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## LITERATURE REVIEW

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### **2.1 Introduction**

In the last chapter, the basic aspects related to energy scenario and importance of alternative energy (especially biodiesel used as a fuel for compression ignition engine) related to the present studies were observed. The present chapter comprises the review of existing literature and their analysis related to our research work. This is followed by the literature related to availability of biodiesel feedstock in the country and its production technique (esterification and transesterification) with using the different catalyst such as homogeneous, heterogeneous, and biocatalyst. The current chapter reviews the literature related to biodiesel as a fuel for CI engine, performance and emission characteristics with application of biodiesel. This chapter also includes the literature review on different mathematical and computational modelling of diesel engine while biodiesel as a fuel and life cycle assessment of biodiesel production from different feedstock. Finally, the research gaps are also identified to meet the objectives of the current study.

### **2.2 Biodiesel as a fuel**

Alternative fuels have become a great subject of interest due to the lower environmental pollution, its feedstock availability, and higher consumption existing conventional energy resources. Several alternative energy sources such as biodiesel, biomass, hydrogen, biogas, etc. are available. Amongst these biodiesel having similar properties as the conventional diesel fuel. The first time peanut oil was used by Rudolf Diesel on August

10, 1893 in the engine designed by him [119]. Since then vegetable oils were used as the substitute of diesel oil whenever needed as it was not having the good characteristic as diesel oil. Around a century later first time the primary concerns like cost, effect on performance of engine, durability and standardization of fuel production were discussed in International conference on plant and vegetable oils as fuels, held in Fargo, North Dakota in August 1982 [120]. Vegetable oils have a great potential to fulfill the requirements of an alternative source of energy. Although, which is in its primary phase of development of efficient fuel for the diesel engine [121]. The main concerns with the vegetable oils are low volatilities, inadequate cold flow properties, high viscosity and lower calorific value. The various derivatives were produced from the vegetable oils using various methods in response to improve the characteristic of vegetable oils. Fatty acid methyl ester is one of the most important derivatives, also known as Biodiesel, obtained from triglycerides through the trans-esterification process [122]. The word biodiesel was used for Fatty acid methyl esters for the first time by national bio diesel board (earlier National Soy diesel Development Board) during 1992 in USA. Biodiesel is better than that of petroleum diesel in terms of renewable, biodegradable, non-toxic, exhaust emission, substantially free from sulfur and aromatics nature. Since biodiesel holds very similar characteristics to petroleum diesel, so it can be mixed homogenously in any proportion. The exhaust emission of petroleum diesel gets reduced when biodiesel is mixed with it, henceforth it can be considered as key to reduce the pollutants level and probable carcinogens in petroleum diesel [123]. According to Ma et al. [124] biodiesel has turn into the centre of attraction due to its environmental and renewable benefits.

### **2.3 Engine performance and emission with application of biodiesel**

The performance parameters like engine torque, brake power (BP), BSFC, brake thermal efficiency (BTE) along with engine tailpipe emission such as unburned hydrocarbon

(UHC), carbon monoxide (CO), smoke, particulate matter (PM), oxides of nitrogen (NO<sub>x</sub>) emission of various biodiesels had been reviewed. The physical and chemical properties of biodiesel such as calorific value, viscosity, density, cetane number, cold flow properties like cloud and pour points, fire point, flash point, carbon residue, acid value, and sulphur content depend on the characteristics of feedstock including length of carbon chain, type of bond (single and double bond), and its location, etc. It has been revealed that the engine performance and tailpipe emissions are affected by these physical and chemical properties; on this ground, it can be assumed that the performance of engine and emission characteristics should be correlated to the biodiesel feedstock.

### ***2.3.1 Performance***

Jincheng H et al. [125] have conducted the experimental work on diesel engine at two different working conditions; maximum torque point (1500 rpm) and state of rated power (2000 rpm) engine speed using Jatropha biodiesel as a fuel. They have reported that the Jatropha biodiesel and its blends have shown the comparable performance of the engine and thermal efficiency but slightly higher brake specific fuel consumption (BSFC) in comparison to diesel fuel. For advance injection timing, the brake thermal efficiency (BTE), peak cylinder pressure (P<sub>max</sub>) and HRR<sub>max</sub> are increased while the BSFC is reduced. On the other hand, the opposite trends obtained retarded the injection timing. A higher value of BSFC, peak cylinder pressure and lower value of BTE are obtained for Jatropha biodiesel in comparison to diesel fuel. Although, the optimum engine performance is obtained at 20° bTDC injection timing [126]. O.S. Valente et al.[127] have reported there was increased in specific fuel consumption (SFC) of the engine with increasing the percentage of Castor biodiesel in blends. Similarly, H. Raheman et al. [128] reported increased the BSFC and decreased the BTE as increases the proportion of

biodiesel in the blends. However, the reverse trend found for injection timing and compression ratio with the engine load.

S. K. Nayak et al. [129] have reported that increased the brake-thermal efficiency and decreased the BSFC with increasing the proportion of additive in Mahua biodiesel. Generally, biodiesel having a high content of oxygen and due to which increased the combustion efficiency and thus temperature, which leads to high exhaust gas temperature (EGT). But its value decreased with increasing the proportion of additives in the Mahua biodiesel. S.Jaichandar et al. [130] have studied the effect of varying the combustion chamber geometry on the performance of a diesel engine fuelled with Pongamia biodiesel blended fuel. The experiments have conducted with three types of combustion chambers, namely hemispherical combustion chamber (HCC), toroidal combustion chamber (TCC) and shallow depth combustion chamber (SCC) at fixed compression ratio. The TCC shows higher brake thermal efficiency than the other two types of the combustion chamber (CC). Atul Dhar and A.K. Agrawal [131] have observed that the higher carbon deposits on engine components; cylinder head, injector tip, and piston top with using Karanja biodiesel blends B20. Comparatively lower wear of pistons, piston rings, liners, valves and small end bearing of connecting rods was observed with biodiesel blends. On the other hand, higher wear was obtained for main bearings, big end of connecting rods, bearings and crankpins. The endurance tests have shown that the surface texture of cylinder liners in acceptable condition with Karanja biodiesel blends. In spite of these results, it was not any defect observed during the test of resistance, in the long run, the engine fuelled with biodiesel blends. Atul Dhar and A.K. Agrawal [132] have reported that the higher torque obtained with lower biodiesel blends, and reverse trends follow for higher blends. The value of BSFC was higher for high biodiesel blended fuel. On the contrary, comparable and lower BSFC obtained for conventional diesel and low biodiesel

blended fuel. A lower value of brake thermal efficiency (BTE) was obtained for high biodiesel blends at low load. And the comparable results obtained for all biodiesel blends when the engine operated at high load. Generally, biodiesel has a higher bulk modulus of compressibility; due to this slightly higher fuel-line pressure was observed for high biodiesel blended fuel than that of diesel. Combustion started earlier for lower blends but slightly delayed for higher blends. Shorter combustion duration was observed for low biodiesel blends than pure diesel and longer combustion duration for higher blends. Similarly, a longer combustion period and shorter ignition delay observed for biodiesel and its blended fuel under all loading conditions. Generally, lower peak heat released rate was observed for biodiesel blended fuel in comparison to diesel [92].

D.H. Qi et al. [133] have evaluated the performance and combustion characteristics of two-cylinder four-stroke DI diesel engine fuelled with biodiesel-diesel methanol blend (BDM). The test results showed that the combustion starts almost identical at high engine load, but at the low engine, load combustion starts later for BDM5 and BDM10 than for BD50. BDM5 and BDM10 have shown the similar peak cylinder pressure at low engine load of 1500 rpm and the peak of pressure rise rate and the peak of heat release rate higher than that of BD50. BDM5 and BDM10 showed the peak of pressure rise rate and peak cylinder pressure are lower than those of BD50 at low engine load of 1800 rpm, but similar heat release rate. The crank angles at which the peak values occur are earlier for BD50 than for BDM5 and BDM10. The peak of pressure rise rate, the peak of heat release rate and the peak cylinder pressure at higher engine load for BDM5 and BDM10 are higher than those of BD50, and almost similar crank angle of peak value for all tested fuels. BDM5 and BDM10 have shown slightly lower torque and power outputs than BD50. M. Habibullah et al. [134] have reported that the average value of brake power reduced by 3.92%, 4.71%, and 4.10% for (Palm biodiesel) PB30, (Coconut biodiesel)

CB30, and PB15CB15 and increased the values of BSFC (8.55-9.03%) than that of diesel fuel. The biodiesel shows the lower BTE than diesel. It may be due to the lower heating value of biodiesel. The BTE and BP were slightly higher for the combined blending of palm and coconut biodiesel (PB15CB15) than PB30, but lower than CB30 fuel. On the contrary, brake power was slightly improved by 0.63% than that of CB30 and slightly reduced by 0.20% than that of PB30. Pedro Benjumea et al.[136] have reported that the fuel consumption was increased with enhancing the altitude from 500 to 2400 meter. They also revealed that there was an additive effect with the advance in injection and combustion timing for biodiesel than that of diesel fuel. The premixed combustion duration depends on altitude and biodiesel; its value increases with altitude and decreases with biodiesel. While the engine is operating with biodiesel at high altitude, increases the cylinder pressure and air-fuel equivalence ratios which lead to a reduction in combustion duration. The value of BTE was slightly reduced with increasing the altitude for both fuels, but very high for B0. The increase in altitude the exergy destruction decreased with biodiesel. M.J. Abedin et al. [137] have reported that the average value of brake power is decreased by 2.3% and 10.7% respectively for blends of 10% Palm biodiesel (PB) and 20% Jatropha (JB) biodiesel. The value of BSFC for PB20 and JB20 blends were increased by 26.4%. Orkun Ozener et al. [138] have reported that the reduction in premixed peak and ignition delay for enhancing the content of biodiesel in the blends. The biodiesel and its blends have shown comparable results such as combustion, performance, and emission with diesel fuel. Due to the lower heating value of biodiesel, the value of BSFC is increased by 2-9%, and engine torque is decreased by 1-4% with enhancing the percentage of biodiesel in the blended fuel. D.H. Qi et al. [139] have reported that the increased in BSFC with enhancing the content of biodiesel in the blended fuel. While engine operated at low load, the value of BTE was slightly reduced

for biodiesel and its blends than diesel. However, its comparable value obtained at a high load. They have also revealed that the combustion starts earlier for biodiesel and its blended fuel in comparison to diesel. Generally, biodiesel and its blend have shown the lower peak cylinder pressure as compared to diesel at low load, while almost the same at high engine load. Higher peak heat release rate and peak pressure rise rate of biodiesel and its blend than that of diesel fuel. Whereas, reverse trends obtained when engine operated high load. Sanjid Ahmed et al. [140] have evaluated the performance, emission, and noise of mustard biodiesel (MB) and its blend. They reported that the superior cloud point, oxidation stability, and calorific value (40.40 MJ/kg) for mustard oil as compare to other biodiesel. The mustard biodiesel blends (MB10 and MB20) have shown the lower brake power and higher BSFC than diesel. They have proposed that the MB10 and MB20 can be used as a fuel for a diesel engine without modifications. Cumali İlkılıç et al. [141] have reported that the engine performance is reduced by 2.2%, 6.3%, and 11.2% respectively for biodiesel blends B5, B20, and B50 in compared to diesel. On the other hand, the values of BSFC were increased by 2.8%, 3.9%, and 7.8% respectively for B5, B20, and B50 biodiesel blends than diesel. Also, for rice bran biodiesel, there was a slightly higher fuel consumption rate and comparable power output in comparison to diesel [142]. Similarly, for waste edible oil (WEO) biodiesel, there was slightly higher fuel consumption fuel compared to diesel. Also, there are slight variations in combustion characteristics such as heat release rate, peak pressure, rate of pressure rise, and ignition delay for the WEO biodiesels compared to diesel [143]. G.R. Kannan et al. [144] have conducted the experiment to study the effect of metal-based additive on performance emission and combustion characteristics of a diesel engine fuelled with biodiesel. They reported that the due to mixing of a fuel borne catalyst with biodiesel there was a slight increment in brake thermal efficiency, BSFC, and BSEC at the optimized operating

condition. Also, due to the addition of fuel borne catalyst with biodiesel cylinder gas pressure and heat release rate were increased and decreased ignition delay at optimized operating conditions.

### **2.3.2 Emissions**

Jincheng H et al. [125] have reported the lower carbon monoxide (CO) and hydrocarbon (HC) emissions for Jatropha and others biodiesels than that of diesel fuel while engine operated at high load, and observed the comparable results at lower load. There was a slight reduction in NO<sub>x</sub> and smoke emissions for Jatropha biodiesel in compared to diesel fuel. T. Ganapathy et al.[126] were studied the influence of injection timing on performance, emission, and combustion characteristics of a diesel engine fuelled with Jatropha biodiesel. For advance injection timing, the value of brake specific fuel consumption, CO, HC, and smoke levels are reduced and increased the BTE, P<sub>max</sub>, HRR<sub>max</sub>, NO emission. On the other hand, opposite trends were obtained retarded the injection timing. At all injection timing, higher NO emissions and lower HC, CO and smoke levels are obtained for Jatropha biodiesel than diesel fuel. A minimum value of CO, HC, and the smoke level was obtained at 20° bTDC injection timing while NO emission at 10° bTDC. Castor biodiesel blends have produced lower carbon dioxide (CO<sub>2</sub>) emission and higher HC and CO emission at load in comparison to diesel fuel [127]. Similarly, H. Raheman et al. [128] have reported a significant reduction in the smoke level and CO emissions and slight increment in the NO<sub>x</sub>, increasing the proportion of biodiesel in fuel. However, the emission levels are increased for all the tested fuel when engine operated at a higher load. Generally, biodiesel has shown the CO and HC emissions due to content of oxygen. The level of CO and HC emission was further decreased with added the additive in Mahua biodiesel. Due to higher viscosity, lower volatility, and heating value of biodiesel have shown a higher smoke and NO<sub>x</sub> emissions,

but its value decreased with enhancing the proportion of additives in Mahua biodiesel [129]. S.Jaichandar et al. [130] have reported there was a significant reduction in CO, UHC, and particulates with TCC with comparison to HCC and SCC combustion chamber. Slightly higher oxides of nitrogen emission were observed for TCC. Atul Dhar and A.K. Agrawal [132] have observed lower CO emission was for both biodiesel blends and diesel when the engine operates at high speed and load. However, higher CO for high biodiesel blends at lower load. Lower HC emissions and smoke opacity while higher NO<sub>x</sub> formation observed for biodiesel blended fuel in comparison to diesel at high load. D.H. Qi et al. [133] have reported smoke emission dramatically reduces for BDM5 and BDM10. At speed characteristic of full engine load, NO<sub>x</sub> and HC are similar, and CO emissions are slightly lower than those of BD50.

M. Habibullah et al. [134] have reported higher NO<sub>x</sub> emissions for all biodiesel blends than that of diesel. Slightly higher NO<sub>x</sub> was observed for CB30 and PB15CB15 in compared to PB30. PB15CB15 have shown slightly lower emission than the CB30. There was a higher reduction in CO and HC observed for CB30, PB30, and PB15CB15 as compared to diesel. L. Labecki et al. [135] have reported that the higher soot formation and lower NO<sub>x</sub> emissions for rapeseed plant oil (RSO) and its blended fuel than diesel. The equivalent level of soot emission observed for 30% RSO blends as diesel with simultaneously retarded the injection timing up to 3°bTDC and increased the injection pressures up to 1200 bar. Under these conditions, NO<sub>x</sub> emission was further reduced by 22%. For the 30% RSO blended fuels, the concentrations of exhaust soot particle number were reduced with retarded injection timing and enhancing the injection pressure. The exhaust soot particle concentrations were still more than diesel for 30% RSO blend, even the equivalent level of soot emission was already achieved by diesel. M.J. Abedin et al. [137] have reported carbon monoxide (CO), and hydrocarbon (HC) emissions are reduced

by 30.7% and 25.8% respectively for B20 (20% of Palm or Jatropha biodiesel). The NO<sub>x</sub> emission is increased by 3% while fuelled with JB10 and JB20 blends, whereas its values are reduced by 3.3% while fuelled with PB10 and PB20 blends. Orkun Ozener et al. [138] have reported the significantly reduced the formation CO, and total unburned hydrocarbon (THC). Whereas, slightly increased the NO<sub>x</sub> and CO<sub>2</sub> with increasing the proportion of biodiesel in the blended fuel. Due to oxygen content in biodiesel better combustion and increased the combustion chamber temperature leads to higher NO<sub>x</sub> emissions; especially engine operated at higher loads. There are slight variations in hydrocarbon (HC) emissions between diesel, biodiesel, and its blends. When the engine runs at high load, the CO and smoke emissions were significantly reduced [139]. During engine emissions and noise tests lower (19-40%) CO, (24-42%) HC, (2-7%) noise and higher (9-12%) NO emissions were observed for mustard biodiesel blends as compared to diesel [140]. Cumali İlkılıç et al. [141] have reported that reduced the CO emission, and particulate matter (PM). Whereas increased the oxide of nitrogen (NO<sub>x</sub>) and HC emissions for biodiesel blended fuel than that of diesel. But increases in HC emissions can be ignored because it has very low amounts of all types of fuel test. Similarly, for rice bran biodiesel, there was a slight reduction in CO, HC, and PM emission, but the slight increment in NO<sub>x</sub> formation for biodiesel as compared to diesel fuel [142]. Similarly, Jinlin Xue [143] has reported the that the reduction in PM, HC and CO emissions and minor loss of power, increase in fuel consumption fuel and NO<sub>x</sub> emissions for waste-edible oil (WEO) biodiesel as compared diesel with no or minor modification on an existing engine. Although, the WEO has shown similar engine performances, combustion characteristics, and emissions as compared to different biodiesel and WEO biodiesel blends, and it could replace the standard diesel to help in controlling the air pollution. On the other hand, at optimized operating conditions, the NO<sub>x</sub> and CO<sub>2</sub> emission were

slightly increased, while CO, hydrocarbon (UHC) whereas significantly reduced the smoke emission.

Since the researchers in various countries carried out many experimental works using vegetable oils as I.C. engine fuel substitutes. They reported the comparable thermal efficiency to that of diesel with small amounts of power loss while using vegetable oils. The particulate emissions of vegetable oils are higher than that of diesel fuel with a reduction in NO<sub>x</sub>. Vegetable oil methyl esters gave the performance, and emission characteristics comparable to that of diesel and these can be used as fuel in diesel engines with some minor modifications. Since, the biodiesel holds the most promising features like renewability, sustainability, and lesser impact on the environment so it can play a vital role in transport sectors in forthcoming years. It possesses all the properties of diesel with added advantages; the biodiesel obtained from the different feedstock having a different chemical composition which influences the properties of biodiesel. A relation established for nature of feedstock, performance, and emission characteristics of biodiesel enable us to produce more efficient fuel. There are several studies has been carried out to investigate performance and emission characteristics with dissimilar biodiesel fuelled and engine. However, a comparative study on the variable compression ratio engine using different biodiesel blends is inadequate. Therefore, select the vegetable oil plants for the study based on its availability and high yields in India.

#### **2.4 Numerical modelling of CI engine with used of biodiesel**

Modeling and simulations are quite often used to minimize the experiments to be conducted on internal combustion engine to reduce time and cost [98]. Computational mathematical modeling or numerical solutions can give more effective forecast results on given engine parameters [145]. Compression ignition (CI) engine using diesel fuel has

become more popular for automotive applications due to its higher energy density, durability and efficiency. While CI engines used for blended fuel, optimization of operating parameters is required to enhance the conversion efficiency of fuel for producing higher indicated power with low pollutants [146]. Due to differences in properties of the fuel, the combustion phenomenon of alternative fuel is not similar to diesel. During the combustion of biodiesel in CI engine, some harmful gases emitted, which can be reduced by appropriate combustion process because nowadays require a cleaner and more fuel-efficient engine. Worldwide, several researches are going for developed the various combustion strategies and model [147-149]. The engineers and researchers have developed several combustion phenomena to understand the performance and combustion characteristics of fatty acid methyl ester [150-153]. C.D. Rakopoulos et al. [154] have conducted the multi-zone modelling to analyse the development of fuel spray while diesel, biodiesel and crude vegetable oil as a fuel for diesel engine. S. Patil [155] was used the MATLAB program to simulate the model to the analysis of a single cylinder 3.5 kW diesel engine using Palm Oil Methyl Ester, diesel and its blends as a fuel. The computational results on BTE and IP were closer (2-3%) to experimental results. In addition, they have developed a single-zone thermodynamic model for diesel engine and it integrated with triple-Wiebe function to simulate heat release and cylinder pressure. The prediction of cylinder pressure and heat release rate by simulation model were found to be closer (2.2% and 2.5%) to experimental results. Furthermore, in respect to modeling of blended fuel use in direct injection diesel engine, ethanol-diesel blend [156], vegetable oil, bio-diesel and diesel [157] fueled engine study have been conducted through 2-dimensional and multi-zone model. Several authors [158-162] have used the Wiebe function to predict the burning duration and performance analysis of CI engine. Shipinski et al. [163], Sitkei [164], and Tinaut [165] were used the

single exponential Wiebe function to express the burning rate of DI and IDI diesel engine and they found that burning duration depends on equivalence ratio and engine speed. Watson et al. [166] were used the combustion correlation for diesel engine simulation describe by Wiebe functions. They reported that the parameters appear in Wiebe functions are depends on engine operating parameters (engine speed and load) and geometry of combustion chamber. On the other hand, two-Wiebe function can be used to describe the burning duration in diesel engine. This function includes premixed and diffusive combustion period and depend on fuel injection timing and crank shaft angle [167-169].

Kunpeng et al. [170] have proposed the new simplified phase-divided spray mixing quasi-dimensional combustion model to predict the engine performance. The MATLAB/Simulink software was utilised build the computational programme. They have reported that the simulated results obtained from the model have good accordance with the experimental results; less than 2.8 % relative error for BP and BSFC and less than 9.1% for NO<sub>x</sub> and soot emissions. Sary et al. [156] have developed the single-zone thermodynamic model for analyzing the combustion characteristics of 1-cylinder CI engine fuelled with waste oil biodiesel. This single model was integrated with a triple-Wiebe function to simulate heat release between the period of IVC and EVO. They have reported that the maximum error for cylinder pressure was less than 2.2%, while for mean indicated pressure (MIP) less than 0.3 bars. They have suggested that the present model can be utilized for predicting the engine performance with a variation the start of injection (SOI).

Ismet Sezer [171] was studied the investigation of performance and emission characteristics of a compression ignition engine fuelled with dimethyl ether and diethyl ether. He used the thermodynamic cycle model to simulate the diesel working process and

reported the lower cylinder temperature and pressure, and engine performance for both dimethyl ether and diethyl ether in comparison to diesel at the same injection timing. The brake power was reduced by 32.1% and 19.4% at 4200 rpm while the BSFC was increased by 47.1% and 24.7% at 2200 rpm respectively for dimethyl ether and diethyl ether than that of diesel fuel. At the same time, the BTE for both dimethyl ether and diethyl ether were obtained a similar value or higher than the diesel fuel. At all the conditions, a value of lower carbon dioxides ( $\text{CO}_2$ ) obtained for both fuel dimethyl and diethyl ethers. At the same equivalence ratio, a slightly lower value of CO and NOx obtained for both fuel dimethyl and diethyl ethers. Gogoi and Baruah [172] have developed a combustion model to predict the performance of diesel engine fuelled with diesel, biodiesel (karanja) and its blends (B20, B40 and B60). The model predicted the biodiesel blends B20, B40 and diesel have shown the similar engine performance. On the contrary, the biodiesel blend B60 has shown the better engine performance in terms of BP and BTE as compared to diesel. They have also revealed that the rate of pressure and temperature were higher for all biodiesel blends in comparison to diesel fuel with this model. Scappin et al. [173] studied a zero-dimensional model to evaluate the engine performance and NOx emissions NOx through an energy balance and a two-zone combustion model. From the studies they have reported that the combustion model is the main part of model and the quantity of emission is decided with quality of combustion. There are several CFD software like KIVA, FIRE, and CONVERGE 2.3 can be used for combustion models. Rakopoulos et al. [174] have developed a multi-zone combustion model to evaluate the engine performance and emission of CI engine fuelled with vegetable oil or its biodiesel. In this, fuel injected from nozzles is separated into various discrete volumes (known as 'zones'). These discrete volumes were established in the direction of the injection of fuel and across it. For the combustion, the amount of fuel and

entrained air in each zones are determined by droplet evaporation and jet mixing models. The temperatures and pressure of cylinder are evaluated by applying the mass, energy, and state equations in each zone. Rakopoulos et al. [175] have developed two-dimensional multi-zone combustion model for DI CI engine fuelled with diesel, ethanol and its blends. They founded that the model was followed with its time history in each zone, as the fuel spray penetrated the swirling air environment of the combustion chamber. They have revealed how widely varying the ethanol properties against pure diesel in its blended fuel; considerably affecting the combustion mechanism and its associated emissions pollutants. Vedran et al. [176] have described a quasi-dimensional model implemented in the existing zero-dimensional model through the direct estimation of cylinder temperature and pressure. The model validated with three randomly selected operating points of the engine. The results of the model have shown the full range of operating parameters that could found in detail at the time of the entire working process of the engine. In this model, agglomeration process used in solving the mathematical and modelling problems of the developed numerical model. Kouremenos et al. [177] were developed a FORTRAN program to evaluate the variation of diesel fuel transport and thermodynamic properties. Kouremenos et al. [178] were developed a FORTRAN program to evaluate the fuel evaporation process in CI engines.

Reiter and Kong [179] were presented a multi-zone model to evaluate the combustion and emissions characteristics of CI engine fuel fuelled with ammonia-diesel dual fuel. They have obtained a longer value ignition delay for dual fuel, and claim that it may be due to increased ammonia, and this leads to a reduction in peak combustion pressure. The value of BSFC was high for below 40% ammonia dual fuel. The NO emission reduced when the ammonia proportion in the duel was less than 40%. Boretti [180] used a multi-zone combustion model for direct ignition diesel engine. They have reported that the diesel

injection during compression and expansion to create pressure is the best option to develop a pressure profile. When the engine operated at high load, thermal efficiency was 10% higher for diesel injection and hydrogen jet ignition combustion models. Komninos and Rakopoulos [181] have conducted the review on modelling HCCI combustion of bio-fuels. They reported that the study of multi-zone models for mixture thermal and fuel stratification is essential because it provides a better and more realistic estimation of combustion duration, peak pressure during combustion, and the formation of pollutants. From the study, they revealed that the multi-dimensional models give a better spatial resolution of the combustion chamber in comparison to the multi-zone model. Visakhamoorthy et al. [182] have described a multi-zone model for mathematical study of a CI engine fuelled with biogas. They reported that the model represented the adequate quality of HRR and prediction of pressure curves after calibration. The cyclic variability was unable to handle this model. They also revealed that the NO<sub>x</sub> formation was increased with small enhance in cylinder temperature. Roberto and Ezio [183] have developed the correlations for the prediction of ignition delay with multiple injections in diesel engines. They reported initially a global-mechanism approach was used for modelling of ignition delay; which accounts the separate contribution of physical and chemical delay. The physical ignition delay estimated regarding the global-mechanism model. It has started with a scaling law to evaluate the length of liquid fuel spray, which was generated by Sandia National Laboratories. They have reported that the physical delay depends on the thermodynamic conditions of fuel, characteristics of an injector nozzle, and injection pressure. On the other hand the chemical delay was modelled by means of an Arrhenius-like expression, which considered the effect of density of charge, temperature and concentration of oxygen. They reported that the burning process of the pilot injection shots is significantly affected the thermodynamic and chemical charge

conditions at the start of the main injection. They also reported that the developed correlations are straightforward and quick to apply with no need for an iterative procedure, and these are accurate both in steady-state and fast engine transient conditions. Hariram and Bharathwaaj [161] developed a zero-dimensional mathematical model for CI engine fuelled with diesel, biodiesel and its blend. They have investigated the combustion parameters, including increase in-cylinder pressure, net heat release, and rate of pressure rise are found to be higher for pure diesel and declined with the increasing the proportion of beeswax biodiesel in blends. They have also reported that the theoretical simulation well supported to experimental data constant injection timing, speed and CR.

Xiuxiu et al. [184] studied the effect of different combustion models on 2-stroke diesel engine performance. They have reported that the acceptable ranges of errors observed in the results of cylinder pressure and emissions. The maximum cylinder pressure obtained with the chemistry solver combustion model (SAGE), and it was very close to the experimental data compared to the results obtained from other models. There was slight variation in the cylinder pressure between n-heptane and n-tetradecane with the similar combustion model, while almost identical integrated heat releases observed for the different models. Although, higher error was accounted with n-heptane-SAGE model compared to other models for the formation of NO<sub>x</sub>. The simulated results for NO<sub>x</sub>, HC, CO, and CO<sub>2</sub> obtained with the model n-heptane-CTC/shell almost closed to the experimental. The critical elements of the alternative fuel system need to be adjusted to ensure the emission of experimental data. Ultimately, for comparison of the results such as the temperature profile, equivalent ratio, and emissions obtained from different models were validated. Hu et al. [185] have used the Wiebe function for analyzing the burnt fraction sensitivity and zero-dimensional model of a diesel engine. They have analysed the sensitivity of each Wiebe's parameters such as efficiency factor ( $a$ ), form factor ( $m$ ),

crank angle of combustion start ( $\theta_s$ ), and combustion crank angle duration ( $\theta_d$ ). They reported that the parameters  $a$  and  $\theta_s$  are more sensitive than  $m$  and  $\theta_d$ . However,  $m$  and  $\theta_s$  should be calculated carefully while  $a$  and  $\theta_d$  can be estimated roughly. The sensitivity of all parameters, such as signal-to-noise ratio, cylinder pressure, and the heat release were more significant during the middle stage of combustion than in the initial than last stages. Consequently, during the establishment of the Wiebe's parameters, it was logical and compulsory to avoid the initial and last stages of the combustion. Finally, they reported that the  $\theta_{ignite}$  and  $\theta_{s-50}$ ,  $\theta_{s-max}$  was most appropriate to be set as  $\theta_s$  in standard and double Wiebe functions.

Furthermore, some other technique such as neural network has been also used to predict the engine performance. Javed Syed et al. [186] developed the artificial neural network (ANN) model to efficiently prediction of performance and emission characteristics of H<sub>2</sub> dual-fuelled diesel engine. They reported the uncertainty analysis was evaluated to determine the error in the experimental results. They also reported that the experiment exhibits the hydrogen flow rate plays a significant role in the evaluation of performance and emissions characteristics of a diesel engine. Nik Muhammad Hafiz et al. [187] have conducted the simulation of the combustion process for a CI hydrogen engine in an argon-oxygen atmosphere. They have used the CONVERGE 2.2.0 software for simulation, and the YANMAR engine NF19SK model to determine the basic parameters. They revealed that the value of pressure and temperature in the combustion chamber were affected with changing the injector location in engine. While increasing the compression ratio, increased in pressure more rapid than the temperature. Although, lowered the maximum heat release rate and increased the combustion duration when combustion at high compression ratio. They also revealed that the hydrogen combustion followed the Arrhenius equation at ambient temperature below 1200 K.

Thus, in the last 20 to 30 years, several research groups have proposed the different combustion models [188-190]. Lu et al. [191] have presented a model that the combined affects of the fuel composition and its management. Sun et al. [192] have proposed studied the NO<sub>x</sub> formation from biodiesel. They reported few advantages of their combustion model, in which there was evidence of a decrease in CO, CO<sub>2</sub>, HC and PM emissions with similar fuel properties. On the contrary, Banapurmath et al. [193] have conducted the experimental investigations of injection timing, injection pressure and compression ratio on performance and emission characteristics of Honge oil methyl ester (HOME) on DI diesel engine. Steinberg et al. [194] have studied both statistics and dynamics of turbulence-flame alignment in premixed combustion. They reported that the surface flame was affected by the orientation of turbulence structures. Apart from these, Ranzi et al. [195] have proposed a hierarchical and comparative kinetic modelling of laminar flame speeds of hydrocarbon and oxygenated fuels. Klimenko and Pope [196] have proposed the modelling of turbulent reactive flows based on multiple mapping conditioning (MMC). In this, the feature of the probability density function, moment closure, and mapping closure models successfully merged.

In this section, the different CI combustion model, including, single-zone, multizone, and multi-dimensional, has been reviewed. It has found that the single-zone model was the more useful tool in the quick prediction of engine parameter but needed adjustment of the Wiebe's function parameters for different working condition. Theses Wiebe function parameters are related to engine operating condition and its geometry. The drawbacks of single-zone have been eliminated in the multi-zone models by accounting the air entrainment, fuel-air mixture inhomogeneities, engine geometries and, temporal and spatial variation of the flow field. Most of the autors have reported the burning duration is the specific parameter, which can be precisely estimated at starting of computational

program to predict the engine performance easily. However, they have not given any information regarding the calculation of burning duration.

## **2.5 Life cycle assessment of vegetable oil plants in biodiesel production**

Life cycle assessment (LCA) of biodiesel is an essential approach for biodiesel production and its uses in the engine, and it shows the complete image from the cradle to the grave. Several researchers have been used the LCA approach to analyze the impacts of environmental and energetic suitability of biodiesels.

### ***2.5.1 Energy and economic consideration***

WMJ Achten et al. [197] have conducted the LCA of Jatropha biodiesel as a fuel for transportation in rural India. They have reported the average 222.0 kJ/FU (functional unit) fossil energy needed for the Jatropha system. The maximum fuel consumption in biodiesel production (48.9%) followed by oil extraction phase (39.1%) and cultivation phase (12%). The value of net energy gain (NEG) and net energy ratio (NER) were 188.7kJ/FU and 1.85, respectively. However, the net energy gain increased to 530.3 kJ/FU and NER to 3.40 when considered all products and by-products. For Neem system, total energy input, and output was to be 2831.28 MJ and 62133.75 MJ per hectare. The cultivation phase (41.76%) share the highest energy input followed by biodiesel production phase (24.83%) and oil extraction phase (23.32%). The maximum energy output was obtained from wood/timber (57750 MJ/ha) and followed by biodiesel (4717 MJ/ha) and glycerine (416 MJ/ha). They reported NER for the life cycle of Neem biodiesel was founded to be 26 times higher as compared to the diesel system. They also revealed that the Neem is ecologically sustainable for producing biodiesel [199]. Lokesh et al. [200] have reported the total energy requirement was 2948.76 MJ/ha for Pongamia biodiesel system. The highest energy consumed in cultivation phase (41.45%) followed

by esterification phase (26.10%) and oil extraction phase (23.35%). The requirement of non-renewable energy was 28 times lower than that of diesel fuel. The total annual output was 74421.52 MJ/ha and the maximum output obtained from fuel-wood (77.6%). M.A. Rajaeifar et al. [201] have considered the five stages; agricultural, transportation, crushing of seed, conversion of biodiesel, and its transportation of the Soybean life-cycle process. They reported the total energy consumption was 42261.15 MJ/ha, from this most of the energy consumed in the cultivation of soybean crops (73.8%) followed by soybean crushing (17.9%) and biodiesel conversion (8.33%). In the cultivation of soybean highest energy consumed in use of electricity (51.12%), it followed by fertilizers (27.02%) and diesel fuel (15.88%). Similarly, in soybean crushing, most of the energy consumed in natural gas (62.58%), followed by electricity (35.50%) used. And in the biodiesel conversion, most of the energy consumed in methanol (85.41%), followed by machinery (7.38%) used. On the other hand, the total consumption of fossil energy with co-product allocation was 8617.7 MJ/ha. From this, most of the energy consumed in agricultural soybean production (50.65%) followed by biodiesel conversion (33.50%), soybean crushing (12.28%), soybean transportation (2.76%) and biodiesel transportation (0.81%). The total renewable energy output was calculated as 16991.4 MJ/ha while biodiesel as the primary outcome. The NEG and fossil energy ratio (FER) were 8373.7 MJ/ha and 1.97 respectively, and revealed that soybean is a suitable energy crop for the production of biodiesel. For the Palm oil system, total annual energy input was 17.19 GJ in the production of 1-ton crude palm oil (CPO). From this, most of the energy consumed in the palm oil mill (58.9 %) and it followed by the production of primary energy e.g., fertilizers (16.15%), cultivation (13.98%) and transesterification (10.47%). They have also reported the total energy output as 60.72 GJ/ton-CPO/year and energy output/input ratio as 3.53 [202]. For the Jatropha system, the net energy ratios were 1.5 to 8.6 and 1.2 to 7.0,

respectively, for irrigated and rain-fed scenarios [203]. Krishan et al. [204] have reported the total energy input during the cultivation of the *Jatropha* system as 93.51 GJ. On the other hand, the total energy released, energy gain, and energy ratios are 161.65 GJ, 70 GJ and 1.77, respectively. And these values could be increased if consider the energy content of the by-products and used more efficient oil extraction methods for seed pressing and lesser fertilizers in cultivation. They have also reported the most of the energy consumed in oil extraction (42.12%) followed by cultivation (33.84%) and oil processing (24.04%). During the cultivation and oil extraction, most of the energy consumed in fertilizers application (96.86%) and seed pressing (82.77%).

A. Mohammadshirazi et al. [205] have reported the total input energy as 30.05 MJ/L for production of biodiesel from waste cooking oil, in which share of direct and indirect energy is 20.38% and 79.62%. From this, most of the energy consumed in waste cooking oil (77.08%) followed by alcohol (19.44%), machinery (1.73%), catalyst (1.0%), electricity (0.52%) and human labour (0.24%). They have obtained energy output, energy ratio, specific energy, energy productivity, net energy, fossil energy ratio, and energy intensiveness energy as 44.91 MJ/L, 1.49, 26.44 MJ/kg, 0.04 kg/MJ, 14.9 MJ/L, 1.3 and 25.01 MJ/\$, respectively. The total expenses were 1.2 \$/L, in which major expenses shared by the crude waste cooking (54.81%) and followed by human labour (27.75%). They have estimated the expenditure and gross production value as 1.20 \$/L and 2.499 \$/L in the production biodiesel. Most of the total expenditure was variable costs (99%), while 1% was fixed expenditures. The major expenses were the catalyst (43%) followed by human labour (23%), machinery (17%), electricity (7%), rent land (3%), service and maintenance (3%), waste cooking oil (2%) and alcohol (2%). They have also estimated the gross return, net return, benefit to cost ratio, productivity as 1.302 \$/L, 1.298 \$/L, 2.081 and 0.946 kg/\$, respectively. M. Omid et al. [206] have used a non-parametric data

envelopment analysis (DEA) technique to investigate the degree of technical efficiency (TE) and scale efficiency (SE) of producers, and evaluated the energy inputs and outputs in the production of cucumber. They have estimated total energy input as 152908.43 MJ per hectare, in which major share of non-renewable (95%) in comparison to renewable energy (5%). They reported the DEA was a useful tool for analyzing and benchmarking productive efficiency of greenhouses and estimated the TE of the inefficient DMUs (decision-making unit) as 91.5%. It means that a similar level of production can be produced with 91.5% resources if these units were working on the frontier. Another explanation of that result was 8.5% of overall resources could be saved by increasing the performance of these DMUs to the highest level.

A. Mohammadshirazi et al. [207] have reported the total consumption of energy in tangerine production as about to 62 GJ/ha. From this, most of the energy consumed in chemical fertilizers (53%), and it followed by chemicals (21%) used in biodiesel production, farmyard manure (9%), human labour (5%), electricity (5%), water for irrigation (3%), diesel (3%) and machinery (2%). They have estimated the energy output, energy ratio, energy productivity, specific energy, net energy, and energy intensiveness as 54GJ/ha, 0.87, 0.43 kg/MJ, 2.32 MJ/kg, -8201.4MJ/ha, and 7.36 MJ/\$. They have also calculated the benefit-cost ratio, mean net return, and productivity and founded to be 1.62, 3223.7 \$/ha and 5.2 kg/\$, respectively. They have suggested for establishing the sustainable and cleaner food production systems with the application better machinery management technique, use of alternative energy sources like organic fertilizers, improvement in timing, amount and reliability of water application and use of new irrigation systems. Somporn and Shabbir [208] studied the full chain energy analysis Palm oil in the production of biodiesel. They have estimated the total energy input as 15.75 MJ/kg of PME (palm methyl ester). From this, most of the energy consumed in

methanol (34.6%) followed by transport (31.8%), fertilizers (24.1%), herbicide (4.5%), electricity (2.1%), diesel (1.4%), NaOH (1.2%) and seed (0.4%). They have calculated the net energy balance (NEB) and NER respectively as 55.51 GJ/ha and 2.42. However, the values of NEB and NER with addition of its co-products were increased as 100.84 GJ/ha and 3.58, respectively. They have suggested that the environmental and economic impacts should be incorporated for overall LCA.

Victoria et al. [209] have conducted the LCA in microalgal biodiesel production with the use of a hybrid cultivation system. They have found the lower environmental impact for microalgal biodiesel production compared to diesel. They have evaluated the GWP, and fossil-energy requirements (FER) decreased by 42% and 38% than that of diesel in the production of 1-ton biodiesel. They have revealed that the mixotrophic cultivation was the most sustainable production process and under which achieved the maximum reduction in GWP and FER with saving of 76% and 75% in comparison to diesel. They have also reported the sustainability of algal biodiesel depends on the efficient utilization of co-products.

### ***2.5.2 Global warming potential***

WMJ Achten et al. [197] have reported the global warming potential (55%) as compared to other life cycle assessment study of *Jatropha* plant. Even though, the acidification and eutrophication potential are increased by 49% and 430% for *Jatropha* system as compared to the reference case. Total CO<sub>2</sub> emission was 123.7 gram CO<sub>2</sub>-eq/FU. The CO<sub>2</sub> emissions from cultivation, oil extraction, and biodiesel production phase were 106.66, 3.74, and 13.34 gram CO<sub>2</sub>-eq FU<sup>-1</sup> respectively. The cultivation of crops phase shown the highest contribution (86%) in CO<sub>2</sub> emissions during the LCA analysis of *Jatropha* system. The major emission observed from fertilizer application (N<sub>2</sub>O). The transesterification

process contributed only 11% of the total, in which major CO<sub>2</sub> emissions from methanol production. Similarly, Kiman Siregar et al. [198] have reported the higher global warming potential (GWP) for the Palm system as compared to Jatropha. The used of agrochemical as a fertilizer or in the form of plant protection for Palm and Jatropha system have generated a considerable amount GWP. The agrochemical shared the GWP 50.46 % and 33.51 % respectively for the Palm oil and Jatropha oil. The GWP emission up to 5 year plantation was 1695.36 kg-CO<sub>2</sub>eq./t-BDF and 740.90 kg-CO<sub>2</sub>eq./t-BDF respectively for Palm oil and Jatropha LCA system. The CO<sub>2</sub> emission from diesel fuel was decreased by 37.83 % and 63.61 % respectively for BDF-CPO and BDF-CJCO when stabilized the production. For both oil plants, most of GWP emissions came from biodiesel production phase followed by fertilizer application and protection plant. A.C. Lokesh et al. [199] have reported total GWP emission from the life cycle of Neem biodiesel system as 1561011.75 g CO<sub>2</sub>-eq/ha and also found the negligible acidification potential (AP). In which, cultivation phase (90%) was shared the maximum GWP emission and it followed by oil extraction (4.8%) and biodiesel production phase (5.2%). They founded negligible acidification potential (AP) for Neem system. They have revealed that 1-hectare plantation of Neem was able to sequestering the 1.35 ton of biogenic CO<sub>2</sub> emitted during the life cycle of Neem biodiesel, with additional sequestration potential of 8.65 ton CO<sub>2</sub>/ha. For the Pongamia system, annual GHG emission from was 1543749.22 g CO<sub>2</sub>-eq/ha. The most of the CO<sub>2</sub> emissions released from cultivation phase (89.11%) followed by oil extraction (5.68%) and biodiesel production (5.20%). The Pongamia biodiesel system was produced 1.25 times more CO<sub>2</sub> emission compared to fossil fuel. They revealed that the GWP emission would be seven times less for Pongamia biodiesel system if the wood not used as fuel. It was evident that about 1 ton CO<sub>2</sub> sequester in one hectare Pongamia plantation. Acidification potential (AP) and eutrophication potential (EP) was

found to be very low in comparison to fossil fuel [200]. For the soybean system, total GHG emissions was 1710.3 kgCO<sub>2</sub>/ha. In which, major GWP emission released during the agricultural soybean production (77.9%) followed by soybean crushing (11.35%) and biodiesel conversion (6%) [200]. Similarly, M.A. Rajaeifar et al. [201] reported total CO<sub>2</sub> emissions released in palm oil LCA system was 3665289.12 kg CO<sub>2</sub>/ton-biodiesel. Most of the emission was come from cultivation of palm (95.6%), in which major emission from respiration process (93.4%). During gross assimilation of palm oil plants sequestrate 5462257.45 kgCO<sub>2</sub>/ton biodiesel (161000 kg CO<sub>2</sub>/ha/year). Sunil Kumar et al. [203] have reported a significant reduction in greenhouse gas (GHG) varies value from 50% to 107% and 40% to 93% respectively for irrigated and rain-fed scenarios for *Jatropha* system. They also reported there were reduction in GHG emission values of 54 and 40 and net energy ratio values of 1.7 and 1.4 respectively these scenarios and it was indicated the renewability and eco-friendly nature biodiesel. Krishan et al. [204] reported the total CO<sub>2</sub> emission was released to be 8.64 metric ton (Mton) during the first five years of *Jatropha* plantation. During that period the most of CO<sub>2</sub> emission released from oilseed pressing (50.81%), followed by oil processing (21.64%) and cultivation (20.83%). They have also found that the used of organic fertilizers in cultivation, biocatalyst in oil or using catalyst-free supercritical alcohol method for processing would help to reduce in nitrous oxide and CO<sub>2</sub> emissions. Edgard and Jegannathan [210] have studied the LCA of Algae in the production of biodiesel. They reported that the algal system producing biodiesel, animal feed, and succinic acid produced less CO<sub>2</sub> emission as compared to that algae system that produces biodiesel and animal feed. The co-products from algae have shown the lower environmental impact as compared to reference products. They have also reported a higher carbohydrate composition in algae favors, lower CO<sub>2</sub> emissions and consumption of fossil fuel in the Algae system in comparison to the reference system. Jinglan Hong

[211] was studied the uncertainty propagations in LCA of biodiesel and conventional diesel fuel. They have revealed that the probability of global warming and non-renewable energy biodiesel was lower for biodiesel in comparison to diesel, which is 92.3% and 93.1%, respectively. The results also indicated the level of confidence of this effect based on global warming potential and non-renewable energy scores, and biodiesel was more environmentally friendly than diesel.

## **2.6 Finding of the Review**

These are the followings findings of the review:

- Acid-base trans-esterification is most common process for biodiesel production.
- Performance is improved and emission is reduced with biodiesel blends.
- The Weibe function is used to describe the burning duration in diesel engine.
- Two-Wiebe function is used for premixed and diffusive combustion period for CI engine.
- The combustion duration of CI engine depends on: engine speed, load, fuel injection timing, equivalence ratio, geometry of combustion chamber, crank shaft angle.
- Fuel evaporation and mixing model are used to describe the combustion of CI engine.
- The fuel evaporation and air entrainment rate affect the burning rate.
- Methanol share most of energy consumed during the biodiesel production.
- Recovery of methanol during biodiesel production.
- By-products are used as energy carrier host.
- Biodiesel is produced from longer life non-edible vegetable oil plants.

## **2.7 Research Gap**

There are following research gaps that need to be worked on:

- Region wise selection of vegetable oil plants for biodiesel production.
- Parametric basis (compression ratio and load) analysis of experimental results for different biodiesel blends.
- Effect of storage time on performance, emission and properties of biodiesel.
- Development of the empirical correlation for burning duration in CI engine.
- The burning duration empirical correlation for CI engine with the incorporation of effecting variables while biodiesel blends using as fuel.
- Estimation of unburned and burned area for heat transfer in CI engine.
- Prediction of results with the variation of engine geometry.
- Comparative life cycle analysis to select the economical vegetable oil to produce the biodiesel.

## **2.8 Objective**

These are the followings objectives of the present thesis:

- Comparative performance and emission analysis of different biodiesel blends (Neem, Linseed, Mahua and Castor) at 1500 constant rpm.
- To develop an empirical correlation for calculating the burning durations for the quasi- dimensional heat transfers for CI engine.
- Estimation of the rate of change of mass in burning zone.
- Calculation of heat transfer (burned and unburned zone) in CI engine combustion.
- Species calculation using biodiesel blends as a fuel.
- Validation of computational results with experimental.

- Prediction of engine performance with the variation of stroke/bore ratios.
- Comparative energy analysis of vegetable oil plants for biodiesel production.
- Comparative economic analysis of vegetable oil plants for biodiesel production.