Renewable and Sustainable Energy Reviews 80 (2017) 620–647

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Effect of different technologies on combustion and emissions of the diesel engine fueled with biodiesel: A review

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ARTICLE INFO

*Keywords:*
Biodiesel
Combustion and emissions
Diesel engine
Particulate matter

ABSTRACT

Due to the shortage of the conventional fossil fuels and air pollution from combustion, new, sustainable and cleaner fuel resources are urgently required. Biodiesel has been introduced as a potential and alternative fuel for years. Biodiesel can be produced from different sources such as vegetable oils, animal fat, waste oil, etc. All of them are renewable and do not affect the food security. When biodiesel is used as a fuel resource for diesel engines, the performance and emission characteristics such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and brake power are almost maintained while hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) is decreased significantly. However, higher $NO_x$ concentration is observed. This disadvantage of using biodiesel or biofuels in general is improved in recent years. The purpose of this work is to do a comprehensive investigation of different approaches applying to biodiesel fueled engine like biodiesel additives, exhaust gas recirculation (EGR), water injection (WI), emulsion technology (ET), injection strategy modification, simultaneous technologies (ST), combustion chamber geometry modification and low temperature combustion (LTC) mode. By the way, the impacts of these technologies on engine performance and emission characteristics are summarized. Upon the comparison, using LTC mode is more efficient and feasible than the others. It can reduce both $NO_x$ and PM emissions simultaneously by up to 95% and 98%, respectively, while engine performance is slightly reduced. Looking inside the LTC mode, the most efficient model is the reactivity controlled compression ignition (RCCI) combustion system. Applying RCCI combustion model might lead to the increase of CO and HC emissions, but this issue can be easily solved by using some available technologies.

## 1. Introduction

In recent decades, total worldwide energy consumption has been increased significantly. It leads to the global warming phenomenon result in higher average temperature of the earth [1] and threatening the energy security [2]. The rate of energy consumption will reach about 53% by 2030 [3] as reported by IEA (International Energy Agency). Thus the depletion of fossil fuels is appeared in clear vision in the near future. In addition, emissions from burning petroleum-derived fuels affected adversely both the environment and human health [4,5]. To cope with this issue, almost every country in the world released the emission legislations which are more and more stringent [6]. For all of those reasons, the alternative, sustainable fuels that can gradually replace the fossil fuels are urgently required. Among the proposed alternative fuels for diesel engines, biodiesel was considered as a reliable potential candidate.

Biodiesel fuels are formulated from animal fat and vegetable oil, which are non-toxic and more bio degradable [7], eco-friendly and more reliable [8]. Biodiesel is now widely accepted as a comparable fuel to fossil diesel owing to its several favorable factors like availability, higher lubricity, and lower exhaust emissions. Conversely, biodiesel fuel has some disadvantages such as lower heating value, higher density, higher viscosity and higher nitrogen oxides ($NO_x$) emission compared to conventional diesel [9]. Regarding $NO_x$ emission, due to strict emission standards might lead to a significant barrier to using biodiesel it is necessary to be concerned about combustion and emissions of the diesel engine fueled with biodiesel. In the literature, there are different approaches to improve diesel engine's performance and emission when shifting to use biodiesel fuel.

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http://dx.doi.org/10.1016/j.rser.2017.05.250
Received 19 April 2016; Received in revised form 6 May 2017; Accepted 26 May 2017
1364-0321/ 

**Nomenclature**

| | |
|---|---|
| IEA | International Energy Agency |
| HTC | High Temperature Combustion |
| IMEP | Indicating Mean Effective Pressure |
| CR | Compression Ratio |
| DI | Direct Injection |
| CI | Compression Ignition |
| TC | Turbocharged |
| LHR | Low Heat Rejection |
| PM | Particulate Matter |
| HC | Hydrocarbon |
| CO | Carbon Monoxide |
| BSFC | Brake Specific Fuel Consumption |
| EAT | Exhaust After-treatment |
| TDC | Top Dead Center |
| PCCI | Premixed Charge Compression Ignition |
| ATDC | After Top-Dead-Center |
| EN14213 | European Union Standards (Bio-Heating Fuels) |
| HCCI | Homogeneous Charge Compression Ignition |
| BTE | Brake Thermal Efficiency |
| SOI | Start of Injection |
| CFD | Computational Fluid Dynamics |
| NA | Naturally Aspirated |
| LL | Low Load |
| HL | High Load |
| ml | Medium Load |
| AC | Air Cooled |
| WC | Water Cooled |
| CS | Constant Speed |
| DE | Diesel Engine |
| CA | Crank Angle |
| rpm | Revolutions per minute |
| PAHs | Polycyclic Aromatic Hydrocarbons |
| JB | Jatropha Biodiesel |
| TOME | Tall Oil Methyl Ester |
| KB | Karanja Biodiesel |
| RB | Rapeseed Biodiesel |
| WCB | Waste Cooking Biodiesel |
| RCCI | Reactivity Controlled Compression Ignition |
| CSB | Cottonseed Biodiesel |
| SB | Soybean Biodiesel |
| SFB | Sunflower Biodiesel |
| COB | Corn Oil Biodiesel |
| RBB | Rice Bran Biodiesel |
| TPB | Thevetia Peruviana Biodiesel |
| JOB | Jojoba Biodiesel |
| MB | Mahua Biodiesel |
| CB | Colza Biodiesel |
| PKB | Palm Kernel Biodiesel |
| COME | Castor Oil Methyl Ester |
| CnB | Canola Biodiesel |
| FOB | Fish Oil Biodiesel |
| BTDC | Before Top-Dead-Center |
| AASTM D6751 | ASTM D6751-01 American Society for Testing and Materials (Biodiesel Standards), USA |
| EN 14213 | European Union Standards (Biodiesel) |
| DPPD | N,N′-diphenyl-1,4-phenylenediamine |
| ODA | Octylated Diphenylamine |
| PPDA | p-phenylenediamine |
| BHT | Butylated hydroxytoluene |
| EDA | Ethylenediamine |
| NPAA | 4-nonyl phenoxy acetic acid |
| DEE | Diethyl Ether |
| EHN | 2-ethyl-hexyl nitrate |
| DMC | Dimethyl Carbonate |
| TCC | Toroidal Combustion Chamber |
| SCC | Shallow Depth Combustion Chamber |
| HCC | Hemispherical Combustion Chamber |
| UBHC | Unburn Hydrocarbon |
| FAAE | Fatty Acid Alkyl Esters |
| TBHQ | Tert-butylhydroquinone |
| MBEBP | 2,2′-methylenebis (4-methyl-6-*tert*-butyphenol) |
| PHC | Pyridoxine Hydro Chloride |
| DEA | Di-Ethyl Amine |
| TPB | Thevetia Peruviana Biodiesel |
| LOME | Linseed Oil Methyl Ester |
| PME | Palm Methyl Ester |
| H50 | 50% Honne oil |

Sivalakshmi et al. [10] analyzed the impacts of biodiesel fuel on $NO_x$ emission and their countermeasures. They concluded that using biodiesel reduces the carbon monoxide (CO), hydrocarbon (HC) and smoke emissions, but $NO_x$ increased. Similar reports have also been presented by other researchers [11–13]. The common known mechanism for the formation of $NO_x$ emission during combustion includes thermal, prompt, and NNH mechanisms [12,14], in which the thermal and prompt mechanisms are the most important ones in biodiesel combustion [15]. Thermal $NO_x$ is originated from high local temperature due to excess hydrocarbon oxidation. Prompt $NO_x$ is produced by the formation of free radicals in the front flame. It was reported that $NO_x$ concentration was mainly affected by the prompt mechanism in biodiesel combustion [16–18] (see Fig. 1).

Combustion and emission characteristics of diesel engine operated

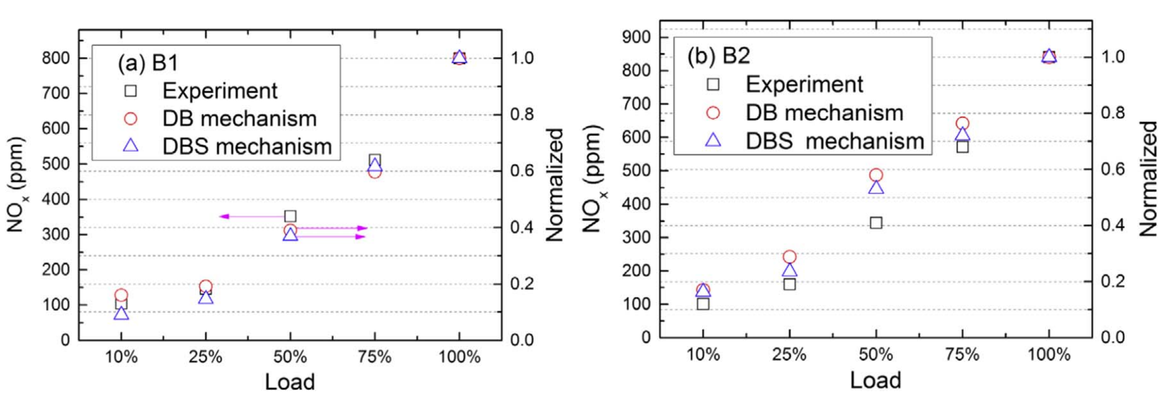



**Fig. 1.** $NO_x$ emission trends prediction testing [16–18].

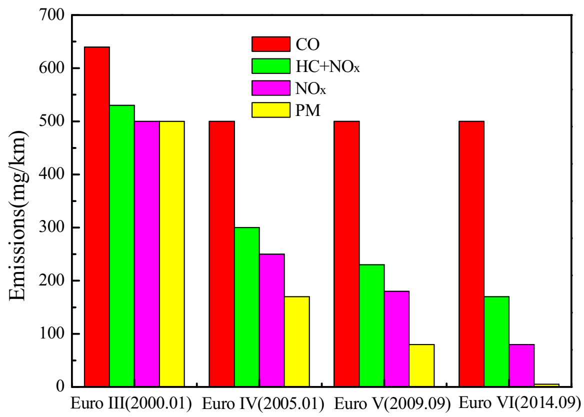



**Fig. 2.** EU Emission Standards for Passenger Cars [43].

using biodiesel and its blend were also investigated by many experts and authors. Sharanappa et al. [19] studied the effect of blend ratio of mahua oil in biodiesel on engine's performance and emission. They found that the higher mahua oil ratio in the blend, the lower HC and CO emissions, higher brake specific fuel consumption (BSFC) and higher $NO_x$ emission. Similar results were reported by Rao et al. [20] when they used rice bran oil biodiesel. In addition, the authors found that soot was reduced when the engine operated with biodiesel. Other researchers [21–23] also reported that using biodiesel as engine fuel will lead to higher BSFC and $NO_x$ emission comparing to using fossil diesel fuel. To improve fuel consumption and emissions, there have been some different techniques applied.

The most common techniques have been applied include the modification of fuel properties, engine design alteration, and exhaust gas treatment. The intention of the fuel properties modification is to enhance the mixture formation and combustion processes without any engine modification. In this way, some different additives including metal based additives, antioxidants and oxygenated additives, cold flow improver, etc. were used with biodiesel [24,25]. It is well known that biodiesel has a high viscosity so these additives could solve the problem of cold flow properties for their large number of usage in diesel engines. In other cases, some additives were applied to improve the engine performance and exhaust emissions as fueling with biodiesel.

The effects of ethanol as oxygenated additive to biodiesel was studied by Gvidonas et al. [26]. They found that adding ethanol to biodiesel fuel reduced the $NO_x$ and the HC emission for richer combustible mixtures. Besides that, the influence of a higher ethanol mass content on CO and PM emissions depends on the air-fuel ratio and engine speed. In another research, Balaji and Cheralathan [27] investigated the effects of antioxidant additives (L-ascorbic) with cottonseed methyl ester on engine performance and emission characteristics. It was concluded that BSFC slightly decreased, HC, $NO_x$, $CO_2$, and smoke emission decreased, but brake thermal efficiency (BTE) and CO emission increased. For metal based additives, Keskin et al. [28] investigated the influences of tall oil biodiesel with magnesium (Mg) and molybdenum (Mo) based fuel additives on diesel engine performance and emissions. It was indicated that CO emission and smoke opacity was decreased by 56.42% and by 30.43%, respectively. However, lower $NO_x$ and $CO_2$ emissions were recorded in case of engine fueling with the biodiesel without additives.

On the other hand, the fuel properties like viscosity, density, and surface tension of biodiesel have much more affects to the fuel vaporization and atomization than those of diesel fuel as reported by Allen et al. [29,30]. The improvement of the spray atomization in the compression ignition process of the diesel engine fueled with biodiesel still had some problems about uncertainties. Biodiesel fuel has the higher kinematic viscosity and surface tension which cause a higher droplet size, leading to the difficult vaporization and atomization. Lee et al. [31] reported that the atomization of biodiesel blends was worse than that of diesel fuel.

As mentioned above, when a diesel engine was operated with biodiesel blends, $NO_x$ emission was increased while HC and CO emissions were decreased [32]. In order to improve $NO_x$-soot trade-off, there are several ways such as changing fuel injection strategies, using additives, exhaust gas recirculation (EGR) [33,34] and so on. In terms of less engine modifications, reducing emissions and improving performance inside combustion chamber are advantageous [35,36]. However, fuel injection strategies like injection timing, injection pressure and injection rate shaping were also applied.

Regarding fuel injection strategies, Jaichandar et al. [37] studied the improved air motion in Trapezoidal Combustion Chamber (TRCC) and Toroidal Combustion Chamber (TCC). It was showed that combustion chamber geometry improved the mixture formation resulting in increased brake thermal efficiency substantially and lowered specific fuel consumption. In another work, Saito et al. [38] also reported that using a re-entrant chamber can reduce ignition lag and provide better fuel economy with delayed injection timing compared to using conventional chambers. The effects of injection timing on direct injection (DI) diesel engine powered by waste plastic oil were investigated by Mani et al. [39]. They stated that when applying retarded injection timing, $NO_x$ concentration decreased, CO emission were decreased by 25%, and unburned hydrocarbons (UBHC) emission were decreased by 30%, while smoke was increased by 35% at all loads. Concerning the effects of injection pressure, Hountalas et al. [40] reported that higher injection pressure as the engine speed and load reduced resulting in proper atomization, good mixing of fuel with air, and finally led to complete combustion [41,42].

In summary, the important point to use biodiesel fuel more effectively is that engine performance and emission characteristics should be improved. As reported, with the increasingly strict emission standards all around the world, the exhaust emission from vehicles should be reduced deeply (see Fig. 2). Fig. 2 expresses the European Union Emission Standards (Euro III, IV, V and VI) as an example. It is very obvious that $NO_x$ and PM emissions are seriously controlled and dropped following new standards. Thus, to meet both targets of engine performance and emission standards simultaneously, many different technologies must be applied, especially in the engine fueling with alternative fuel such as biodiesel. In the literature, there are only few works considering the impacts of using these technologies on the combustion. To fill this gap, we have conducted the comprehensive review of different technologies affecting the combustion and emissions of the diesel engine fueled with biodiesel.

This paper presents a comprehensive review of the impact of different technologies on combustion and exhaust emissions including details of engine and operating condition. The main aim of this work is to provide information to the engineers, industrialists and researchers who are interested in biodiesel and to emphasize the application of RCCI combustion mode as a promising technology in biodiesel engines to utilize the advantages of biodiesel. A large number of literatures from highly rated journals in scientific indexes are reviewed including the most recent publications.

## 2. Cost-benefit analysis of biofuel

Biofuel has been recommended to substitute the traditional fossil energies as studied in many literatures and motivated in many countries due to gaining economic value and having less negative effects on the environment; however, there are still concerns about its economic viability. According to Larson [44,45], because of their manufacture characteristics, commercial biofuels used predominantly feedstock produced from food crops such as sugar cane, sugar beet, and oily seed. However, rapid fast progress in biofuel production will affect directly to global food price increases and this will have a problem of food security, especially in poor and developing country. According to the studies [45–48], biofuels have been partially assigned responsibility for the food price increment in the years from 2003 to 2008. Some other studies [49–51] also showed that the increment of food price in the last decades has been explained as the biofuels production expansion effects, which reduced the food supply availability at the international market and increased food prices. Fig. 3 describes the high fluctuation of the prices of some types of feedstock in the period from 1996 to 2009 [49,52].

Generally, in the first period, these commodity prices decreased and reached a trough in 2000. It can be explained that the world energy demand had been increased in this period, but biofuels production made from feedstock types was not developed. However, after the year of 2000 feedstock prices increased dramatically, especially rapeseed and soybean oil, and reached the highest prices in 2008. From 2009, all feedstock prices have decreased due to the decrement of crude oil price. Oil price increases impact feedstock prices because of transportation, farming and food distribution costs; in addition the price of fertilizer also directly affects to the prices.

It is clearly observed that the price of feedstock plays an important role in the biofuel production and biofuel cost. To make biofuels competitive with fossil fuels, many countries have been implemented subsidies in order to reduce the biofuel prices [53–55]. Some studies conducted biofuels from an economic perspective and evaluated biofuel promotion in the context of the policy's multiple objectives, life-cycle implications other unintended consequences [55–58]; however, comparisons of cost-effectiveness between biofuels and fossil fuels have not yet been investigated properly. As mentioned in [59–61] numerous economic factors relate to the biofuel production, such as capital cost, process technology, feedstock material cost and chemical cost. Among them, the cost accounting for 80% of the total cost has been considered to be the major economic factor; meanwhile, the labour costs, methanol and catalyst are also significant in the biofuel production. To compare the social costs of biofuels and fossil fuels, Loan et al. [62] conducted a case study of Vietnam in detail. They compared the biofuels and fossil fuel prices for a functional unit defined as 1 km of vehicle transportation. This research conducted two biofuels (ethanol and biodiesel) and respectively their alternative fossil fuels, including gasoline, diesel with a focus on the blends of E5 (5% ethanol blended) and E10 (10% ethanol blended) for ethanol, and B5 (5% biodiesel blended) and B10 (10% biodiesel blended) for biodiesel as shown in Tables 1–3.

The fuel costs are calculated as the break-even price which is determined by setting the net present values of fuel projects equal to zero at a given discount rate. Generally, the social costs of ethanol and biodiesel are respectively higher than those of gasoline because of higher private cost components when comparing in term of per MJ. However, if we consider the fuel efficiency in transportation, the ethanol substitution for gasoline in the form of E5 and E10 saves 0.02 $/km, corresponding to 33.4% of social cost per km of vehicle movement compared to gasoline if the fuel consumption of E5 and E10, in terms of L/km is equal to the fuel consumption of gasoline. The lower fuel consumption of E5 and E10 in comparison with that of gasoline results in a higher achievement of this saving. For the cost effectiveness of biodiesel, the biodiesel substitution would be cost-effective if the fuel consumption of B5 and B10, in terms of L km/1 in comparison with that of diesel, would reduce by more than 1.4% and 2.8% for B5 and B10 respectively.

## 3. The using of biodiesel

It is known that engine emissions from combustion of petroleum derived fuel affected seriously to environment and human health. Global warming is increasing due to the greenhouse gases including methane, nitrogen oxides and carbon dioxides. Liaquat et al. [63] stated that as the average global temperature increased, ice at the poles would melt, seawater level would increase, many lands would be flooded, about hundreds of millions of people would lose their lives. Many researchers have demonstrated that carbon monoxide (CO), hydrocarbon (HC), formaldehyde (HCHO), nitrogen oxides ($NO_x$), particulate matter (PM) and organic gases other than methane (Non-Methane Organic Gases -NMOG) which are emitted from internal combustion engines as harmful to the human health and environment. The impact of exhaust emissions on human health is showed in Table 4 [64–67].

Apart from the impacts on the environment and humans, the commercial use of biodiesel has been limited due to some downsides relating to the steady state during the storage and use over time, the balance between the cots-benefits of using biodiesel with fossil fuel, between biodiesel production and prices of food from which biodiesel is made, between the use of land and water to grow crops used for food and biodiesel [68]. When these obstacles can be overcome by the application of various technical measures, biodiesel is truly a fuel of the future.

The stability of biodiesel is influenced by many factors. Biodiesel is highly sensitive to light, temperature [69], more susceptible to oxidation reactions [70–72], more hygroscopic in nature [70], and more corrosive than diesel [73,74]. These factors are the cause to the degradation of biodiesel due to compositional changes. Exposure to air [75,76], sunlight, exposed metal surfaces, sometimes changing the storage container [77], temperature [78] affect the storage stability of biodiesel. After 6-months, it loses its stability and therefore it cannot be used. Temperature also plays an important role on the deterioration of the biodiesel quality. When increasing temperature enhances the oxygenated molecules and thereby improves the lubricity [78], oxidation at elevated temperature may produce different products such as aldehydes, ketones, carboxylic acids, etc. In cold climate conditions [79,80], the biodiesel fuel turns into a cloud of wax crystals. These formed crystals affect the conditional operation of the engine because they cause problems such as plugging the fuel lines and filter [72]. This is a barrier for countries with cold climates when using biodiesel. It is clear that the state of biodiesel changes over time like a living substance. To ensure the steady state during the storage and use over time a number of methods can be applied such as the use of proper additives and modification of storage condition, in which uses the additive is a method being applied efficiently. A few additives have been used to improve the oxidation stability, reduce the corrosiveness and some other additives used to enhance other fuel properties.

Besides, it is necessary to build a book of standards covering the production, use and storage of each type of biodiesel, and environmental standards when using this fuel for each country with different climate to minimize the disadvantages caused by using biodiesel. The European standard EN 14214 is went into effect in 2003. This standard is applied in the following member countries: Austria, Belgium, Cyprus,

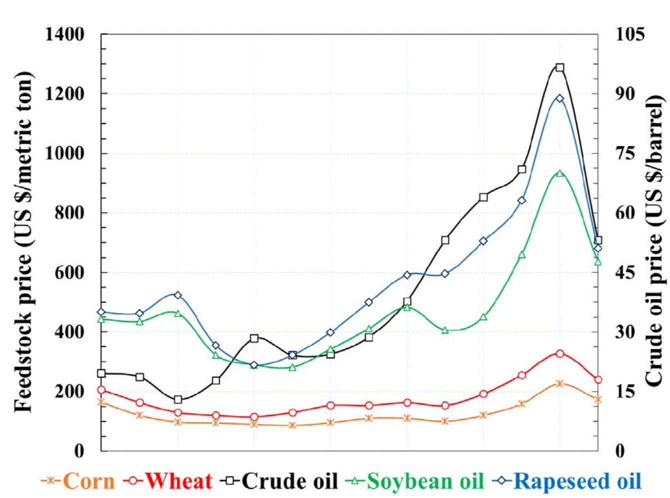



**Fig. 3.** Crude oil price and feedstock prices in the period from 1996 to 2009 [49,52].

**Table 1**
Costs of production and utilization of ethanol, gasoline, biodiesel and diesel ($/GJ).

| Cost items | Ethanol | | | Gasoline | | | Biodiesel | | | Diesel | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Discount rate | | | Discount rate | | | Discount rate | | | Discount rate | | |
| | 4% | 8% | 10% | 4% | 8% | 10% | 4% | 8% | 10% | 4% | 8% | 10% |
| Private cost | 18.57 | 20.13 | 20.93 | 15.78 | 15.78 | 15.79 | 29.2 | 30.64 | 31.4 | 14.91 | 14.91 | 14.91 |
| - Cassava production | 10.76 | 11.24 | 11.48 | | | | 28.41 | 28.86 | 29.11 | | | |
| - Ethanol conversion | 7.33 | 8.37 | 8.91 | | | | 0.5 | 1.47 | 1.96 | | | |
| - Distribution and blending | 0.48 | 0.52 | 0.53 | | | | 0.29 | 0.31 | 0.32 | | | |
| External cost | 1.63 | 1.7 | 1.74 | 4.11 | 4.12 | 4.13 | −2.19 | −2.24 | −2.26 | 4.21 | 4.24 | 4.26 |
| - GHG emissions | 1.22 | 1.29 | 1.33 | 2.76 | 2.76 | 2.76 | −2.58 | −2.65 | −2.69 | 2.76 | 2.76 | 2.76 |
| - Non-GHG emissions | 0.4 | 0.41 | 0.41 | 0.25 | 0.26 | 0.26 | 0.4 | 0.42 | 0.43 | 0.46 | 0.49 | 0.5 |
| - Security of supply | NA[a] | NA[a] | NA[a] | 1.1 | 1.1 | 1.1 | NA[a] | NA[a] | NA[a] | 0.99 | 0.99 | 0.99 |
| Social cost | 20.2 | 21.83 | 22.67 | 19.89 | 19.9 | 19.91 | 27.02 | 28.41 | 29.14 | 19.12 | 19.15 | 19.17 |

[a] Not applied.

Czech Republic, Denmark, Finland, France, Estonia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. The European standard EN 590 for conventional diesel fuel contains a provision that conventional diesel fuel can contain up to 5% FAME meeting the standard EN 14214. For low-temperature properties, national standardizing committees are given the option of selecting among six CFPP (cold-filter plugging point; method EN 116) classes for moderate climates and five for arctic climates. The total temperature range for these CFPP classes is from +5 °C to −44 °C [81]. For the other countries like Turkey, India, Malaysia, etc. the biodiesel standards basically based on the standard ASTM D6751 from the US. Some amendments may be added to adapt with the local conditions.

Processes of biodiesel demand a lot of energy and materials [68]. There has also been concerned on land sources for biodiesel and food crops when the global food security is not stable. Selection of material sources and catalyst can reduce the total investment cost by 25%. Among materials for processing biodiesel, non-edible and waste oils is feasible as they do not impact the food sources and they are diversified, which include algal oil, microalgae, jatropha and grease. These sources cut the expenditures by 60–90% [82]. Besides, the use of non-edible

**Table 2**
Cost-effectiveness of ethanol and gasoline.

| Scenarios | Social cost | Fuel efficency | Social cost ($ /km) | | Cost difference | |
|---|---|---|---|---|---|---|
| | ($/GJ) (1) | (GJ/km) (2)[a] | Ethanol (3)= (1×(2) for ethanol | Gasoline (4)= (1)× (2) for gasoline | ($/km) (5)= (3)- (4) | (%) (6)= (5)×100/ (4) |
| At the discount rate of 4% | | | | | | |
| Gasoline | 19.89 | 0.0026 | | 0.05 | | |
| Ethanol | | | | | | |
| - S1 (E5, 5%) | 20.2 | 0.0353 | 0.71 | 0.05 | 0.66 | 1298.53 |
| - S2 (E5, 0%) | 20.2 | 0.0017 | 0.03 | 0.05 | −0.02 | −33.4 |
| - S3 (E5, −5%) | 20.2 | 0.0008 | 0.02 | 0.05 | −0.03 | −67.56 |
| - S4 (E10, 5%) | 20.2 | 0.0032 | 0.06 | 0.05 | 0.01 | 27.14 |
| - S5 (E10, 0%) | 20.2 | 0.0017 | 0.03 | 0.05 | −0.02 | −33.4 |
| - S6 (E10, −5%) | 20.2 | 0.0011 | 0.02 | 0.05 | −0.03 | −5637 |
| At the discount rate of 8% | | | | | | |
| Gasoline | 19.9 | 0.0026 | | 0.05 | | |
| Ethanol | | | | | | |
| - S1 (E5, 5%) | 21.83 | 0.0353 | 0.77 | 0.05 | 0.72 | 1410.55 |
| - S2 (E5, 0%) | 21.83 | 0.0017 | 0.04 | 0.05 | −0.01 | −28.07 |
| - S3 (E5, −5%) | 21.83 | 0.0008 | 0.02 | 0.05 | −0.03 | −64.96 |
| - S4 (E10, 5%) | 21.83 | 0.0032 | 0.07 | 0.05 | 0.02 | 37.23 |
| - S5 (E10, 0%) | 21.83 | 0.0017 | 0.04 | 0.05 | −0.01 | −28.07 |
| - S6 (E10, −5%) | 21.83 | 0.0011 | 0.02 | 0.05 | −0.03 | −52.87 |
| At the discount rate of 10% | | | | | | |
| Gasoline | 19.91 | 0.0026 | | 0.05 | | |
| Ethanol | | | | | | |
| - S1 (E5, 5%) | 22.67 | 0.0353 | 0.8 | 0.05 | 0.75 | 1468.3 |
| - S2 (E5, 0%) | 22.67 | 0.0017 | 0.04 | 0.05 | −0.01 | −25.32 |
| - S3 (E5, −5%) | 22.67 | 0.0008 | 0.02 | 0.05 | −0.03 | −63.62 |
| - S4 (E10, 5%) | 22.67 | 0.0032 | 0.07 | 0.05 | 0.02 | 42.57 |
| - S5 (E10, 0%) | 22.67 | 0.0017 | 0.04 | 0.05 | −0.01 | −25.32 |
| - S6 (E10, −5%) | 22.67 | 0.0011 | 0.02 | 0.05 | −0.03 | −51.07 |

b A minus sign means cost-effectiveness.
[a] These are the figures in the column 8 in Table 3 divided by 1000.

**Table 3**
Cost-effectiveness of biodiesel and diesel.

| Scenarios | Social cost | Fuel efficency | Social cost ($/km) | | Cost difference | |
|---|---|---|---|---|---|---|
| | ($/GJ) (1) | (GJ/km) (2)[a] | Biodiesel (3)= (1)× (2) | Diesel (4)= (1)× (2) | ($/km) (5)= (3)- (4) | (%) (6)= (5)×100: (4) |
| At the discount rate of 4% | | | | | | |
| Diesel | 19.12 | 0.0019 | | 0.04 | | |
| Biodiesel | | | | | | |
| - S7 (B5, 0%) | 27.02 | 0.0018 | 0.05 | 0.04 | 0.01[b] | 28.58 |
| - S8 (B5, +5%) | 27.02 | 0.0370 | 1.00 | 0.04 | 0.96[c] | 2600.22 |
| - S9 (B10, 0%) | 27.02 | 0.0018 | 0.05 | 0.04 | 0.01 | 28.58 |
| - S10 (B10, +5%) | 27.02 | 0.0034 | 0.09 | 0.04 | 0.05 | 145.47 |
| At the discount rate of 8% | | | | | | |
| Diesel | 19.15 | 0.0019 | | 0.04 | | |
| Biodiesel | | | | | | |
| - S7 (B5, 0%) | 28.41 | 0.0018 | 0.05 | 0.04 | 0.01 | 34.98 |
| - S8 (B5, +5%) | 28.41 | 0.0370 | 1.05 | 0.04 | 1.01 | 2734.64 |
| - S9 (B10, 0%) | 28.41 | 0.0018 | 0.05 | 0.04 | 0.01 | 34.98 |
| - S10 (B10, +5%) | 28.41 | 0.0034 | 0.10 | 0.04 | 0.06 | 157.69 |
| At the discount rate of 10% | | | | | | |
| Diesel | 19.17 | 0.0019 | 0.04 | 0.04 | | |
| Biodiesel | | | | | | |
| - S7 (B5, 0%) | 29.14 | 0.0018 | 0.05 | 0.04 | 0.01 | 38.31 |
| - S8 (B5, +5%) | 29.14 | 0.0370 | 1.08 | 0.04 | 1.04 | 2804.43 |
| - S9 (B10, 0%) | 29.14 | 0.0018 | 0.05 | 0.04 | 0.01 | 38.31 |
| - S10 (B10, +5%) | 29.14 | 0.0034 | 0.10 | 0.04 | 0.06 | 164.04 |

[a] These are the figure in the column 8 in Table 3 divided by 1000.
[b] A plus sign means cost- ineffectiveness.
[c] The high cost- ineffective in S8 due to low contribution of biodiesel to the blend B5.

**Table 4**
Impact of engine exhaust on human health.

| Exhaust emissions | Impact on health | Refs |
|---|---|---|
| PM | Aggravated asthma, bronchitis, emphysema, decreased lung function, weakening of the heart, heart attacks, premature death, Lung cancer and cardiopulmonary deaths, coughing and difficult or painful breathing | [64] |
| $NO_x$ | Bronchitis and pneumonia, irritate the lungs and cause oedema; and sensitivity to dust and pollen in asthmatics | [65] |
| CO | Promote morbidity in people with respiratory or circulatory problems, grow thing fetal in pregnant women and tissue development of young children | [65] |
| HC | Eye irritation, coughing and sneezing, drowsiness and symptoms akin to drunkenness. Some hydrocarbons have a close affinity for diesel particulates and may contribute to lung disease | [65] |
| PAHs | Eye and nose irritation, coughing, nausea and shortness of breath | [66] |
| Formaldehyde | Eye and nose irritation, coughing, nausea and shortness of breath | [67] |

**Table 5**
Classification on different biodiesel feedstock sources.

| Group | Sources of oil |
|---|---|
| Vegetable oil | *Edible vegetable oil:* sunflower, rapeseed, rice bran, soybean, coconut, corn, palm, olive, pistachia palestine, sesame seed, peanut, opium poppy, safflower, mustard, castor, false flax (Camelina sativa), egusi (Citrullus colocynthis L.), sugar apple seed (Annona squamosa), tigernut, radish, ramtil (Guizotia abyssinica) oil, etc.<br>*Non-edible vegetable oil:* jatropha, karanjaor pongamia, yellow Oleander (Thevettia peruviana), neem, moringa peregrina seed, jojoba, cottonseed, linseed, mahua, deccan hemp, kusum, orange, rubber seed, Aphanamixis polystachya, Schleichera oleosa L., sea mango (Cerbera odollam), polanga (Calophyllum inophyllum L.), tobacco (Nicotiana tabacum), hochst (Crambe abyssinica), nahor, milk bush (Euphorbia tirucalli), soapnut (Sapindus mukorossi), Acrocomia aculeata (macaúba) oil sea mango, hodgsonia macrocarpa seed, silk cotton oil tree (Ceiba pentandra), pongamia, hemp (Cannabis sativa Linn), Guizotia abyssinica L, macauba coconut (Acrocomia aculeata), Moringa oleifera, croton megalocarpus, Pangium edule Reinw, paradise, Thespesia populnea seed, algae, halophytes etc. |
| Animal fats | Tallow, yellow grease, chicken fat, by-products from fish, animal fats, poultry fat, mucor circinelloides, pig fat, beef tallow oil etc. |
| Waste oil | Waste salmon, moroccan waste frying, animal fat wastes or recycled cooking oil |
| Algae | Microalgae, spirulina platensis algae |

oils has many advantages such as cheap prices, daily quantity of up to millions of tons, creating opportunities for farmers and environment, and being environment-friendly [83]. Among those sources, algae is a potential material for biodiesel as the oil content seems to be 100 times higher than the other available sources. Algae yields were reported to be 5000 gallons per acre while other vegetable oil was less than 1000 gallons per acre [84].

Compared to other alternative energy sources, biodiesel is a potential fuel that meets the demands on energy and environment-friendliness. In different climates, the use of biodiesel needs to pay attention to a variety of factors such as mixing ratio, types of additives and corresponding ratio, storage conditions, fuel standards and using cautions as well.

## 4. Biodiesel production and its properties

### 4.1. Biodiesel production

Biodiesel is produced from animal fat and vegetable oils through the chemical reactions and processes. The feedstocks for biodiesel production are primarily categorized into four main groups [85], as shown in Table 5.

There are several generally accepted technologies for production of biodiesel from different feedstocks such as transesterification, micro-emulsification, direct use and blending of oils, pyrolysis.

#### 4.1.1. Transesterification

Transesterification of oils (triglycerides) with alcohol is the most advanced and promising technology of biodiesel production, so called fatty acid alkyl esters (FAAE). The transesterification reaction is occurred between the triglyceride present in the oil or fat and methanol or ethanol in the presence of a catalyst such as sodium or potassium hydroxide. The result from this reaction is glycerol (also called glycerin) [86]. The overall reaction of the transesterification process is shown in Fig. 4 according to Abbaszaadeh et al. [87].

The catalysts are used to enhance the reaction rate and to shorten reaction time. Transesterification process is also influenced by other parameters like concentration of catalyst, mixing intensity, reaction temperature, reaction time, reaction pressure, ratio of alcohol to oil and kind of feedstock.

#### 4.1.2. Micro-emulsification

Microemulsion is defined as a colloidal equilibrium dispersion of optically isotropic fluid microstructures with dimensions generally in the 1–150 nm range. It is formed spontaneously from two normally immiscible liquids and one or more ionic or non-ionic [88]. Microemulsions have three components, namely an oil phase, an aqueous phase and a surfactant. In addition, some solvents such as methanol, ethanol should be used in order to satisfy the maximum viscosity limitation for diesel engines [86].

#### 4.1.3. Direct use and blending of oils

The direct use of biodiesel as a fuel is inappropriate because after a long operation there will be coking formation on the injectors, carbon deposits, oil ring sticking and thickening of the lubricant [88]. However, mixing crude vegetable oils with diesel fuel can solve the problems of high viscosity in compression ignition (CI) engine. Besides, preheating vegetable oils also decreases the viscosity, improves the atomization and mixing process, which results in better combustion [89]. Regarding this issue, Adams et al. [90] used a six-cylinder, direct injection, turbocharged engine for a total of 600 running hours to test the mixtures of degummed soybean oil and diesel fuel in the ratios of 1:2 and 1:1. The results showed that the lubricating oil thickening and potential gelling existed in case of the 1:1 blend, but it did not occur in case of the 1:2 blend. The authors suggested that the 1:2 blend ratio may be a suitable fuel for agricultural equipment without major modification. Further study is needed on the long term effect on engine, though.

#### 4.1.4. Pyrolysis

Heating or with the aid of catalyst in the absence of oxygen to convert one substance into another is called pyrolysis [91]. The pyrolysis process is simple, wasteless, pollution free and effective compared to other cracking processes. The pyrolysed materials can be vegetable oils, animal fats, natural fatty acids, wood, bio-waste and methyl esters of fatty acids [92]. This method was used in many research works to get biodiesel using for diesel engines [92–96].

### 4.2. Properties of biodiesel

The thermo-physical properties of biodiesel effect on engine performance and emission characteristics. Normally, major considered properties of biodiesel are viscosity, density, cetane number, calorific value, flash point, pour point, etc. In the literature, some researchers stated that fatty acid contents and chemical compositions of biodiesel have important influences on properties of biodiesel [97]. Hence biodiesel is mandatory to measure its properties as specified by ASTM D6751 and EN 14214 standards, the most common standards for biodiesel using as a fuel for CI engine. Table 6 showed different properties of biodiesel produced from various sources [98]. From this table, it can be said that the properties of biodiesel are similar to those of petro-diesel.

Viscosity of biodiesel is the most important parameter to be checked because it directly affects on the injection system of the engine. In general, the higher viscosity makes poorer fuel atomization, incomplete combustion and higher emissions [72,99]. For fuel atomization, high viscosity causes large droplet sizes, poor vaporization, increased oil dilution, narrow injection spray angle, and greater in-cylinder penetration of the fuel spray [100–104].

Cetane number is another important parameter impacting on combustion quality. The higher cetane number, the shorter ignition delays, which finally increases the combustion duration. The cetane number of biodiesel is higher than that of petro-diesel due to its longer fatty acid carbon chains [127–129].

Flash point of a fuel is the temperature at which it will ignite when exposed to a flame or a spark. The flash point of biodiesel is higher than the prescribed limit of fossil diesel, so it is safe for transport, handling and storage [130–133]. Flash point is influenced by several factors such as residual alcohol content, the number of double bonds, number of carbon atoms, and so on [134].

Calorific value indicates the energy content of a fuel [135]. Biodiesel has lower mass energy value than petroleum diesel due to its high oxygen content. With higher density and lower heating value, the power output and the torque of the engine fueling with biodiesel are lower than those of petro-diesel as reported by Jain et al. [86].

Biodiesel from all of the difference feedstocks is generally regarded as having excellent lubricity with a very small amount of sulfur content. Therefore, the wear of engine parts and injection system is reduced. Moreover, the emission of oxides of sulfur ($SO_x$) is almost negligible [136].

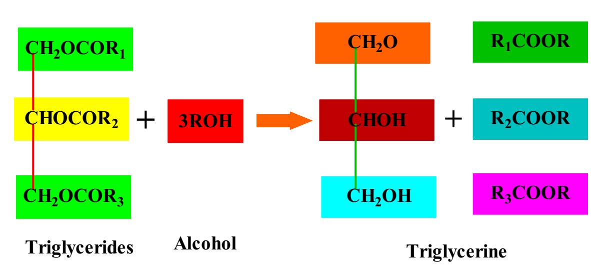



Fig. 4. Transesterification reaction [87].

**Table 6**
Properties of biodiesel produced from different feedstocks.

| Fuel | Density (kg/m$^3$) | Kinematic viscosity at 40 °C (mm$^2$/s) | Cetane no. | Heating value (MJ/kg) | Cloud point (°C) | Flash point (°C) | Fire point (°C) | Pour point (°C) | Refs. |
|---|---|---|---|---|---|---|---|---|---|
| Diesel | 850 | 2.44–2.60 | 47–50 | 42–44.3 | – | 68–75 | 80 | −20 | [105–108] |
| Camelina | 918 | 24 | 50.4 | 38 | 3 | > 220 | – | −7 | [109] |
| Coconut | 877 | 3.18 | 60 | 36.98 | 1 | 136.5 | – | −4 | [109] |
| Safflower | 920 | 26.64 | 51.1 | – | −4 | 174 | – | −7 | [93] |
| Canola | 872 | 4.22 | 53.7 | 39.289 | −4 | 153 | – | −6 | [110] |
| Mahua | 880–916 | 3.98–5.72 | – | 37–39.4 | – | 129–208 | 141 | 6 | [105,111,112] |
| Karanja | 880–890 | 4.37–9.6 | 48–58 | 36.12–42.13 | −2–14.6 | 170–205 | – | −6–5.1 | [106,113,114] and [115–117] |
| Palm | 870–878.4 | 4.5–5.11 | 50–62 | 37.2–39.91 | 14 | 173 | 182 | 8 | [107,115,118] |
| Cotton seed | 850–885 | 6–9.6 | 52 | 37.5–41.68 | −2 | – | – | −4 | [115,119] |
| Jatropa | 873 | 4.23 | – | 42.673 | 10.2 | 148 | – | 4.2 | [120] |
| Polanga | 869 | 3.99 | – | 41.397 | 13.2 | 140 | – | 4.3 | [114] |
| Soybean | 885–914 | 4.057–39.5 | 37–51.3 | 37.3–39.66 | – | 69–163 | – | – | [115,118,121,122] |
| Sunflower | 880–885.6 | 4.381–4.4 | 50–51.6 | 37.5–39.95 | – | 183 | – | – | [115,118] |
| Rapeseed | 872–885 | 4.585–11 | 37.6–54.5 | 37.3–39.9 | – | 177–275 | – | – | [115,121,123] |
| Honge | 890 | 5.6 | 45 | 36.01 | – | 163 | – | – | [124] |
| Peanut | 886.4 | 5.251 | 54 | 39.7 | – | 193 | – | – | [118] |
| Corn | 885.8 | 4.363 | 55.4 | 39.87 | – | 167 | – | – | [118] |
| Palm Kernel | 876.6 | 3.248 | 62.1 | 38.53 | – | 131 | – | – | [118] |
| Tallow | 832 | 4.89 | 58.9 | 37.2 | 13 | 124 | – | 10 | [125] |
| Waste Fried | 884.2 | 4.869 | 55 | 39.68 | – | 167 | – | – | [118] |
| Jojoba | 866 | 19.2 | 63.5 | 43.38 | – | 61 | – | – | [108] |
| Neem | 820 | 8.8 | 51 | 40.1 | – | – | – | – | [126] |
| Chicken fat | 869 | 2.8 | 48 | – | −7 | 74 | – | – | [85] |
| Mutton fat | 856 | 8.15 | 59 | – | −4 | – | – | −5 | [85] |

Besides, average fatty acid profile have significantly impacts on the physical/chemical properties of biodiesel [137]. The fuel properties of biodiesel are strongly influenced by the properties of the individual fatty acid methyl esters in biodiesel. Both the fatty acid and alcohol can have considerable influence on fuel properties as cetane number with relation between combustion and exhaust emissions, cold flow, oxidative stability, viscosity and lubricity [138,139]. Jiaqiang et al. [140,141] found that the higher saturation level could shorten the chemical ignition delay time, but the higher saturation contents would increase the kinetic viscosity, resulting in the poor fuel–air mixing and evaporation process.

Fig. 5 shows the indicated power of the engine operated with four typical biodiesels at different load conditions. In which, the engine fueled with sunflower biodiesel had a better performance than the others in all tests. This can be explained that sunflower biodiesel the largest C18:2 with a lower kinetic viscosity, hence the evaporation and combustion are improved [140]. Lower kinetic viscosity methyl esters was favorable for better fuel–air mixing and subsequent combustion, however, $NO_x$ emission was increased [97,142].

Table 7 shows average fatty acid profile for different feedstocks for biodiesel fuel.

## 5. Effect of different techniques on combustion and emissions of the engine using biodiesel fuels

### 5.1. Pre-combustion techniques

#### 5.1.1. Use of different fuel additives

Fuel additives are the chemicals that mixed with fuels in order to improve the efficiency and fuel economy. The selection of additives for biodiesel fuel depends on the fuel blending property, economic feasibility, additive solubility, toxicity, viscosity of the fuel blend, flash point of the fuel blend, solubility of the water in the blend and water partitioning of the additive. There have been many researchers used different additives for biodiesel such as metal based additives [151,152], oxygenated additives (dimethyl ether, ethanol, methanol) [153–155], antioxidants [156,157], cetane number improvers [158,159].

Kannan et al. [160] investigated the influences of ferric chloride ($FeCl_3$) additive on performance, emission and combustion characteristics of a DI diesel engine operated at 1500 rpm, fueled with waste cooking palm oil based biodiesel. The authors concluded that this metallic additive had an effect of decreasing the brake specific fuel consumption (BSFC) of 8.6% at an optimum operating condition (280 bar injection pressure, 25.5° BTDC injection timing). In another research, Gürü et al. [152] studied the effect of the synthetic Mg additive on the performance and emission of a single-cylinder, DI diesel engine. The diesel fuel (EN 590) and a blend of 10% chicken fat biodiesel and diesel fuel (B10) were used. The engine was operated at full load and speed range from 1800 to 3000 rpm. The results indicated that the engine torque did not change significantly, while the specific fuel consumption increased by 5.2%. In a similar work, Kalam et al. [157] investigated the effect of NPAA additives added in biodiesel fuel blends on the performance and emission of an indirect injection, naturally aspirated, four stroke, four cylinder and water cooled diesel engine. The authors revealed that B20 fuel with 1% NPAA additives gave 2.7% higher brake power and 5% lower brake specific fuel consumption than pure B20 due to lower viscosity and combustion quality of additives.

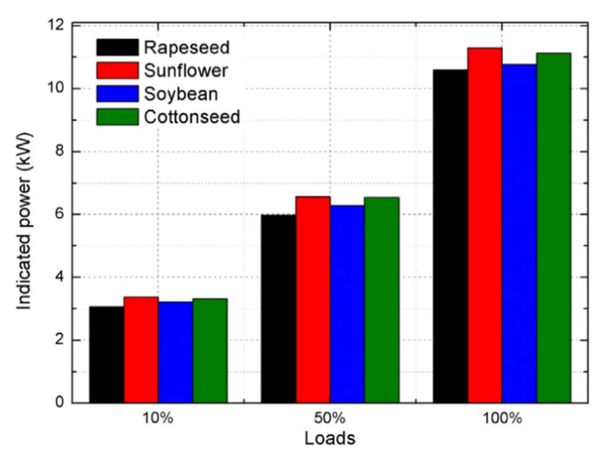



**Fig. 5.** Indicated power by one-cylinder engine operated with four typical biodiesels [140].

**Table 7**
Average composition (%) of fatty acids for different feedstocks.

| Feedstock | Palmitic | Stearic | Palmitoleic | Oleic | Linoleic | Linolenic | Arachidic | Refs. |
|---|---|---|---|---|---|---|---|---|
| Tallow | 23.3 | 19.4 | – | 42.4 | 2.9 | 0.9 | – | [143] |
| Scum | 42.139 | 15.7632 | – | 19.2093 | 0.4822 | 0.2509 | – | [144] |
| Micro-algal | 12–1 | 1–2 | 55–7 | 58–60 | 4–20 | 14–30 | – | [145] |
| Mahua | 16–28.2 | 14–25.1 | – | 41–51 | 8.9–17.9 | – | 0–3.3 | [105,111,112,146] |
| Rubber seed | 10.2 | 8.7 | – | 24.6 | 39.6 | 16.3 | – | [147] |
| Sunflower | 4.9–6.8 | 2.3–3.26 | – | 16.93–32.6 | 59.4–73.73 | 0 | – | [118,147] |
| Rapeseed | 3.49–5.2 | 0.85–1.4 | – | 64.4–66 | 18.9–22.3 | 5.6–8.23 | 1.9 | [118,147] |
| Cotton seed | 11.67 | 0.89 | – | 13.27 | 57.51 | 0 | – | [147] |
| Soybean | 11.7–11.75 | 3.15–3.97 | – | 21.27–23.26 | 53.7–55.53 | 6.31–8.12 | 1.23 | [118,147] |
| Jatropha | 13.23–16 | 5.40–7 | 0.85 | 41.62–49.39 | 33–36.99 | 0.22 > 0.80 | 0.2 | [148–150] |
| Honge | 10.5 | 5.56 | – | 49.39 | 20.37 | 3.66 | 1.36 | [149,150] |
| Karanja | 3.7–11.65 | 2.4–8.9 | – | 44.5–71.3 | 10.8–18.3 | – | | [114,116] |
| Peanut | 17.2 | 2.7 | – | 40.5 | 36.6 | 0.5 | 0.9 | [118] |
| Corn | 11.4 | 1.3 | – | 27.1 | 60.2 | – | – | [118] |
| Palm | 49.8 | 2.9 | – | 38.6 | 6.6 | – | – | [118] |
| Palm Kernel | 11.5 | 1.4 | – | 15.9 | 1.8 | – | – | [118] |

The operating conditions of engine as speed, load, injection pressure and timing also exert impacts on the fuel consumption of an engine fueled with biodiesel. Many researchers have studied the effect of additives on the fuel consumption of engine fueled with biodiesel. Palash et al. [161] studied the effect of jatropha biodiesel fuel with N,N′-diphenyl-1,4-phenylenediamine (DPPD) on the engine performance and emission of a compression ignition diesel engine at different engine speeds and they found that the BSFC was decreased by 1.86% compared to Jatropha biodiesel fuel (B10).

The effects of additives on the bake thermal efficiency of a diesel engine fueled with biodiesel are studied. Kannan et al. [160] investigated the influences of the waste cooking palm oil with ferric chloride ($FeCl_3$) additive on the performance, emission and combustion characteristics of a direct injection diesel engine at different operating conditions and they found that BTE increased by 3.1% compared to biodiesel fuel. Gürü et al. [152] studied the effect of the synthetic Mg additive added in biodiesel fuel blends on diesel and stated that the bake thermal efficiency of biodiesel fuel decreased by 4.8% compared to biodiesel without additive. Subbaiah and Gopal [162] reported that BTE of the rice bran oil biodiesel (RBD) with enthanol increased by 3.93% higher than biodiesel fuel.

Mainly two oxides of nitrogen, namely, nitric oxide (NO) and nitrogen dioxide ($NO_2$) are formed due to the oxidation of nitrogen present in the intake air during the combustion process. $NO_x$ is the most dreadful emission from the compression ignition. $NO_x$ formation mostly depends on the combustion temperature, the oxygen concentration and residence time for the reaction to take place and the equivalence ratio [163]. Many researchers found that $NO_x$ emission increased when using biofuel blends [164–167]. Higher cetane number of biodiesel fuel leads to a shorter ignition delay time and therefore $NO_x$ formation rate was lower [168,169]. In addition, a very important reason for increasing $NO_x$ by using biodiesel fuel relates to faster burn rate as well as advanced start of combustion, low radiation heat transfer, variable adiabatic flame temperature, concentration oxygen ($O_2$) of biodiesel fuel [170]. A few additives such as metal based additives, oxygenated additives and cetane improver additives were used to reduce $NO_x$ emission. Kannan et al. [160] investigated the influences of waste cooking palm oil with ferric chloride ($FeCl_3$) additive on performance, emission and combustion characteristics of a direct injection diesel engine at different operating conditions. The authors found that the use of $FeCl_3$ increased $NO_x$ emission by 4.1% compared to biodiesel fuel without additive. Kalam et al. [157] investigated the comprehensive study on the effect of NPAA additives added in biodiesel fuel blends on performance and emission of an indirect injection, naturally aspirated, four stroke, four cylinder and water cooled diesel engine. They reported that the addition of 1% NPAA additives with B20 fuel, the $NO_x$ emission was reduced by 23% and also HC emission was reduced by 15% compared to biodiesel without additives. Palash et al. [161] studied the effect of jatropha biodiesel fuel with N,N′-diphenyl-1,4-phenylenediamine (DPPD) on the engine performance and emission of a compression ignition diesel engine at different engine speeds and they found that the $NO_x$ decreased slightly compared to the Jatropha biodiesel fuel (B10) without additives.

Complete combustion inside the combustion chamber helps in increasing $CO_2$ (carbon dioxide) emission rapidly. $CO_2$ emission is the main culprit causing the greenhouse effect. A few researchers reported lower $CO_2$ emission for a diesel engine fueled with biodiesel than diesel fuel [22,171,172]. Swaminathan et al. [173] reported that $CO_2$ emission with the use of diethylene glycol dimethyl additive with pongamia methyl reduced by 2–8% compared to biodiesel without additive. On the other hand, some authors observed that $CO_2$ emission for a diesel engine fueled with biodiesel is higher than diesel fuel [174–176]. Rao et al. [177] found a higher $CO_2$ emission with rice bran oil biodiesel. They noticed that when a small amount of ethanol was added to biodiesel, a further increase of $CO_2$ emission was observed because of the presence of oxygen in ethanol molecules. Availability of oxygen in biodiesel and relatively lower amount of carbon is the reason affecting the concentration $CO_2$ emission [178].

CO emission is produced by the incomplete oxidation of carbon-containing fuel. The more oxygen in the content is, the less CO emission is due to complete combustion [179–181]. CO emission was also affected by the feedstock of biodiesel and it decreased with the increase of chain length [182,183]. The increase of cetane number of biodiesel will lead to engine load and engine speed decreased CO emission [131,152,180]. The use of different additives may also decrease CO emission of biodiesel. Ganesh et al. [131] studied nano-fuel additives [Magnalium (Al-Mg) and cobalt oxide ($Co_3O_4$)] on the performance and emission characteristics of Jatropha biodiesel (B100) in a single cylinder, air cooled, direct injection diesel engine and obtained CO emission decreased by 50% compared to biodiesel fuel without additives. Sivalakshmi and Balusamy [10] evaluated the effect of diethyl ether with 5% as an additives with neem oil biodiesel on the performance and emission. The reduction in CO emission was 25% when the engine was running at full load compared to biodiesel fuel (B5) without additives. Kalam et al. [157] tested palm biodiesel and 1% NPAA additives to control $NO_x$ and CO while improving the efficiency in diesel engines. They found that CO emission decreased by 50% compared to biodiesel fuel (B20) without additives.

HC emission which is the product of unburned fuel, depends on the compositions and combustion characteristics of the fuels used. If the combustion is improved and completed, then HC emission decreased

**Table 8**
Effect of additives on performance and emissions in the engine fueled biodiesel.

| Engine type | Test Condition | Feed stock of Biodiesel | Additive | Performance | | | Emission | | | | | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Power | BSFC | BTE | $NO_X$ | $CO_2$ | CO | HC | Smoke | |
| 1-Cylinder, 4 stroke, WC, DI, CR: 17.5:1, RP: 5.2 kW, CI engine | Constant speed (1500 rpm) | Palm oil (B100) | 2% Ferric chloride | – | ↓ 18.4% with the addition of FeCl3 | ↑ 3.1% with the addition of FeCl3 | ↑ 4.1% with the addition of FeCl3 | ↑ 6.7% with the addition of FeCl3 | ↑ 9.7% with the addition of FeCl3 | ↓ 26.6% with the addition of FeCl3 | ↓ 6.9% with the addition of FeCl3 | [160] |
| 1-Cylinder, 4 stroke, AC, DI,CR: 17.5:1, RP: 4.4 kW | Variable load, Constant speed (1500 rpm) | Jatropha oil (B100) | Magnalium (AL-Mg) | – | ↓ 3% with the addition of AL-Mg | ↑ 1% with the addition of AL-Mg | ↓ 45% with the addition of AL-Mg | – | ↓ 50% with the addition of AL-Mg | ↓ 76% with the addition of AL-Mg | – | [188] |
| | | | Cobalt oxide (Co3O4) | – | ↓ 2% with the addition of Co3O4 | No change | ↓ 19% with the addition of Co3O4 | – | No change | ↓ 52% with the addition of Co3O4 | – | |
| 1-Cylinder, 4-stroke, AC, DI diesel | Constant load, Variable speed (1060–3400 rpm) | Tall oil (B60) | Manganese (Mn) | ↓ 1.36% with the addition of Mn | ↓ 10% with the addition of Mn | – | – | – | – | – | – | [190] |
| | | | Nickel (Ni) | – | ↓ 5% with the addition of Ni | – | – | – | – | – | – | |
| 1-Cylinder, 4-stroke, AC, DI diesel | Constant load, Variable speed (1000–2400 rpm) | Tall oil (B60) | Magnesium (Mg) | No change | ↓ with the addition of Mg | – | – | – | – | – | – | [191] |
| | | | Molybdenum (Mo) | No change | ↓ with the addition of Mo | – | – | – | – | – | – | |
| 1-Cylinder, 4-stroke, AC, DI diesel | Constant load, Variable speed (1600–3400 rpm) | Tall oil (B60) | Magnesium (Mg) | No change | No change | – | ↑ slightly | ↓ 8.82% with the addition of Mg | ↓ 36.21% with the addition of Mg | – | ↓ with the addition of Mg | [28] |
| | | | Molybdenum (Mo) | No change | No change | – | ↑ slightly | ↓ with the addition of Mo | ↓ 24.12% with the addition of Mo | – | ↓ with the addition of Mo | |
| 1-Cylinder, 4 stroke, AC, DI, CR: 18:1 | Constant load, Variable speed (1800–3000 rpm) | Chicken fat biodiesel (B10) | Magnesium (Mg) | No change | – | – | – | – | – | – | – | [152] |
| 1-Cylinder, 4 S, DI, WC, CR: 16.5:1,CI Engine | Different load, Constant speed (1500 rpm) | Fish oil (B100) | (1%, 2%, 3%) DEE | – | No remarkable change | – | ↓ avg. 80% for 2% DEE blends | ↓ avg. 33% for 2% DEE blends | ↓ avg. 38% for 2% DEE blends | ↓ avg. 38% for 2% DEE blends | – | [192] |
| 1-Cylinder, 4 S, DI, RP: 3.73 kW, WC, CR: 16.5:1 | Different load, Constant speed (1500 rpm) | Mahua oil (B100) | (3%, 5%, 10%, 15%) DEE | – | ↑ slightly for all DEE blend percentages | ↓ slightly for all DEE blend percentages | ↓ for DEE all blend percentages | – | – | – | – | [193] |
| 1-Cylinder, 4 S, DI, CI engine | Different load, Injection Pressure: 210, 250, 290 bar | Neem oil (B20) | 10%, 15% DEE | – | ↓ approx. 25% for 15% DEE blend | ↑ approx. 6% for 15% DEE blend | – | – | – | – | – | [194] |
| 1-Cylinder, 4 S, DI, CI: 16.5:1, RP: 3.5 kW | Different load, Constant speed (1500 rpm) | Neem oil (B5) | 5%, 10%, 15% DEE | – | – | ↑ 5% for 5% DEE blend | ↑ for all DEE blend | – | ↓ 25% for 5% DEE blend | Higher for all DEE blend percentages | ↓ 10% for 5% DEE blend | [10] |
| 1-Cylinder, 4 S, DI, RP: 3.72 kW, WC, CR: 16.5:1, CI engine | Different load, Constant speed (1500 rpm) | Rice bran oil (B100) | 2.5%, 5% Ethanol | – | ↑ 3.93% for 2.5% ethanol blend | ↑ slightly for all blend percentages | – | – | ↓ 17.39% and 13.04% for 2.5% and 5% ethanol blend respectively | – | ↓ 6.66% and 15% for 2.5% and 5% ethanol blend | [162] |
| 1-Cylinder, 4 S, DI, RP: 5.2 kW, | Different load, Constant speed | Cottonseed oil (B15) | 5% Ethanol | – | – | – | ↓ for all ethanol blend | – | – | – | – | [195] |

(continued on next page)

**Table 8** *(continued)*

| Engine type | Test Condition | Feed stock of Biodiesel | Additive | Performance | | | Emission | | | | | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Power | BSFC | BTE | $NO_X$ | $CO_2$ | CO | HC | Smoke | |
| WC, CR: 17.5:1, | (1500 rpm) | | | | | | | | | | | |
| 1-Cylinder, 4 S, DI, RP: 3.5 kW, WC, CR: 16.5:1, CI engine | Different load, Constant speed (1500 rpm) | Neem oil (B100) | 5%, 10%, 15%, 20% Ethanol | – | – | – | – | – | – | Higher for all ethanol blend percentages | – | [196] |
| 1-Cylinder, 4 stroke, WC, RP: 3.7 kW CR: 16.5:1, | Different load, Constant speed | Fish oil (B30) | 10%, 20%,30% Isobutanol | – | – | – | – | – | – | – | – | [197] |
| Audi 1.9 TDI 1Z, CI engine | Different load, Variable speed (2000–3500 rpm) | Rapeseed oil (B30) | 10% Methanol | | ↑ 9.1% with the addition of Methanol | ↓ slightly | ↑ 5.3% with the addition of methanol | ↑ slightly | ↓ 4.6% with the addition of methanol | – | ↓ 19% with the addition of methanol | [198] |
| 4-Cylinder, 4 S, DI, RP: 60 kW | Different load, variable speeds (1400,1800, 2200 rpm) | Rapeseed oil (B5) | 5%, 10%, 15% Ethanol | ↑ slightly for 15% ethanol blend | ↑ slightly for 15% ethanol blend | – | Lower for for 15% ethanol blend | – | Higher for for 15% ethanol blend | Lower for for 15% ethanol blend | – | [199] |
| 4-Cylinder, 4 stroke, WC, IDI, RP: 39 kW, CR: 21:1, CI engine | Variable speed (1800–3000 rpm) | Palm oil (B35) | 1% NPAA | ↑ 6.12% with the addition of NPAA | ↓ avg. 11% with the addition of NPAA | – | ↓ 16.7% with the addition of NPAA | ↓ 14% with the addition of NPAA | ↓ 10% with the addition of NPAA | ↓ 20% with the addition of NPAA | – | [200] |
| 4-Cylinder, 4 stroke, WC, IDI, RP: 39 kW, CR: 21:1, CI engine | Variable speed (1800–3000 rpm) | Palm oil (B20) | 1% NPAA | ↑ 2.93% with the addition of NPAA | ↓ 19.8% with the addition of NPAA | – | ↓ 23% with the addition of NPAA | – | ↓ 50% with the addition of NPAA | ↓ 15% with the addition of NPAA | – | [157] |
| 4-Cylinder, 4 stroke, RC, RP: 55 kW, CR: 21:1 | Variable speed (1000–4000 rpm) | Jatropha oil (B10) | 0.15% DPPD | – | – | – | ↓ slightly with the addition of DPPD | – | – | – | – | [161] |
| 4-Cylinder, 4 stroke, WC, CR: 19.5:1 | Variable speed (1600–4400 rpm) | Canola oil (B20) | BHA | – | ↓ 4.09% with the addition of BHA | – | ↓ 1.33% with the addition of BHA | – | ↑ 20.47% with the addition of BHA | – | – | [201] |
| | | | EHN | – | ↓ 4.12% with the addition of EHN | – | ↓ 5.8% with the addition of EHN | – | ↑ 9.84% with the addition of EHN | – | – | |
| | | | BHT | – | ↓ 4.22% with the addition of BHT | – | ↓ 4.92% with the addition of BHT | – | ↑ 1.72% with the addition of BHT | – | – | |
| | | | TBHQ | – | ↓ 10.19% with the addition of TBHQ | – | ↓ 1.21% with the addition of TBHQ | – | ↑ 8.5% with the addition of BHT | – | – | |
| 4-Cylinder, 4 stroke, WC, CR:18.5:1, RP:42 kW | Variable speed (1000–4000 rpm) | Palm oil (B20) | BHA | ↑ 0.6% with the addition of BHA | ↓ 0.64% with the addition of BHA | ↑ 0.92% with the addition of BHA | ↓ 12.6% with the addition of BHA | – | ↑ 12.3% with the addition of BHA | ↑ 13.6% with the addition of BHA | – | [202] |
| | | | BHT | ↑ 0.3% with the addition of BHT | ↓ 0.18% with the addition of BHT | ↑ 0.37% with the addition of BHT | ↓ 9.8% with the addition of BHT | – | ↑ 8.6% with the addition of BHT | ↑ 22% with the addition of BHT | – | |
| 1-Cylinder, 4 stroke, WC, DI, CR: 17.5:1, RP: 4.4 kW | Constant speed (1500 rpm) | Jatropha oil (B100) | 0.025%-m L-ascorbic acid | – | ↑ with the addition of L-ascorbic acid | – | ↓ with the addition of L-ascorbic acid | – | ↑ with the addition of L-ascorbic acid | ↑ with the addition of L-ascorbic acid | – | [15] |
| | | | 0.025%-m BHT | – | ↑ with the addition of BHT | – | ↓ with the addition of BHT | – | ↑ with the addition of BHT | ↑ with the addition of BHT | – | |
| | | | 0.025%-m α-tocopherol | – | ↑ with the addition of α- | – | ↓ with the addition of α- | – | ↑ with the addition of α-tocopherol | ↑ with the addition of α- | – | |

*(continued on next page)*

**Table 8** *(continued)*

| Engine type | Test Condition | Feed stock of Biodiesel | Additive | Performance | | | Emission | | | | | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Power | BSFC | BTE | $NO_X$ | $CO_2$ | CO | HC | Smoke | |
| | | | | | tocopherol | | tocopherol | | | tocopherol | | |
| | | | 0.025%-m EDA | – | ↓ with the addition of EDA | – | ↓ with the addition of EDA | – | ↑ with the addition of EDA | ↑ with the addition of EDA | – | |
| | | | 0.025%-m PPDA | – | ↓ with the addition of PPDA | – | ↓ with the addition of PPDA | – | ↑ with the addition of PPDA | ↑ with the addition of PPDA | – | |
| 1-Cylinder, 4 stroke, WC, DI, RP: 3.5 kW, CR: 12:1 to 18:1, CI engine | Constant speed (1500 rpm) | Cottonseed oil (B100) | 0.01% L-ascorbic acid | – | ↑ 1% with the addition of L-ascorbic acid | ↓ slightly with the addition of L-ascorbic acid | ↓ 5.65% with the addition of L-ascorbic acid | ↓ 1% with the addition of L-ascorbic acid | ↓ 13% with the addition of L-ascorbic acid | ↓ 7.08% with the addition of L-ascorbic acid | ↓ slightly with the addition of L-ascorbic acid | [27] |
| 4-Cylinder, 4 stroke, WC, DI, CR: 22:1 | Variable load, Constant speed (1500 rpm) | Soybean oil (B100) | TBHQ | – | ↓ with the addition of TBHQ | – | – | – | – | – | – | [156] |
| 1-Cylinder, 4 stroke, WC, RP: 4.4 kW, CI engine | 75% load, Constant speed | Soybean oil (B100) | DPPD | | | ↓ slightly | | | ↑ 14.28% with the addition of DPPD | ↑ 10.52% with the addition of DPPD | – | [203] |
| 1-Cylinder, 4 stroke, WC, RP: 7.5 kW, DI | Variable speed (1000–1800 rpm) | Calophyllum inophyllumoil (CB30) | 1% BHT | – | ↓ 0.43% with the addition of BHT | ↑ 0.36% with the addition of BHT | ↓ 5.91% with the addition of BHT | – | ↑ 10.62% with the addition of BHA | ↑21.77% with the addition of BHA | ↑ with the addition of BHT | [204] |
| | | | 1% MBEBP | – | ↓ 0.57% with the addition of MBEBP | ↑0.45% with the addition of MBEBP | ↓ 5.27% with the addition of MBEBP | – | ↑ 10.12% with the addition of MBEBP | ↑ 20.67% with the addition of MBEBP | ↑ with the addition of MBEBP | |
| 1-Cylinder, 4 S, DI, RP: 5.9 kW, WC | Constant speed (1800 rpm) | mango seed oil (B100) | PHC | – | No change | – | ↓ 18.19% with the addition of PHC | – | ↑ 14.44% with the addition of PHC | ↑ 12.35% with the addition of PHC | ↑ 8.2% with the addition of PHC | [205] |
| | | | TBHQ | – | – | – | ↓ 14.4% with the addition of TBHQ | – | ↑ with the addition of TBHQ | ↑ with the addition of TBHQ | – | |
| | | | DEA | – | – | – | ↓ 16.3% with the addition of DEA | – | ↑ with the addition of DEA | ↑ with the addition of DEA | – | |

Note: ↓= Decrease, ↑= increase, 4 s = stroke, DI = direct injection, RP = rate power.

and vice versa. When the engine was fueled with biodiesel instead of diesel, HC emission decreased due to some amount of oxygen within its own structure [22,112,120,179,184–187]. Besides, higher cetane number also reduces HC emission due to the reduction of burning delay [179–182]. Higher oxygen content in biodiesel fuel leads to complete combustion, then HC emission decreases. Kalam et al. [157] investigated palm biodiesel and 1%NPAA additives and they reported that HC emission decreased by 15% compared to biodiesel fuel (B20) without additive. Kannan et al. [160] investigated the effect of ferric chloride ($FeCl_3$) as metal based additive in the engine fueled with waste cooking palm oil biodiesel. The authors concluded that the use of $FeCl_3$ decreased HC emission by 26.6% compared to biodiesel fuel without additive. Ganesh et al. [188] studied the addition nano-fuel additives Magnalium (Al-Mg) and cobalt oxide ($Co_3O_4$) and the results showed that they gave mean reductions in HC emission by 66% and 33% compared to biodiesel without additives. The experiment was carried out on a one cylinder, four strokes, water cooled, indirect injection diesel engine which used jatropha oil biodiesel.

Smoke which is the main reason to produce smoke opacity, is formed due to the incomplete combustion of the fuel. Oxygenates has a strong effect on the reduction of smoke when adding to diesel fuel. The presence of excess oxygen content in biodiesel led to better combustion and resulted in less smoke formation. In addition, smoke emission is affected by higher density and higher viscosity of biodiesel fuel which leads to the increase in smoke opacity [189]. Kannan et al. [160] studied the effect of waste cooking palm oil biodiesel with ferric chloride($FeCl_3$) as metal based additive on the engine performance and emissions. The authors revealed that the smoke emission decreased by 6.9% compared to biodiesel fuel without additive. Sivalakshmi and Balusamy [10] indicated that the smoke opacity reduced with the use of diethyl ether with 5% as an additives with neem oil biodiesel (B5). They found that smoke opacity decreased by 10% compared to biodiesel fuel (B5) without additive. Table 8 describes the effect of additives on engine performance parameters and emissions.

Based on the summary in Table 8, the following conclusions can be drawn:

Adding oxygenated additives like ethanol, diethyl ether, isobutanol in biodiesel blend increases the oxygen content of the blend as well as reduces the density, viscosity and least improvement of flash point. In most of the cases, oxygenated additive blended biodiesel increased higher brake thermal efficiency by up to 9.1% except for 15% of DEE in a neem biodiesel-fueled engine and decreased the brake specific fuel consumption compared to biodiesel without additives. Brake specific fuel consumption depends on the ethanol content present in the blend. If the ethanol content of the blend increases, the brake specific fuel consumption also increases. Generally adding oxygenated additives to biodiesel fuels reduced exhaust emissions such as CO, HC and smoke, about 4.6–38%, 38%, 6.7–19% respectively, especially isobutanol, ethanol and diethyl ether were more effective to reduce emissions due to excess oxygen content. However, $NO_X$ emission reduced significantly by up 80% with 2% DEE in fish biodiesel-fueled engine but the most of cases, $NO_x$ emission increased because of more oxygen content present in the biodiesel.

Metal based additives like Mg, Mn, Ni, Co, Mo, etc. reduced the pour point, viscosity and increased the flash point of biodiesel fuels. Adding metal based additives in biodiesel fuels decreases significantly the brake specific fuel consumption by about 2–18.4% as well as increases the brake thermal efficiency 1–3.1% due to their catalyst effect compared to biodiesel without additives. Fuel born catalyst and cerium oxide additive with biodiesel are more effective for increasing brake thermal efficiency compared to biodiesel without additives. Exhaust gas emissions also improved with the addition of metallic additives. Exhaust emissions such as $NO_X$, CO, HC and smoke, about 19–45%, 50%, 26.6–76%, 6.9% respectively, except for 2% of ferric chloride in a paml biodiesel-fueled engine.

Adding antioxidant additives like NPAA, BHA, BHT, L-ascorbic acid, EHN, TBHQ in biodiesel blend increased flash point, cetane number and oxidation stability of biodiesel but reduced calorific value of biodiesel. Antioxidant additives affect BTE, BSFC and emissions with different degrees. With BHA, BHT antioxidants, brake thermal efficiency increased slightly but with L-ascorbic acid, brake thermal efficiency reduced slightly compared to neat biodiesel. With L-ascorbic acid and a-tocopherol, BSFC increased slightly whereas other antioxidants reduced slightly compared to neat biodiesel without additives. The antioxidant additives are quite effective in controlling the $NO_x$ formation of biodiesel fuels. HC and CO emissions of all antioxidant-added biodiesel fuels were higher than those of biodiesel without antioxidant. HC and CO emissions of NPAA and L-ascorbic acid blended biodiesel fuel were lower than biodiesel without additives.

### 5.1.2. Exhaust gas recirculation (EGR)

Today, exhaust gas recirculation (EGR) is a $NO_x$ emissions reduction technique used with both diesel and biodiesel [206–213]. Many researchers [212,214,215] reported that EGR is a highly potential $NO_x$ mitigation technology. EGR works by recirculating a portion of an exhaust gas of engine back to the engine cylinders. This dilutes the $O_2$ in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures. Hence, the formation of $NO_x$ can be reduced drastically [216] which is the main application of EGR technology. Two actions of its mechanisms are dilution (due to increased non-combustible mass), and chemical (due to increasing molecular complexity lead to increased dissociation during reaction) [214,217]. In naturally aspirated engines, exhaust gas comes straight forward into the cylinder because the exhaust tailpipe back pressure is generally higher compared to the intake pressure. A flow passage is established between the exhaust and the intake manifolds and is regulated by a throttling valve, as shown in Fig. 6.

If the exhaust gas is recycled to the intake manifold directly, the operation is called hot EGR. In modern diesel engines, the EGR gas is cooled with a heat exchanger to allow the introduction of a greater mass of recirculated gas, the operation is called cooled EGR [218]. The $NO_x$ emission reduced the chronological trends by raising the EGR rate [219,220]. EGR ratio was defined with the following Eq. (1) which has been used by several researchers [181,221,222].

$$EGR(\%\text{mass}) = \frac{\dot{m}_{EGR}}{\dot{m}_{EGR} + \dot{m}_{AIR}} \times 100\% \quad (1)$$

where EGR (%mass) is the mass percent of the recirculated exhaust gas $\dot{m}_{EGR}$ in total intake mixture and $\dot{m}_{AIR}$ is the mass of intake air in total intake mixture.

Although using EGR in a CI engine is an effective technology to reduce the $NO_x$ emission, there are some disadvantages such as significantly increasing smoke, HC, CO, fuel consumption and reducing thermal efficiency unless it is suitably optimized [222]. Saleh et al. [221] found that the BSFC increased by 9% and HC, CO emission slightly increased and $NO_x$ emission reduced by 36% with optimum EGR rate 12% at full load, 1600 rpm compared to biodiesel without EGR. Kass et al. [223] studied the effect of EGR on the engine

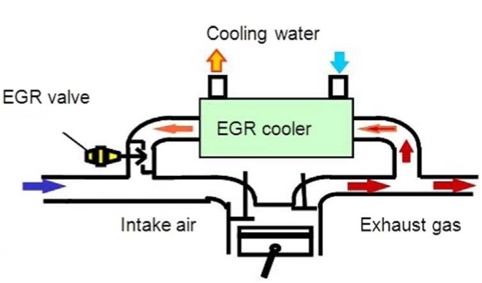



**Fig. 6.** EGR technology.

**Table 9**
Review of emissions and performance analysis using EGR for biodiesel fuels.

| Engine used | Fuel used | EGR condition | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|---|
| | | | BTE | BSFC | $NO_x$ | HC | CO | Smoke | |
| 1 S, DI, DE | RB100 | 10% & 20% EGR, CS: 1500 rpm | Overall efficiency ↓ for all condition | Overall efficiency ↓ for all condition | ↓with ↑ of EGR | ↑ with ↑ of EGR | ↑ with ↑ of EGR | ↑with ↑ of EGR | [215] |
| Kirloskar, 1 C, 4 S, DI, DE | PKB100 | 4%, 7%, 12% & 14% EGR with cooler | Not significant change | Not significant change | ↓ with ↑ of EGR | ↑ with ↑ of EGR | ↑ with ↑ of EGR | ↑ with ↑ of EGR | [226] |
| Comet diesel engine, 2 C, Vertical, WC | JB100 | 5%, 10% & 15% EGR at various engine load | ↑ slight | ↓ with ↑ (% of EGR & BP) | ↓a with ↑ of EGR | ↓ with ↑EGR | ↑ with ↑EGR | | [227] |
| Ford Lion 6 C, 4 S, DI, WC, DE | SB100 | 38%, 43%, 49% and 54% of EGR rate used | ↑ | ↑ | ↓ | – | – | ↑ slight | [225] |
| 2 C, DI, CI, DE | KB40 | 15% EGR, 80% load | ↓9.16% | | ↓25.75% | ↑17.5% | ↑11.11% | ↑16.92% | [228] |
| Lister-Petter, AC, 1 C, DI, DE | RB100 & RB50 | C1: 10%EGR, IMEP = 6.1 bar C2: 20%EGR, IMEP = 6.1 bar | Near same for C1 & RB100;↓1.9% for C2 & RB100; ↓0.6% for C1 & RB50; ↓2.5% for C2 & RB50 | ↑ | ↓30.17% for C1 & RB100; ↓51.76% for C2 & RB100; ↓27.6% for C1 & RB50; ↓49.2% for C2 & RB50 | ↑6.2% for C1 & RB100; ↑15% for C2 & RB100; ↑4.2% for C1 & RB50; HC↑7.9% for C2 & RB50 | ↑ for C1, C2 & RB100;↑↑ for C1, C2 & RB50 | ↑ for C1 & RB100; ↑↑ for C2 & RB100; ↑51.9% for C1 & RB50;↑↑ for C2 & RB50 | [224] |
| 4 C, 16 valve Mercedes | SB100 | 27% EGR, Load = 68 Nm | – | ↑4.25% | ↓87.7% | – | ↑↑ | ↑↑ | [223] |
| 2 C, 4 S, WC, DI diesel engine | JOB100 | Optimum EGR rate 12% at full load, 1600 rpm | – | ↑9% | ↓36% | ↑ | ↑ | – | [221] |
| 1 C, DI, 4 S, WC, DE | JB100 | Hot EGR 15% at full load. | ↓ slightly | – | ↓74.8% | ↑ | ↑ | ↑ | [222] |
| 1 C, DI, 4 S | SB20 | 5%, 10% & 15% EGR at various engine load, CS: 2200 rpm | ↓3% with 15% of EGR | ↑6% with 15% of EGR | ↓55% | ↑ | Not significant change | ↑15% | [229] |

Results compared to biodiesel without EGR, ↑↑= about more than 100%.

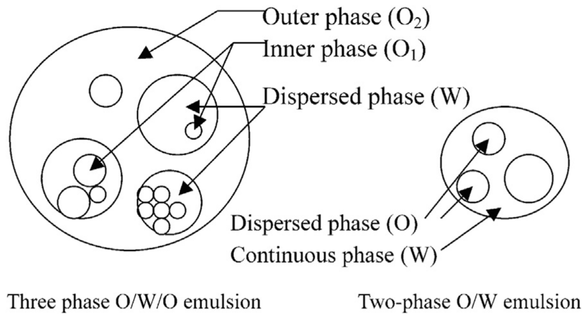



**Fig. 7.** Physical structures of two-phase and three-phase emulsion [235].

performance and emissions for a diesel engine operated with soybean biodiesel (SB) fuel. They revealed that the use of 27% EGR was more effective and achieved a reduction of $NO_x$ emission of about 87.7% with B100 at 68 Nm load. Using EGR technology on a biodiesel-fueled engine, the BSFC may increase because of altering the air–fuel ratio, the dilution effect, reducing the oxygen content, and the falling burn rate, therefore making achieving stable combustion more difficult and so on [220,221]. Farther, this technology increases temperature of the mixture of EGR and fresh inlet air, hence leading to a damnatory effect on the volumetric efficiency at the high engine load because of reducing the cylinder-trapped mass [209]. Generally, in biodiesel-fueled engines, the use of EGR results in increasing smoke, HC, CO and reducing $NO_x$ emission compared to cases without EGR application [222]. At peak loads, dissociation of $CO_2$ to CO can also contribute to increased CO emission while the variation in HC emission was not significant with increasing EGR levels in the biodiesel-fueled engine [224]. The issue is caused by the oxygen content in bio-diesel compensating for oxygen deficiency and facilitating complete combustion. The increasing EGR rate leads to increasing PM or soot emission because of the lower oxygen concentration [216,225]. However, many engine researchers and manufacturers reported that although using EGR in a diesel engine increases PM and reduces $NO_x$, it is still widely used due to its simplicity, lower required volume and cost compared to the others. In Table 9, the emissions and performance data shows a considerable spread as there are variations in the EGR condition, different feedstock sources, and engine operating conditions.

From Table 9, the following conclusions are reached:

When increasing EGR rates reduces $NO_x$ and increases PM or soot emissions for biodiesel combustion, it increases the BSFC by about 4.25–9%. At 10–20% EGR, it decreases the $NO_x$ emission by up to 87% with reducing the engine efficiency of about 0.6–9.16% when fueled with RB100, RB50 and KB40 compared to the biodiesel combustion without EGR.

When engines operated 10–20% EGR with biodiesel fuels such as rapeseed, sunflower, jatropha, karanja, rice bran and jojoba biodiesel, exhaust emissions raise significantly, namely CO about 6.2–15%, HC and smoke about more than 100% but they are still below the acceptable stage.

When using EGR technology at high EGR rates, more than 25%, $NO_x$ reduces to a great extent but increases other emissions on a large scale compared to the biodiesel combustion without EGR.

#### 5.1.3. Water injection (WI)

An important strategy to control the $NO_x$ emission from a CI engine is injecting water into the combustion chamber, directly or through the intake manifold. One important advantage using WI (water injection) is the enhanced possibility of reducing the $NO_x$ over the entire engine load range with a lesser negative effect on the PM emission [230]. Water decreases the local adiabatic flame temperature by absorbing its heat of evaporation [231] which leads to reduced $NO_x$ emission. WI can be achieved in two ways: Inlet water injection (IWI) or water fumigation and direct water injection (DWI) into the combustion chamber [230,232]. Fumigation is the technique of injecting water into the intake manifold upstream of the intake valve. Although WI technology decreased $NO_x$, there are some disadvantages such as it significantly increases the CO and HC emissions as well as BSFC at low load and low combustion temperature engine mode.

Tauzia et al. [230] studied the effects of WI on ignition delay, rate of heat release and emissions of an automotive direct injection diesel engine. The authors found that higher water flow rate contributes to longer ignition delay, higher peak heat release, and lower $NO_x$ emission but higher production of CO and HC emissions. Tesfa et al. [233] investigated an experiment into the effects of WI on engine performance, combustion and emission characteristics of a 4-cylinder, 4-stroke, turbocharged direct injection CI engine fueled with RB. They reported that the water injection at a rate of 3 kg/h results in the reduction of $NO_x$ emission by about 50% without causing any significant change in the specific fuel consumption, little effect on the in-cylinder pressure and heat release rate of the CI engine under different operating conditions and increased CO emission of about 40% compared to fuel-based combustion.

Using WI technology decreased $NO_x$ but it increased CO, HC and BSFC, so it's better to combine WI technology with other technologies.

#### 5.1.4. Emulsion technology (ET)

Fuel emulsification is the technique used to introduce water into the combustion chamber. The main aim of using emulsion technology is to enhance the fuel combustion efficiency and to reduce the emission of $NO_x$, PM, smoke, and other pollutants [234,235]. An emulsion is a mixture of two immiscible fluids. For example, oil phased emulsion helps the water droplets -in the dispersed phase - to be uniformly distributed throughout the fuel oil -in the continuous phase by mechanical, electronic, magnetic, or ultrasonic forces with the help of a suitable surfactant. An emulsion takes on the characteristics of the continuous phase. Hence, oil phased emulsions exhibit characteristics of fuel oil, not water. Two types emulsion are two-phase emulsion and three-phase emulsion. In which, two – phase emulsions are mainly two types, that is water-in-Oil (W/O) emulsions and oil-in-water (O/W) emulsions, and three – phase emulsions are also two types: oil-in-water-in-oil (O/W/O) and water-in-oil-inwater (W/O/W) emulsions [236]. Emulsions are inherently unstable. A schematic diagram of the W/O and O/W/O emulsion structures is shown in Fig. 7.

Over time they will separate into the stable states of the dispersed and continuous phase materials. To maintain the composition of an emulsion, surface active agents, or "surfactants", are incorporated into the production of an oil phased emulsion. In an oil phased emulsion, these surfactant agents encase the droplets of water distributed throughout the continuous oil phase and prevent the water droplets from coming together and coalescing. The addition of water results in a decrease in temperature inside the combustion chamber due to the evaporation, dissociation of water during the combustion and an increase in the local specific heat capacity [237]. The emulsion technology can be applied to bind various base fuels with water, creating a wide array of environmentally friendly products that reduce both $NO_x$ and PM pollution simultaneously which are created during the combustion process with or without penalty to fuel economy. On the other hand, the mass of the added water has been shown to increase the momentum of the fuel jet, thereby allowing improved atomization and air entrainment, which subsequently leads to premixed combustion and lower PM formation [238–240]. Water in the biodiesel emulsion increases the kinematic viscosity and reduces the heating value of the fuel [241]. Biodiesel emulsions also reduce PM soot fractions compared to B100 and diesel fuels [223]. Additionally, OH radicals may also be formed by the dissociation of water to further lower $NO_x$ and PM emissions [242]. However, this technology increases HC and CO emissions with increasing water content in emulsified fuel [243].

**Table 10**
Review of emissions and performance analysis using emulsion technology for biodiesel fuels.

| Emulsion | Test condition | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|
| | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| BD5W=JB(93%) +1% Span80 + 1% Tween80 + 5% water; BD10W=JB(88%) + 1% Span80 + 1% Tween80 + 10% water | CS = 1500 rpm | – | ↑6.87% for BD10W | ↓27% for BD10W | – | – | ↓8% for BD10W | [248] |
| 5.6% and 10% $H_2O$ with neat biodiesel | Low and medium load conditions | – | – | ↓ | ↑ | ↑ | ↓ | [249] |
| B100 (83% TOME + 17% COB) + 10% $H_2O$ | Rated engine speed (2800 ± 50) and peak torque conditions | No change at peak torque | ↑ at peak torque | ↓ at rated speed, ↓14.5% at peak torque | – | – | – | [250] |
| B20 (83% TOME + 17% COB) + 10% $H_2O$ | Speed (rpm) = 2400, 2900, 3300 & 3600 | ↑15% | ↓14.2% | ↓10.5% | – | – | – | [247] |
| 83% JB + 15% $H_2O$ + 2% surfactant | Full load | ↓2.7% | ↑2.4% | ↓22.9% | ↑ little | ↑45.8% | ↓14.9% | [244] |
| X = TPB (85%) + 15% $H_2O$ Y = TPB (80%) + 20% $H_2O$ | Full load | – | ↑6.87% for X; ↓3.78% for Y | ↓38% for X; 41% for Y | – | ↓1.94% for X; HC↓3.05% for Y | ↓7.22% for X; ↓9.63% for Y | [251] |
| SB (80 ml) + $C_2H_5OH$ (20 ml) + $H_2O$ (1/0.5 ml) + surfactant (4 g) | CS = 1500 rpm | ↑ | – | ↓ | ↑ (LL & ML) | ↑ (LL & ML) | ↓(HL) | [220] |
| (10 wt% $H_2O$ + 3.5% surfactant + 86.5% SB) | Load = 68 N m | ↓1.65% | – | ↓21.8% | ↑94.8% | ↑56% | – | [223] |
| SB (90%) + $H_2O$ (10%) + aqueous $NH_3$ (5%) | Speed varied 1000–2200 rpm | ↑ | – | ↓ | ↑ | – | – | [172] |
| RB80 + 10% $H_2O$ + 0.5% surfactant + 10% algae | With and without load | ↑4.95% | – | ↓(22.3–34.2)% | ↑(19.5–32.8)% | – | – | [252] |
| 10% $H_2O$ + PB90 | 39 kW rating, variable speed (1000–4000) rpm | – | ↓ | ↓15.6% | ↓8.7% | ↓9.3% | ↓13.9% | [253] |

Results compared to biodiesel without emulsion technology.

Basha et al. [244] investigated the effect of jatropha emulsified biodiesel (83% jatropha biodiesel with 15% water and 2% surfactant) on exhaust emissions and the performance of diesel engines. They reported that BTE increased by 2.4%, BSFC decreased by 2.7% and $NO_x$ decreased by 22.9%, PM decreased by 14.9% while HC increased by 45.8% and CO increased little compared to biodiesel without emulsion. Generally, the effect of emulsion on the performance is not clear, a several researchers [245,246] found increased engine power; others [223,247] observed a reduction. In Table 10, the emissions and performance data shows as using emulsion technology for biodiesel fuel.

From Table 10, the following conclusions are reached:

Using ET with 10–20% $H_2O$ in biodiesel fuel shows the penalties for BSFC and BTE. For example, BSFC increases by about 4.95–15% and BTE reduces by up 14.2% except for emulsified JB and TPB but $NO_x$ can reduce by about up 41% in various engine conditions. Emulsified biodiesel mostly increases CO and HC emissions by about 15.9–94.8%, 45.8–56% respectively but remains at the same or a lower level when compared to diesel combustion without emulsion and reduces smoke emissions by about 7.2–14.9%.

### *5.1.5. Fuel injection strategies modification*

*5.1.5.1. Injection timing retardation (ITR).* Injection timing which is an important parameter plays a significant role in determining both engine performance and pollutant emissions [254]. The combustion process is retarded due to the retardation of the injection timing. The concentration level of thermal $NO_x$ mainly depends on the combustion peak temperature; the $NO_x$ level will be lowered when the peak temperature remains low. However, using ITR meets some disadvantages such as the increased HC emission, the increased smoke emission, the increased fuel consumption, the decreased BTE and the reduced power [222].

Many researchers [212,255] reported that the control retarding the injection timing not only affects exhaust emissions but also affects the engine's performance. Ganapathy et al. [256] used a single cylinder DI diesel engine fueled with jatropha biodiesel to observe the effect of ITR of about 5° CA from the original 15° CA BTDC at 15 Nm and 1800 rpm, on the engine performance and emissions. They reported that this technique reduced the engine performance due to the lower calorific value. Although it reduced $NO_x$ emission due to the shorter ignition delay which reduced the air– fuel mixing time, hence leading to the slowing of the burning rate in turn slowly raising the combustion temperature, other emissions such as HC and smoke were increased marginally because of the poor initial phase of combustion. ITR reduced soot oxidation rates which increased soot or PM emission [257,258]. Table 11 reveals the emission and performance data when using ITR for biodiesel fuel.

*5.1.5.2. Injection pressure.* The injection pressure in diesel engines plays an important role for emission control strategies and performance. Increasing the injection pressure causes an earlier start of combustion due to the improved atomization which results in better air fuel mixing. Many researchers [267–271] have studied the effects of fuel injection pressure on diesel engine performance and emissions. They reported that increased injection pressure gave better results for BSFC, BTE, BSEC. CO, smoke and HC decreased but slight increased $NO_x$ emission compared to the original. Canakci et al. [272] tested the effects of injection pressure on the performance and emission characteristics of diesel engine fueled with methanol blended diesel fuel. The authors chose three different injection pressures 180, 200, 220 bar to investigate its effect on four different loads 5, 10, 15 and 20 Nm at constant engine speed of 2200 rpm. It was found that increasing injection pressure increased $NO_x$ and $CO_2$ while smoke, CO and HC

**Table 11**
Review of emissions and performance analysis using ITR for biodiesel fuels.

| Engine Specification | Retard the SOI timing | Fuel | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|---|
| | | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| 1 C, 4 S, DI, AC, CI | 3° CA from original 23° CA BTDC, IOP: 200 bar | WP100 | – | ↑2.3% | ↓25% | ↓30% | ↑35% | – | [259] |
| Lister-Petter TR1 NA, AC, 1 C, DI | 3° CA from original 22° CA BTDC, IMEP = 4.5 bar | RB100, RB50 | – | – | ↓17.3% for RB100;↓25.9% for RB50 | 9.3% for RB100,↑6.3% for RB50 | ↑5.5% for RB100,↑4.2% for RB50 | – | [224] |
| Lombardini 6 LD 400 1 C, DI | 5° CA from original 20° CA BTDC | RB5, RB20, RB50 & RB100 | ↑(14.07–16.59)% | – | ↓30.1% for RB5,↓28% for RB20,↓15.59% for RB50,↓9.77% for RB100 | ↑11.39% for RB5,↑21.08% for RB20,↑31.25% for RB50,↑35.11% for RB100 | ↑9.1% for RB5,↑33.3% for RB, ↑20,27.03% for RB50,↑44.68% for RB100 | – | [254] |
| 1 C, 4 S, DI, WC, CI, engine | 2° CA from original 23° CA BTDC, IOP: 190 bar | PME20 | ↓3.08% | ↑ | ↓18.84% | ↓3.5% | ↑5.81% | – | [260] |
| John Deere 4276 T TC, DI, DE | 3° CA from standard IT | Oxidized (SB) | – | – | ↓21.2% | – | – | ↑ exceedingly | [261] |
| Diesel engine | Retard SOI timing from original IT | KB | – | – | ↓ | ↓ | ↓ | – | [262] |
| 4 S, 1 C, DI, WC, CI, engine | 4° CA from original 23° CA BTDC | KB | – | ↑2.64% | ↓37.89% | ↓10.9% | ↓7.75% | ↓17% | [263] |
| Small power DE | Retarded SOI | KB | – | – | ↓8.2% | – | – | – | [264] |
| 1 C, 4 S, AC, vertical, Greaves Cotton GL 400 II A, DE | 5° CA from original 15° CA BTDC at 15Nm & 1800 rpm | JB | ↑5.5% | ↓2.4% | ↓24.79% | No change | ↑47% | ↑66% | [256] |
| Kirloskar, 4 S, TV, 1 C, DI, WC, DE | 3° CA from original 23° CA BTDC, IOP: 250E5 N/m2 | MB25 | ↓4.10% | – | ↓24.89% | – | ↓10% | ↓26.70% | [265] |
| | | MB50 | ↓3.79% | – | ↓23.73% | – | ↓8.11% | ↓18.52% | |
| | | MB75 | ↓3.41% | – | ↓24.74% | – | ↓8.33% | ↓14.29% | |
| | | MB100 | ↓2.92% | – | ↓24.89% | – | ↓3.26% | ↓16.51% | |
| 1 C, 4 S, DI, WC, DE | 3° CA from original 23° CA BTDC, IOP: 200 bar | JB20 | – | ↓4.1% | ↓36.84% | – | ↑15.26% | ↑40.98% | [266] |
| | | JB100 | – | ↓2.4% | ↓28.25% | – | ↑38.5% | ↑38.6% | |

Results compared to biodiesel with original IT.

decreased and performance parameters like BSFC, BSEC and BTE were best at original injection pressure of 200 bar and became poor on either increased or decreased injection pressure. Jindal et al. [273] investigated the effect of injection pressure on the performance and emission characteristics of diesel engine fueled with jatropha methyl ester diesel fuel. They chose three injection pressures 150, 200, 250 bar for their study. The results showed that at injection pressure of 250 bar, BTE was improved by 8.9%, with a reduced HC and smoke compared to the base injection pressure. Puhan et al. [274] studied the effect of injection pressure on high linolenic linseed oil methyl ester fueled diesel engine. At higher injection pressure of 240 bar, BTE and BSFC is improved accompanied with decreased CO, smoke and HC but slight increased $NO_x$ emission. Table 12 shows the effect of injection pressure on the performance and emission characteristics of diesel engine fueled with biodiesel fuel.

From Tables 11 and 12, the following conclusions are reached:

Using ITR technology in a biodiesel engine deteriorates fuel consumption and performance characteristics, namely, BSFC increases by 16.6% and BTE reduces by up 4.1% except for ITR technology with KB, MB and P20.

In most biodiesel engines except KB and MB, ITR technology increases the CO, HC and smoke emissions by about 11.39–35.11%, 5.5–38%, 17–66% respectively and the $NO_x$ emission reduces by about 8.2–37.89% compared to the original IT.

In general, increasing injection pressure results in increased thermal efficiency 1.1–8.9% and reduced fuel consumption by about 10–17.26%. While CO, HC and smoke emissions reduce by about 2.51–39%, 0.3–66%, 0.3–27% respectively, $NO_x$ emission increases significantly by about 4.5–28.6% compared to the original IP.

Therefore finding the set optimal parameters for any engine and fuel based on a balance between performance and emissions plays a vital role. Hence the combination of one or more strategies may help to strike a balance between reducing emissions and improving the performance of the engine. These studies also provide facts on major reductions in pollutions particularly with respect to $NO_x$ and PM reduction and hence provide the flexibility in controlling the PM-$NO_x$ trade-off for future vehicles to meet more and more stringent emission norms.

### 5.1.6. Simultaneous technology (ST)

Many researchers believed that using simultaneous technology will give better efficiency on the performance and reduction in exhaust emissions from a biodiesel-fueled CI diesel engine than using single technology. Some STs have been applied to achieve optimum results as emulsion with EGR [223], additives with EGR [281–283], EGR with ITR [212,225]. Qi et al. [225] studied the combined effect of EGR and ITR technologies on the combustion and emission characteristics of a split injection strategy DI-diesel engine fueled with soybean biodiesel. They authors reported that a higher EGR rate with ITR was an effective technology to reduce $NO_x$ emission without the penalties of soot emission and BSFC. Saravanan et al. [284] investigated experiment the combined effect of 10% EGR with 220– 230 bar injection pressure on the combustion and emission characteristics of DI-diesel engine fueled with RBB. The authors found that the most effective result for the reduction of $NO_x$ emission with small penalties for smoke density and BTE at no load and partial load while injection timing is a more influential factor at full load. Table 13 shows the effect of using simultaneous technology on the performance and emission characteristics of diesel engine fueled with biodiesel fuel.

From Table 13, the following conclusions are reached:

This combined technology can adversely affects performance characteristics of the engine, BSFC increases by 3% and BTE reduces by up 1.43% except for ST with crude rice bran biodiesel fuel.

**Table 12**
Review of emissions and performance analysis varied IP for biodiesel fuels.

| Engine Specification | Injection pressures | Fuel | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|---|
| | | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| Lombardini 1 C, 4 S, DI, AC | 180, 200, 220, and 240 bars; MEP: 12.5, 25, 37.5, and 50 kPa & 2200 rpm | Biodiesel (B0, B5, B20, B50, 100) | ↓ | ↑slightly | ↑ | ↓ | ↓ | ↓ | [271] |
| Lombardini 6 LD 400, 1 C, 4 S, DI, AC | 180, 200, 220 bars at 20 Nm & 2200 rpm | Biodiesel (B5, B20, B50, 100) | ↓17.26% | ↑ | ↑28.36% for B100 | ↓6.85% for B20 | ↓0.3% for B5 | ↓0.3% for B5 | [275] |
| Lombardini 6 LD 400, 1 C, 4 S, DI, AC | 180, 200, 220 bars at 5,10,15,20 Nm & 2200 rpm | Methanol blends | – | – | ↑4.5% for M5 | ↓ 2.51% for M15 | ↓13.6% for M15 | ↓ 2.1% for M15 | [272] |
| Kirloskar 1 C, 4 S, DI, AC | 200, 220 and 240 bars at 3.5 kW & 1500 rpm | LOME | ↓ | No change | ↑ | ↓ | ↓ | ↓ | [274] |
| Kirloskar 1 C, 4 S, DI, WC | 150,175, 200, 225, 250 bars at 7.5 kW & 1500 rpm | Jatropha methyl ester | ↓10% at 250 bar | ↑ 8.9% at 250 bar | ↓21.2% | ↑ | – | ↑ exceedingly | [264] |
| 2 C, 4 S, CIDI | 150, 200, 250 bars at 4.4 kW & 1500 rpm | Pongamia biodiesel | ↓slightly | ↑ | ↑ | ↓ | ↓ | ↓ | [276] |
| 1 C, 4 S, DI, WC | 200, 220, 240, 260 bars at 4.4 kW & 1500 rpm | H50 | – | ↑ | ↑ | ↓ | ↓ | ↓ | [277] |
| TV_SR II, 1 C, 4 S, CIDI | 220, 220, 240, 260, 280, 300 bars at 5.2 kW & 1500 rpm | waste cooking palm oil | – | ↑ 1.44% at 280 bar | ↓6.5% at 280 bar | – | – | ↓17.2% at 280 bar | [278] |
| 1 C, 4 S, AC, DI | 215, 235, 255 bars at 4.4 kW & 1500 rpm | Orange Skin Powder Diesel Solution (B30) | – | ↑1.1% at 280 bar 235 | ↑26% at bar 235 | ↓39% at 235 bar | ↓66% at 235 bar | ↓27% at 235 bar | [279,280] |

Results compared to biodiesel with original IP.

**Table 13**
Review of emissions and performance analysis using simultaneous technology for biodiesel fuels.

| Engine Specification | Condition technology | Fuel | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|---|
| | | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| Kirloskar - AVI, 1 C, 4 S, WC, DI | 2% DEE (A) + 15% EGR at no load condition<br>2% DEE (A) + 15% EGR at maximum load condition | FOB | ↑<br>↑ | No change<br>No change | ↓75.5%<br>↓94.8% | ↓25%<br>↓52% | ↓68.8%<br>↓90.2% | –<br>– | [192] |
| Twin cylinder, 4 S, WC, DI | 10% DMC + 15% EGR at 80% load | KB40 | ↑0.35% | ↓1.43% | ↓22.01% | ↑0.69% | ↑2.5% | ↑1.54% | [228] |
| 1 C, 4 S, WC, DI | (10 wt% H2O + 3.5% surfactant + 86.5% SB) + 27% EGR, 68 N m load | SB | ↑3% | – | ↓91% | ↑69.9% | ↑↑ | ↑↑ | [228] |
| DEUTZ FL1 906, 1 C, 4 S, WC, DI | Increasing the EGR rate from 38% to 43% + retardation of injection at 4° CA from original IT | SB | ↑ | – | ↓50% | – | – | ↓ slightly at LL | [225] |
| Kirloskar 1 C, 4 S, AC, DI | Increasing the EGR rate with three levels 0%, 10%, 15% + retardation of injection at 2.5° CA from original IT + Increasing injection pressure rate with three levels 210, 230,250 bar | Crude rice bran oil methyl ester | – | ↑3.6% | ↓14% | – | – | ↑4% | [284] |

Note: A = Additives, results compared to biodiesel without ST.

Using simultaneous technology strongly reduced $NO_x$ emission by up 95% with 2% DEE, and 10% DME and EHN additives in FOB, KB, JB and 15–20% EGR at no load, maximum load and 80% load respectively but increased CO emission by about 0.7–69% and more than 100% with HC, smoke emissions.

*5.1.7. Combustion chamber geometry modification*

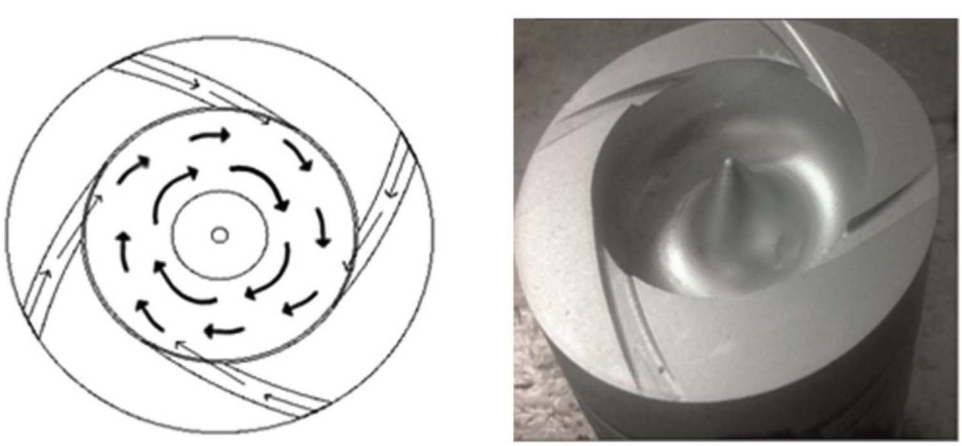
Another way to overcome the disadvantages of biodiesel fueled DI diesel engine is appropriate engine modification without compromising the combustion performance and emission characteristics. Among the various engine modifications, changes in combustion chambers, injection timing, and injection pressure play a vital role. When the engine is run by biodiesel, the need for modification in the combustion chamber has to be taken into account to evaluate its performance and emissions. The improved air motion in the combustion chamber due to its geometry facilitates the mixture formation of biodiesel with air, hence increasing the brake thermal efficiency and lowering the specific fuel consumption. Novel swirling grooves were provided in the piston top face to enhance the biodiesel air mixing by improving the swirling motion. Isaac et al. [285] studied the combined effect of injection pressure and turbulence inducer piston (TIP) on the performance, and emission characteristics of biodiesel from Adelfa as a blend of 20% diesel (A20) which could be used in the diesel engine with turbulence inducer piston operated at 21°BTDC and 220 bar pressure at a constant speed of 1500 rpm. The schematic diagram of TIP is shown in Fig. 8.

The authors reported that considerable improvement in the emission characteristics like HC, CO, smoke with increased injection pressure due to the presence of oxygen in the blend and improvement in fuel air mixing was facilitated by turbulence inducer grooves on the crown of the piston. $NO_x$ emission increased due to the improved combustion rate and combustion chamber temperature. The brake specific energy consumption dropped and the brake thermal efficiency showed a swifter profile for TIP with A20 due to better air enhancement and fuel air mixing which led to improved combustion.

Jaichandar et al. [37] investigated a blend of 20% Pongamia Oil Methyl Ester (POME) with standard diesel as fuel and three types of combustion chambers namely Hemispherical combustion chamber (HCC), Toroidal combustion chamber (TCC) and Shallow depth combustion chamber (SCC) without altering the compression ratio of the engine. Fig. 9 shows the shapes of three combustion chamber geometries. They found that the brake thermal efficiency for toroidal combustion chamber is higher than for the other two types of combustion chambers. PM, CO and HC reduced significantly for toroidal combustion chamber compared to the other two. However $NO_x$ were slightly higher for toroidal combustion chamber.

*5.2. Low-temperature combustion (LTC)*

A promising new technique which covers a number of advanced combustion strategies, includes HCCI and PCCI. The entire fuel and air charge is premixed prior to the start of combustion in LTC advanced combustion strategies. In the LTC mode, the combustion is controlled to occur in the pre-defined relative air–fuel ratio and temperature zones which limit the formation of $NO_x$, PM, and soot emissions simultaneously. Fig. 10 shows that $NO_x$ emissions are not formed in the rich mixture zone if the flame temperature is under 2200 K, while soot



(a) Schematic representation. (b) Fabricated turbulence inducer piston.

**Fig. 8.** Turbulence inducer piston [235]. (a) Schematic representation. (b) Fabricated turbulence inducer piston.

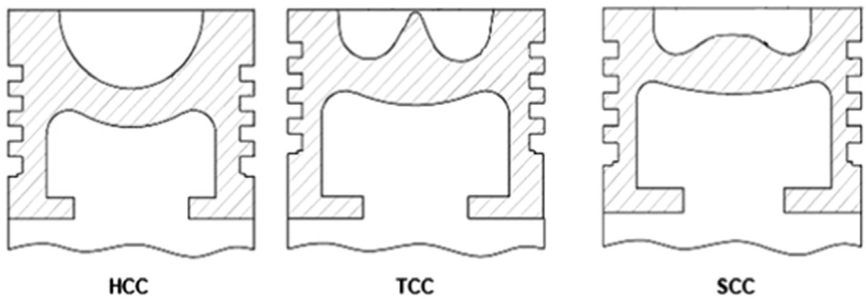



**Fig. 9.** Schematic of different open combustion chambers [37].

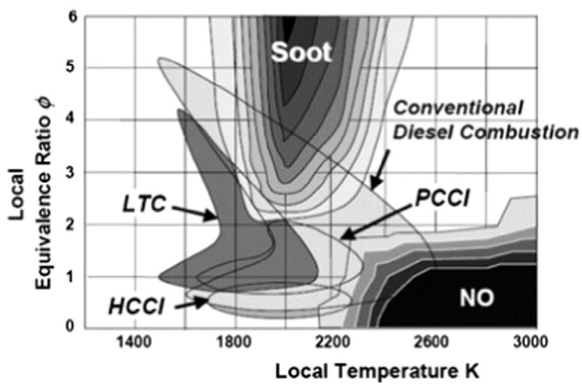



**Fig. 10.** LTC model for PCCI, HCCI and soot, $NO_x$ formation zones [286].

is not formed in the lean mixture zone under 1800 K. Compared to the conventional diesel combustion, LTC strategies generally increased the pre-combustion mixing, which helps to avoid locally rich regions and reduces the peak combustion temperature, thus leading to the reduction of NOx and soot simultaneously. Moreover, the LTC modes of combustion [138] also use high EGR rates (up to 50%), high injection pressures, multiple fuel injection, and late main injection even after TDC.

Recently, a new invention of LTC, Reactivity Controlled Compression Ignition (RCCI) has been reported by several authors [287–289]. This technology has the potential to solve some of the disadvantages of HCCI and PCCI. With the LTC mode, the ignition delay increases, so increasing the premixed combustion phase and decreasing the diffusion flame combustion phase in which the overall in-cylinder temperature is reduced substantially, resulting in reducing $NO_x$ formation. At the same time, PM is reduced due to the dominance of homogeneous lean charge in the combustion chamber, higher injection pressure facilitates the atomization of the fuel and higher oxygen content of biodiesel ensures the complete oxidation of soot. HC and CO emissions in LTC modes are affected by several factors like injection pressure and timing [290], operating load, injection style [291], intake air temperature [292], in-cylinder temperature and combustion phasing [293], etc. In the premixed mode, both the early and late injection increased higher HC and CO than conventional combustion of biodiesel. Besides, HC was increased by extended ignition delay of LTC mode which created over-lean regions and increased the quantity of injected fuel species outside lean flammability limits. It means that, in spite of reducing HC and CO at the premixed LTC than diesel fuel, LTC mode releases higher HC and CO than conventional combustion of biodiesel. In fact, this is one of the principle disadvantages of applying HCCI, PCCI or RCCI.

Soloiu et al. [294] investigated the use of port fuel injection with *n*-butanol in a 100% peanut biodiesel-fueled engine to attain an LTC/PCCI mode at idling speeds and loads with 1–3 bar IMEP and reported that by controlling the combustion phases and modifying the classical $NO_x$-soot trade-off, soot/PM and $NO_x$ reduced about 98% and 74% respectively, at 3 bar IMEP compared to diesel without LTC mode but HC and CO emissions increased greatly due to the incomplete combustion during the premixed burn phase. Besides HC and CO are also affected by other factors such as the lack of intake manifold heating, crude manifold injection strategy, which consequently produces fuel pooling in the intake and allows the passage of some butanol directly from the intake into the exhaust manifold. Using a high EGR rate like an LTC technology, reducing the combustion temperature due to the high heat and energy absorption capacity of the introduced diluted exhaust gas [295] lead to reduced $NO_x$ missions. However, Karra et al. [296] notified that PM emission increases at first with increasing EGR rate and then reduces at high levels of EGR rate. Espadafor et al. [219] also examined a diesel engine fueled with Colza biodiesel and its blends, applying the LTC mode of combustion as HCCI gained by high swirl ratio, EGR and late injection. The authors reported that $NO_x$ and PM emissions decrease with increasing EGR rates and biodiesel blends; however, increased HC and CO emissions happened for all tested fuels. They explained that exhaust gas temperature reduces with increasing percentages of EGR, which results in a reduction in the oxidation rate for HC and CO. LTC mode can also be affected by fuel properties. Higher surface tension, lower volatility and narrow boiling range, which increase fuel wall impingement, are worse biodiesel mixture formation characteristics which increase the scale of CO and HC emissions due to incomplete oxidation. Therefore, the addition of oxygenated ethanol with biodiesel blends was not proved fully to be a better way to solve the problem of higher CO and HC emissions with LTC due to its incomplete combustion, because of having higher latent vaporization heat which leads to a lower combustion temperature [297,298]. Table 14 shows the effect of using LTC on emissions and performance for biodiesel fuels.

Based on the summary in the Table 14, the following conclusions are drawn:

Generally LTC affects slightly the performance, in which BSFC increases by about 3–5%, BTE reduces by about 5.5% but it reduces $NO_x$ and PM emissions simultaneously with a very high rate by about 66–93.5%. However it also shows a little penalty to CO and HC emissions as they increase by 11% and 43.17%, respectively because of slight incomplete combustions.

HCCI combustion mode is the extremely effective method of reducing PM emission due to the fuel impinging on the cylinder and piston walls. The PM emission decreases due to the improved atomization, and better vaporization and homogenization when the injection pressure increases.

RCCI combustion mode has not been tested with biodiesel as a higher reactive fuel yet. Different fuels should be tested to cover a wide range of reactivity.

## 6. Summary and future of the combustion and emissions of the diesel engine fueled with biodiesel

According to the above analysis, low-temperature HCCI or PCCI combustion modes are promising solutions for low-emission biodiesel

**Table 14**
Review of emissions and performance analysis using LTC for biodiesel fuels.

| Fuel type | Test condition | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|
| | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| Peanut biodiesel (PNB100) | PCCI/LTC (*n*-butanol injected into intake manifold & 3 bar IMEP, idling speed) | – | ↓ but ↑ with ↑ IMEP | ↓75% | ↑ large scale | ↑ large scale | ↓98% | [294] |
| CB0, CB30, CB65, CB100 | HCCI (high swirl ratio, EGR & late injection) | – | – | ↓ (CB0 > CB100 & CB30 = CB65) with ↑% of EGR rate | ↑(CB100 > CB65 > CB30 > CB0) with ↑% of EGR rate | ↑(CB100 > CB65 > CB30 > CB0)with ↑% of EGR rate | – | [219] |
| A = RB0, B=(RB40 + 20%E) | LTC for A (36% EGR, Pr. Rail: 860 bar, SOI main −0.3° CA & SOI pilot 31.9° CA) where for B (43.7% EGR, Pr. Rail: 600 bar, SOI main 7° CA & SOI pilot NA) at 1500 rpm & 3 bar of BMEP as optimized condition | ↑13.28% for fuel type B compared to A | – | ↓69.84% for fuel type B compared to A | ↓3.19% for fuel type B compared to A | ↑43.77% for fuel type B compared to A | ↓71.4% for fuel type B compared to A | [298] |
| PB0 PB20, PB100 | Later-phased LTC (high EGR level + retard IT) | – | unchanged (PB100), ↓ for PB0 & PB20 with retard IT | ↓ (PB0 > PB100 & PB20 > PB100) with retard IT | ↓ (PB20), ↓85% (PB100) | ↑(PB0 > PB20 & PB0 > PB100) | ↓ for all fuels | [299] |
| RB100 | HCCI (variation of IP: a = 400 bar, b = 500 bar, c = 3600 bar, d = 700 bar, 1500 rpm speed | Fewer penalties on performance. | Fewer penalties on performance | ↓8.68% (a), ↓15.85% (b), ↓11.31% (c), same (d) compared to diesel | ↑(1.15–11.5)% compared to diesel | ↓up to 41% compared to diesel | ↓(0–13)% compared to diesel | [300] |
| B0, B20, B100 | LTC (IP: 180 MPa, multiple injections & 30% EGR) | ↑ at LTC mode | – | ↑(B20; B100) with ↑IP, $NO_x$ identical among B0 & B20 but ↑ for B100 at LTC mode | ↑ at LTC mode but ↓ with retardation of IT | ↑ at LTC mode but ↓ with retardation of IT | ↓ (B20; B100) at LTC mode | [296] |
| SB0, SB20, SB50, SB100 | CS: 1500 rpm, IP: 600 bar. Single injection, IMEP: 2.0 bar. a = −25, b = −10 and c = 3 CAD ATDC | ↓ for (b) & (c) condition compared to (a) for all fuel samples | – | ↓78.7%(SB0);↓76% (SB20);↓68.6%(SB50);↓66.3% (SB100) for b: a & ↓93.5%(SB0); ↓92.7% (SB20);↓91.4%(SB50); ↓91.3% (SB100) for c: a. | ↑ | ↑ | ↓ | [301] |
| B100 | LTC (speed: 1500 rpm, Pr. Rail: 950 bar, Pr. Intake: 1.7 bar (abs), IMEP: 8 bar & 50–70% EGR | – | Improved indicated thermal efficiency at 340° CA SOI with LTC | ↓ with increasing EGR rate, $NO_x$ formation rate was about constant but little at 60–70% EGR | ↑ appreciably for early injection strategy, however improve at 340° CA SOI | ↑ appreciably for early injection strategy, however improve at 340° CA SOI. | ↑ appreciably for early injection strategy | [302] |
| SB0, SB20, SB50 & SB100 | Late-injection premixed LTC mode (50% EGR and Injection Timing 5, 7 & 9° CA BTDC) | ↑ with retardation of IT | – | ↑ for IT advance and increasing biodiesel content, ↓ with ↑ (% of EGR & retardation of IT) | ↑ for all cases | ↑ for retardation of IT but ↓ with ↑ biodiesel blends | very low specially for SB100 | [234,303] |
| Colza biodiesel (B100, B65, B30) | HCCI + 32% EGR, IP: 650 bar, speed: 3000 rpm | ↑ with ↑EGR | – | ↑ 32% | ↑ 16% | ↑ 52% | ↓ 61% | [304] |
| Soy biodiesel (B100) | High EGR (60%) enabled HCCI, variable loading | – | ↓ with ↑ EGR | ↓ as EGR ↑ | ↑ | ↑ | ↓ as ↑ EGR | [305] |
| Canola biodiesel (B100) | | ↑ | Same trend like soy but relatively higher emission | Same trend like soy but relatively lower emission | ↑ | ↑ | Same trend like soy but relatively higher emission | |
| Biodiesel blend of Soy, Canola, Yellow grease and Tallow biodiesel | Variable loading (IMEP 5–10 bar), Variable boost pressure, single shot, EGR assisted LTC for low loads, multi-pulse EGR assisted HCCI for heavy loads, single and multiple injections with wide range sweep of IT, EGR up to 70% according to the condition. | – | – | ↓ for low load retarded IT up to 368 °CA and higher EGR | ↓↓ at low load up to IT 368 °CA and no effect of EGR | ↓↓ at low load up to IT 368 °CA and slight ↑ as EGR ↑ | Almost zero at low load conditions | [28] |
| | | – | – | ↓ at higher loads↑ EGR and ↑ boost pressure, lowest for two early injections at 340 °CA | ↑ at higher loads,↑ EGR and↓ boost pressure, lowest E for two early injections | ↑ at higher loads ↓boost pressure,lowest E for two early injections | ↑ for single injection at higher loads, ↑ EGR, two early injections gave good results | |

(continued on next page)

**Table 14** *(continued)*

| Fuel type | Test condition | Performance | | Emission | | | | Refs |
|---|---|---|---|---|---|---|---|---|
| | | BSFC | BTE | $NO_x$ | CO | HC | Smoke | |
| Biodiesel blend of Soy, Canola, Yellow grease and Tallow biodiesel. | Late injection assisted LTC mode; EGR up to 70%; IP: 950 bar, injection system: common rail, single shot injection (IMEP 8 bar) variable intake pressure (1.2/1.5 bar), multi-pulse injection (IMEP 6 bar); Wide range (347–367 °CA) sweep of IT | ↑↑ for above 50% EGR and at late IT, multiple injection gave ↑ value than single shot injection. | – | For single shot injection E got zero value at 50% EGR. For multi-pulse, retarded IT and reduced number of injection ↓ E. | ↓ for multiple (4shots) injections at lower EGR. Otherwise increased. | ↑↑ for single injection, ↓ for multiple (4shots) injections | ↓↓ both single and multiple injections. | [306] |
| Soy-based methyl ester (B20, B50, B100) | Late injection premixed LTC mode; 50% EGR; speed: 1500 rpm, load: 400 kPa, IP: 800, 1000, 1200 bar, injection system: common rail; IT: 5°, 7° and 9° BTDC | ↑ at retarded IT | ↓ at retarded IT | ↑ as IT advanced and BD content ↑ up to 50% increment for BD than ULSD at retarded IT | Higher than 1500 ppm for all the cases | ↑ for retarded IT and ↓ for ↑ BD portion up to 42% decrement for BD than ULSD at retarded IT | ↓↓ especially for 100% BD | [307] |
| Soy based methyl ester (B50, B100) | Late and early injection partially premixed LTC, EGR: 45%(LLTC) + 55%(ELTC); speed: 4400 rpm, IP: on average 870 bar, injection system: common rail; IT: 5.9° to 7.1° BTDC (for LLTC), 17.3° to 24.1° BTDC (for ELTC) | – | – | – | – | ↓ as BD content ↑, ELTC, LLTC and CC gave 64%,25% and 66% ↓ respectively for B100 than ULSD | ELTC gave the highest E, 94% ↑ when used B100 than ULSD, CC gave lowest emission. | [308] |
| Soy biodiesel (B20, B50, B100) | Late injection LTC, speed: 1500 rpm, IP: 600 bar, Injection system: common ral; sweep of injection timing from −25° ATDC to 3° ATDC | ↓ 11.1% as the IT was retarded. | – | Retarded IT gave ↓ E than early IT; except early IT, E ↑ as BD content ↑ up to 68% decrement than CC | – | – | ↓↓ for retarded injection | [309] |
| Biodiesel (B40) | Late injection EGR assisted LTC, speed 1600 rpm and 25% loading, 38% EGR, IP: up to 1600 bar, injection system: common rail; single injection (6° BTDC), double injection (pilot: 25° BTDC, main: 2° ATDC) | ↓at 6° BTDC IT even at higher EGR. | 6° BTDC IT gave high thermal efficiency even at higher EGR. | ↓ as EGR ↑, BD blend showed slight ↑ E than ULSD Single injection with EGR showed better results than double injections. | – | – | – | [283] |
| Biodiesel–ethanol (80–20%) blend. | Late injection premixed LTC, 40% EGR for high load and 50%EGR for low loads; variable loading, speed 1500 rpm, IP: 100 MPa, Intake pressure: 120/150 kPa, Injection system: common rail; IT: 13–10.5° BTDC | – | Maintained at least 96% combustion efficiency | less than 1*g*/kg-fuel at each loading for BD-ethanol | – | – | For BD and BD-ethanol blend less than 0.25FSN found almost all over engine load. | [160] |
| Biodiesel (B100) | Fuel vaporizer with port fuel injection assisted HCCI, variable loading; speed 1500 rpm, IP: 2 bar, Injection system: port fuel injection with fuel vaporizer, direct injection; IT: 23° BTDC (for direct injection) | ↑ 3–5% value than CC system | ↓ about 5.5% value than CC system | BD vapor induction gave very low E, up to 87% decrement at 2–4 bars BMEP than DI system | ↓ as load ↑ up to 20% decrement for BD vapor induction | ↓ as load ↑, BD vapor induction emitted lowest | ↑ as load ↑, BD vapor induction emitted almost 1/3 of the DI system | [207] |
| Neat soybean biodiesel and 20–50% blend of biodiesel | Late injection HCCI; speed 1500 rpm, IP: 600 bar, injection system: common rail, injection cone angle: 150°, IT: −25° ATDC, −10° ATDC and 3° ATDC, | ↓ For all the fuels late injection (3° ATDC) | – | ↑ At IT −25° ATDC, lowest E for all fuel blends at 3° ATDC, ↑ as BD content ↑ | – | – | ↓ at 3° ATDC | [310] |

engines compared to the others thanks to the reduction rate of $NO_x$ and PM emissions with little penalty in terms of engine performance. The expense of using additives increases while the emissions are not decreased; ITR is easy to modify while BTE is reduced and smoke strongly increases; using ET and WI in a long period of time, the engine components tend to corrosion. Using EGR independently reduces significantly $NO_x$ emissions and energy efficiency, operational stability is reduced, and PM generation of the engine is increased. High injection pressure with in-cylinder swirl formation requires modifying engine. In this case, LTC modes appear cleanly as the extremely effective modes to ensure the engine performance with the ultra-low emissions. However, these modes have some drawbacks which can be solved in the near future. Besides using after treatment technologies to reduce HC and CO emissions, different technologies can be used such as higher injection pressure, intake pressure or multiple injection methods during biodiesel combustion for both PCCI and HCCI. The fuel consumption of LTC modes can be reduced by proper optimization of the combustion conditions and fuel chemistry. Fuel reactivity stratification method used in RCCI combustion has opened an approach to reduce BSFC through LTC modes as well as increasing the operating load with high thermal efficiency. Regardless of any fuel-using combustion, $NO_x$ is reduced better in premixed LTC than in HCCI. However, RCCI is the most efficient. This study suggests that the future studies should deeply investigate the RCCI combustion system using different biodiesels. Besides the stringent emission standards are more and more increased, the LTC performance is improved continuously, too. Therefore LTC is the most optimal technology of the combustion and emissions of the diesel engine fueled with biodiesel in the future.

## 7. Conclusion

From this study, the use of biodiesel-fueled CI engines is inevitable due to the increasing demand of human and environmental pollution problems. Many authors reported that using biodiesel in diesel engines significantly reduce PM, HC, CO emissions. $NO_x$ emission increases while the brake power and brake thermal efficiency are slightly lowered, but the BSFC increases more than diesel fuel because that is unavoidable. So the selection of a technology which increases the engine performance and reduces emissions of the diesel engine fueled with biodiesel, plays an extremely important role. The characteristics of the performance and emission of a compression ignition engine fueled with different biodiesel blended with different technologies were investigated and compared with those fueled with neat biodiesel and blends. According to the analysis of the above literature the following summery can be drawn:

(1) Metal based and oxygenated additives increased the brake thermal efficiency and decrease the brake specific fuel consumption, reduced exhaust emissions such as CO, HC and smoke, but $NO_X$ emission increased significantly. Antioxidant additives in biodiesel have different effects on BTE, BSFC and emissions. Antioxidant additives in biodiesel can reduce the prompt $NO_x$ (by up to 43.5%) with increasing CO, HC emissions. To apply this technology commercially, further studies are needed to determine the effects of additives on unregulated emissions, $SO_3$ and $SO_2$ generation, acid dew point, corrosive properties of engine and cost.
(2) EGR is the simple technology which is widely used due to lower cost and lower volume requirements. EGR can increase BSFC and reduces the engine efficiency slightly but it significantly reduces the $NO_x$ emission compared to biodiesel combustion. To apply this technology, further studies need to determine then optimal EGR rate for different biodiesel on base characteristics of performance and emissions.
(3) WI and ET technologies are applied less for biodiesel-fueled CI engines. These technologies can reduce $NO_x$ and PM simultaneously but also increase the CO and HC emissions with some penalties of BSFC and BTE. Moreover, those technologies increase the corrosive properties of the engine components.
(4) Fuel injection strategy modification was also a method that gained a lot of attention. Using ITR technology in a biodiesel-fueled engine reduces the $NO_x$ emission, deteriorates fuel consumption, performance characteristics, as well as increases the CO, HC and smoke emissions compared to the original IT. Increasing the injection pressure increases the thermal efficiency, better fuel consumption while less CO, HC and smoke emissions, however with higher $NO_x$. Therefore, the further investigations need to find the set optimal parameters for any engine and fuel.
(5) Simultaneous technologies such as additives or emulsion, with EGR on a biodiesel-fueled engine showed obviously effects on the performance and $NO_x$ emission but increases CO, HC and smoke emissions significantly.
(6) The LTC mode of combustion in biodiesel-fueled engines achieved extremely good results in reducing $NO_x$ and PM emissions simultaneously by up to about 95% and 98%, respectively, with little penalty on the engine performance. However, HC and CO emissions increased greatly but this can be minimized by using post-combustion equipment.
(7) Modifying combustion chamber geometry improved the emission characteristics like HC, CO, smoke, brake thermal efficiency. However, $NO_x$ emission increased due to the improved combustion rate and combustion chamber temperature. Hence, further investigations need to combine a modified combustion chamber geometry with injection strategies.

From this review article, modern LTC technology has many advantages of modern technology compared to others as the reduction rate of $NO_x$ and PM emissions is very high simultaneously with little penalty in terms of engine performance and emissions which can be solved by using many different technologies. This technology is really promising in biodiesel-fueled engines, in which the RCCI combustion system can be the future of diesel engine fueled with biodiesel.

## Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

## Acknowledgements

This work is supported by the National Natural Science Foundation of China (51676066), Singapore Ministry of Education AcRF-Tier 1 Grant RG91/13-M4011228 and RG92/16-M4011618.

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