<td>CO:0.18, H₂:0.18</td>
<td>N₂: 45-55</td>
</tr>
<tr>
<td>Density at (STP) kg/m³</td>
<td>2.24</td>
<td>0.09</td>
<td>0.79</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>Octane number</td>
<td>103-105</td>
<td>130</td>
<td>130</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Auto-ignition</td>
<td>493-549</td>
<td>585</td>
<td>730</td>
<td>700</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°C) (propane)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stoichometric (A/F) ratio</td>
<td>15.5</td>
<td>34.3</td>
<td>17.3</td>
<td>6</td>
<td>1.12:1</td>
</tr>
<tr>
<td>Lower heating Value (MJ/kg)</td>
<td>46.000</td>
<td>120</td>
<td>50</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Flame speed (cm/s)</td>
<td>38.25</td>
<td>34</td>
<td>265-325</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Flammability limits (vol. % in air)</td>
<td>2.15-9.6</td>
<td>4-755</td>
<td>5.3-15</td>
<td>7.5-14</td>
<td>-</td>
</tr>
<tr>
<td>Adiabatic flame temperature (K)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1546±25</td>
</tr>
<tr>
<td>Energy density (MJ/m³)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.6</td>
</tr>
<tr>
<td>Gas calorific value (MJ/m³)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.6</td>
</tr>
<tr>
<td>Laminar burning velocity (m/s)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5± 0.05</td>
</tr>
</tbody>
</table>
2.9 The knowledge gap in earlier investigations

The facts cited in relevant published articles have been analysed critically and the following salient features are found not being addressed properly.

- A lot of research work has been reported on dual fuel mode of the engine using variety of gaseous fuel such as Biogas, Natural gas, LPG, Hydrogen etc. However, a limited work has been reported on producer gas along with vegetable oil and its bio-diesel as pilot fuel.

- Most of the research work has been done on performance, combustion and emission analysis of single cylinder as well as multi-cylinder diesel engine in single mode and dual fuel mode operation. But in particular on twin cylinder engine which has large potential for use in agriculture and small decentralized power generating units, no work has been published in dual fuel mode using producer gas and vegetable oil.

- Though much work has been reported on producer gas application and its effect on the performance and emission characteristics of diesel engine in dual mode with variation of gas composition, speed of the engine, load of the engine, injection pressure and timings of the engine. But the effect of variation of gas flow rate on the performance and emission characteristics of the engine at optimum load condition has not been reported.

- A wide variety of non edible vegetable oils and its bio-diesel such as Hong oil, rubber seed oil, Jatropha oil and Neem oil have been used by many researchers as pilot fuels with producer gas in dual fuel mode for engine applications. No work has been reported regarding blends of Karanja oil and its bio-diesel as pilot fuels with producer gas in dual fuel mode.

- Most of the research work has been reported on performance and emission analysis of dual fuel diesel engine using producer gas operated in natural aspirated mode. However, no work has been reported for engine operated in turbocharged mode for the above analysis.

2.10 Objectives of the present work

It is thus clear that the effect of blends of Karanja oil and its bio-diesel with producer gas in dual fuel diesel engine with and without turbocharged mode has still remained a less studied area. It is felt that a further study in this respect is needed particularly with the inclusion of combustion analysis of producer gas in dual fuel mode both in view of the scientific
understanding and commercial importance. In view of the above, the present work is undertaken to investigate the performance and emission analysis of a twin cylinder dual fuel diesel engine using producer gas under multiple impact conditions.

To address the knowledge gap mentioned in the published research on dual fuel engines, the objective of the present research work has been formulated to:

1. Develop the test fuels and study their physico-chemical properties before use in engine
2. Development of engine test bed without turbocharger
3. Study the performance and emission characteristics of a twin cylinder diesel engine both in single mode as well as in dual fuel mode operation using base line diesel, blends of non edible Karanja oil and its biodiesel under variable load at optimum gas flow rate and variable gas flow rate at maximum load condition. Compare and analysis of obtained results.
4. Modify the existing dual fuel engine test bed to accommodate turbocharger.
5. Study the performance and emission characteristics of a twin cylinder dual fuel diesel engine under with and without turbocharged mode using the above test fuels under variable load at optimum gas flow rate and variable gas flow rate at maximum load condition. Compare and analysis of obtained results.

2.11 Method of Study
Pongamia pinnata (Karanja oil) and woody biomass producer gas are selected for purpose of study. This is because of these two fuels are readily available in India and are cost effective. Different experiments are carried out to find the physical and chemical characteristics of the oil in neat, transesterified and blended form. A twin cylinder diesel engine has been considered for the present research as it has great future potential for use in agriculture and small decentralized power generating units. The performance and emission study of this engine using blends of Karanja oil and its bio-diesel with producer gas as fuel in normal mode of operation under different engine test conditions are studied. The test conditions are at optimum gas flow rate and variable load and variable gas flow rates at optimum load. To improve the engine combustion performance and reduces the emissions parameters, a turbocharger is added to the engine. The effect of turbocharger on the performance and emission of the engine using the above test fuel under the same test conditions is studied. The entire research activity has been planned to carry out as per the sequence given below.
Chapter Summary

This chapter has provided

- An exhaustive review of research works on single mode as well as dual fuel mode operation of different alternative fuels reported by various investigators.
- The knowledge gap in earlier investigations.
- The objectives of the present research work.
- Method of study of this research work.