

Injection Parameter Optimisation in Biodiesel-Fuelled Variable Compression Ratio Engines: Interactions Governing Combustion, Performance and Emissions

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ABSTRACT

Biodiesel is an accepted renewable replacement fuel for conventional petroleum diesel, but its higher viscosity and lower volatility and heating value make biodiesel blends impractical in a single compression ratio engine. Variable compression ratio removes that constraint by allowing the compression ratio to be used as an experimental variable, and adding a variable to injection pressure and injection timing. This review concerns thirty-four experimental and theoretical research frameworks published between 2008 and 2025 using biodiesel and biodiesel-oxygenate blends in variable compression ratio and parameter-controlled compression ignition engines, including diethyl ether, dimethyl carbonate, higher alcohols including n-butanol and n-pentanol, other oxygenated ethers and cetane improvers in addition to the biodiesel blend. Each study is characterized by the fuel scheme, the engine configuration, the controlled and response variables. Quantitative data is reported only for those studies whose results were verifiable in the original publication. In both of the studies, there was a correlation between increased compression ratio and reducing carbon monoxide and hydrocarbon emissions, and increasing NO_x emissions. Increased compression ratio and injection pressure improved brake thermal efficiency and reduced specific fuel consumption. As a general trend, moderate quantities of diethyl ether decreased NO_x and CO emissions while increasing total HC emissions. A mixture of dimethyl carbonate and EGR always decreased NO_x and smoke emissions while increasing CO and HC emissions. Taguchi designs, response surface methodology, grey relational analysis, artificial neural networks and computational fluid dynamics are compared in how they deal with these factors, but different baselines, undisclosed additive units, and the omission of non-confirmed levels prevent quantitative comparisons of the methods from the literature. These issues are discussed along with suggested common reporting sets.

Keywords: Variable compression ratio engine; Biodiesel; Diethyl ether; Dimethyl carbonate; Injection pressure; Response surface methodology

Abbreviations: ANN: artificial neural network, BSFC: brake specific fuel consumption, BTE: brake thermal efficiency, CFD: computational fluid dynamics, CI: compression ignition, CN: cetane number, CO: carbon monoxide, CR: compression ratio, CRDI: common rail direct injection, DEE: diethyl ether,

DI: direct injection, DMC: dimethyl carbonate, EGR: exhaust gas recirculation, EGT: exhaust gas temperature, GRA: grey relational analysis, HC: hydrocarbon, HRR: heat release rate, HSDI: high speed direct injection, IP: injection pressure, IT: injection timing, LHV: lower heating value, LTC: low temperature combustion, NO_x: oxides of nitrogen, RSM: response surface methodology, THC: total hydrocarbons, VCR: variable compression ratio

1. Introduction

Compression ignition engines remain the dominant technology for freight transport, for agricultural machinery and for decentralized power generation. This plus growing demand for diesel fuel in developing countries has maintained interest in renewable liquid fuels which can be drop-in compatible with existing engines without the need for modification of hardware. Biodiesel is produced by the transesterification of vegetable oils, animal fats or waste cooking oil. It has been by far the most extensively tested of these fuels because it is miscible with diesel, is biodegradable and is sulphur free. Its properties vary with the source used to produce it. The difference in the properties of a range of biodiesel fuels when tested in a single engine has been quantified. [1] The use of non-edible and waste feedstocks is preferred because it does not compete with the food supply and lowers production costs [2]. There are some limitations on biodiesel use due to biodiesel's properties. For example, kinematic viscosity of soybean methyl ester is 4.95 cSt (centistokes) at 40 °C, compared with 3.30 cSt for a diesel reference sample at the same temperature in the same laboratory. A soybean methyl ester's heating value is lower at 37.45 MJ/kg, than diesel with 42.50 MJ/kg. The oxygen in methyl ester is 10.8 per cent by mass, while diesel does not contain any oxygen [25]. Higher viscosity and lower heating value means more fuel is needed for the same brake power. When the compression ratio, the injection pressure and the injection timing are fixed at diesel values (for diesel operation) the specific fuel consumption tends to increase. For blends of waste cooking oil methyl ester, thermal efficiencies lower than those of diesel were measured over a range of compression ratios and injection pressures. [3]

Because the engine factors behind these penalties are often a mismatch between fuel and engine settings, the engine settings (e.g. compression ratio) can be varied. Compression ratio is one factor that determines the temperature and pressure of the charge at the end of compression. Compression ratio has been varied for mahua and for waste fried oil and waste cooking oil esters [5,15,16]. Injection pressure has an effect on atomization. An increase in injection pressure along with the compression ratio has increased brake thermal efficiency and reduced specific fuel consumption for *Jatropha* methyl ester [6]. Injection timing shifts the phasing of the heat release of the fuel into the combustion cycle and has been treated as a third control variable [4]. A variable compression ratio (CR) engine which allows the clearance volume to be changed with the engine assembled has also been used as the basis for a study of the effect of CR range and has since become the industry standard for this application [2,17]. The nozzle geometry has also been varied in conjunction with the CR and injection pressure [7].

Another approach is to optimize the fuel formulation by adding small quantities of a low-viscosity, highly volatile oxygenate, which restores the physical behavior of diesel, while preserving the benefits of bound oxygen in the form of emissions reductions in a biodiesel blend. Diethyl ether (DEE) has been the most studied, CN 120, viscosity 0.23 cSt at 40 °C, oxygen 21.6 per cent by mass, compared to a reference diesel fuel with 46 CN, 3.30 cSt and nil oxygen [25]. Dimethyl carbonate (DMC) C₃H₆O₃, 53 per cent by mass oxygen, no carbon-carbon bond, has been used in an attack on both smoke and NO_x emissions at

once [10]. Higher alcohols like n-butanol and n-pentanol are intermediate, and have been tested directly against each other in the biodiesel-diesel blend [11].

This is because the fuel formulation and engine calibration interact: changing the oxygenate will change the ignition delay period, which will change the premixed fraction of the heat release, which in turn will change the response of the engine to changes in compression ratio and injection pressure. A test plan consisting of single factor tests cannot disentangle all of these effects, and a full factorial test is impractical when there are four or more factors, hence the use of statistical design. Response surface methodology includes curvature and interaction terms, and a desirability approach [12]. Taguchi designs rank factors, using a reduced number of runs [13]. Grey relational analysis combines multiple conflicting responses into an index [2]. Artificial neural networks interpolate above and below runs [18]. Computational fluid dynamics (CFD) has been used with measurement at some locations, and for in-cylinder behavior [14].

This review was carried out on compression ignition engine performance considering the effect of compression ratio, injection pressure, injection timing, biodiesel blend, and oxygenate dose. A study of 34 experimental and modeling works published from 2008 to 2025 in Scopus- and SCI-indexed journals is presented. In addition, each study was required to report at least one performance and one emission response, to systematically vary at least one engine control parameter or fuel formulation variable, and to use diesel oil, a biodiesel blend, or a biodiesel blend with an oxygenated additive as their fuel. These specific characteristics of each study are summarized by fuel system, engine configuration, controlled variables, and measured variables in Tables 2 and 3 below. Details of these numerical results are shown in Table 4. It is only for studies where the results could be confirmed from the primary abstract or paper that the results are described in detail. For studies where only the bibliographic record and scope could be confirmed, the study design is reported instead so that the strength of the evidence can still be appreciated.

2. Fuel systems and their physical basis

A small number of fuel properties strongly govern the operation of a compression ignition engine using a renewable blend. The metering of fuel into the engine and the atomization of the fuel spray are controlled by density and viscosity. The volatility and enthalpy of evaporation will determine how quickly a liquid fuel vaporizes. Cetane number determines the chemical ignition delay, whilst the heating value (energy released on combustion) and bound oxygen affect the amount of energy released per kg of fuel burnt, and the local oxidiser availability. Table 1 shows a single internally consistent set of measurements for diesel, biodiesel, ethanol and DEE, carried out in one laboratory on the same instrumentation, allowing a direct comparison of the fuels without the discrepancies that would arise from drawing the values from different sources.

Table 1

Measured properties of the diesel, soybean biodiesel, ethanol and diethyl ether used in a single experimental study, as reported by Carvalho et al. [25].

Property	Diesel	Biodiesel	Ethanol	DEE
Formula	C ₁₀ H ₁₈	C ₁₈ H ₃₄ O ₂	C ₂ H ₆ O	C ₄ H ₁₀ O
Oxygen content (%)	0	10.8	34.7	21.6
Density at 20 °C (g/cm ³)	0.840	0.878	0.786	0.713

Property	Diesel	Biodiesel	Ethanol	DEE
Kinematic viscosity at 40 °C (cSt)	3.30	4.95	1.20	0.23
Flash point (°C)	96	158	15	−45
Cetane number	46	56	6.5	120
Lower heating value (MJ/kg)	42.50	37.45	28.40	36.87
Enthalpy of evaporation (kJ/kg)	260	200	836	356

All values are taken from one source so that the fuels are directly comparable. Properties vary with feedstock and measurement standard, and values for dimethyl carbonate and for the higher alcohols are not given here because no equivalent single-source measurement set was available among the studies reviewed.

2.1. Biodiesel blends

Most modern variable compression ratio engines have researched waste, non-food feedstocks because of their low cost and non-competitive status to food. Waste-cooking oil, waste-fried oil, *Jatropha curcas*, *Pongamia pinnata*, mahua, rice bran and *Shorea robusta* have been converted to methyl esters and tested as diesel fuel substitutes [2,3,5,15,17]. This is a result of the differences in chain length and saturation of the fatty acids. A composition with the same nominal blending ratio may behave differently with different feedstocks. To verify these behaviors, several biodiesel feedstocks have been tested in this same generator engine at these same intended operating conditions [1].

For any given feedstock, the blend ratio and the compression ratio have generally been used in conjunction. Muralidharan and Vasudevan tested the performance of waste cooking oil methyl ester blended with diesel in ratios of 20%, 40%, 60% and 80% and at compression ratios of 18:1, 20:1 and 22:1 at 1500 rpm and at half load. Thermal efficiencies were lower than diesel fuel and specific fuel consumption was higher for all blends, but the forty per cent blend had the highest thermal efficiency of the blends tested [3]. Similar sweeps of compression ratio against blend ratio have been reported for waste fried oil methyl ester and for waste cooking oil biodiesel from B10 to B50 [15,16] and for mahua biodiesel with injection timing varied at the same time [5]. Because they are all designed this way, no information can be obtained about either variable once the other one is held fixed.

2.2. Diethyl ether

Of all the additives, diethyl ether is used the most and its usage is due to the reasons in Table 1. It has one-fourteenth the viscosity of diesel fuel, a cetane rating about two and a half times that of diesel fuel, and more than 20% oxygen by mass [25]. A small proportion of biodiesel (approximately a few per cent) in a diesel fuel blend will reduce the viscosity, increase its evaporation, and increase the oxygen present in the spray periphery. It has a higher enthalpy of evaporation than diesel or biodiesel, and hence cools the charge as it evaporates, and these two effects work against each other in controlling flame temperature. Carvalho et al. added five per cent DEE to a biodiesel-ethanol blend and in a two cylinder direct injection engine. The engine had an 18:1 compression ratio and was run at 1700 rpm. They saw decreases of three to thirteen per cent for NO_x and three to fourteen per cent for carbon monoxide at the two higher loads as compared with the baseline blend. They also observed increases (up to thirty-seven per cent) for total hydrocarbons. Engine performance improved by half to two per cent [25]. Following on from this trend,

Naik et al., using a ternary blend of diesel, waste cooking sunflower oil biodiesel and DEE, found a near 10% dosage reduced specific fuel consumption and increased brake thermal efficiency compared to B20, with carbon monoxide, oxides of nitrogen and smoke reducing and hydrocarbons increasing [18]. The hydrocarbon penalty is the most consistent negative effect of DEE addition across both fields of data.

Higher DEE fractions were also tested separately. Rakopoulos et al. tested 8, 16 and 24 per cent DEE by volume in a single-cylinder high speed direct injection engine at three engine loads. Fuel consumption, smoke, oxides of nitrogen, and levels of carbon monoxide and unburned hydrocarbons were all compared against neat diesel [8]; the DEE dosage cannot be studied as an independent parameter, since the mixture's volumetric heating value would decrease. There is more literature on optimizing DEE dosage, as opposed to using a constant DEE addition on top of the main fuel [13,23]. DEE has also been added via port injection and was tuned separately from the main fuel alongside a variable compression ratio [24].

2.3. Dimethyl carbonate

The molecular formula for dimethyl carbonate ($C_3H_6O_3$) has a mass percentage of oxygen of about 53 per cent, which together with the absence of carbon-carbon bonds is not conducive to soot formation. DMC is not used as a base fuel, but only used in small percentage amounts. Kumar and Saravanan applied DMC to a direct injection engine as a partially premixed low temperature engine to try and achieve an appropriate trade off between smoke and oxides of nitrogen [10].

Further blends with biodiesel were affected by what was added at the same time. Ramesh et al. added 5mL DMC to a B20 Prosopis juliflora biodiesel blend, in a single-cylinder common rail diesel engine with an injection pressure of 600 bar, injection timing of 21° bTDC and a compression ratio of 16, with 20 percent exhaust gas recirculation. Due to the DMC blending and recirculation of the DMC-Diesel blends the oxides of nitrogen and smoke decreased, while the carbon monoxide and hydrocarbons increased [27]. Aguado-Deblas et al. found that triple blends of diesel, DMC and straight vegetable oil replaced up to 40% of the fossil diesel without changing power or specific consumption under the tested conditions, while also reducing exhaust emissions [28]. More recently, it has been shown that adding carbon quantum dot nanoparticles to a DMC-biodiesel mixture makes it impossible to isolate the influence of DMC [29].

2.4. Higher alcohols and other oxygenates

Alcohols have an intermediate effect between DEE and DMC, decreasing the viscosity and increasing the bound oxygen content of the fuel while lowering the cetane number and heating value. Ethanol has a cetane number of 6.5 and a heating value of 28.40 MJ/kg. Its enthalpy of evaporation is more than three times that of diesel (46 MJ/kg and 42.50 MJ/kg respectively) [25]. However, longer-chain alcohols reduce but do not eliminate these differences. Yeşilyurt et al. compared 1-butanol and n-pentanol in blends with biodiesel and diesel in terms of combustion and performance and exhaust of each [11]. Wei et al. have done the equivalent work for ethanol and butanol [30]. For example, Rakopoulos has compared n-butanol and DEE in blends with cottonseed oil and cottonseed biodiesel in a high speed direct injection engine so that two oxygenates of very different cetane number could be compared under one protocol [32].

Other oxygenates have been studied less frequently. Glycerol tert-butyl ethers, that can be produced from the glycerol by-product of transesterification, have been tested at variations in compression ratio and injection timing, such that the fuel and calibration were treated as one system [33]. Although it is not used as an oxygen carrier, 2-Ethylhexyl nitrate is used as a cetane improver in its Taguchi process optimization design [34]. Ramalingam and Mahalakshmi (2014) additionally included hexanol and ethanol as the alcohols in Moringa oleifera biodiesel [31]. Fig. 1 brings together these fuel formulation factors and

engine control factors, acting on the same chain of in-cylinder processes before arriving at the measured responses.

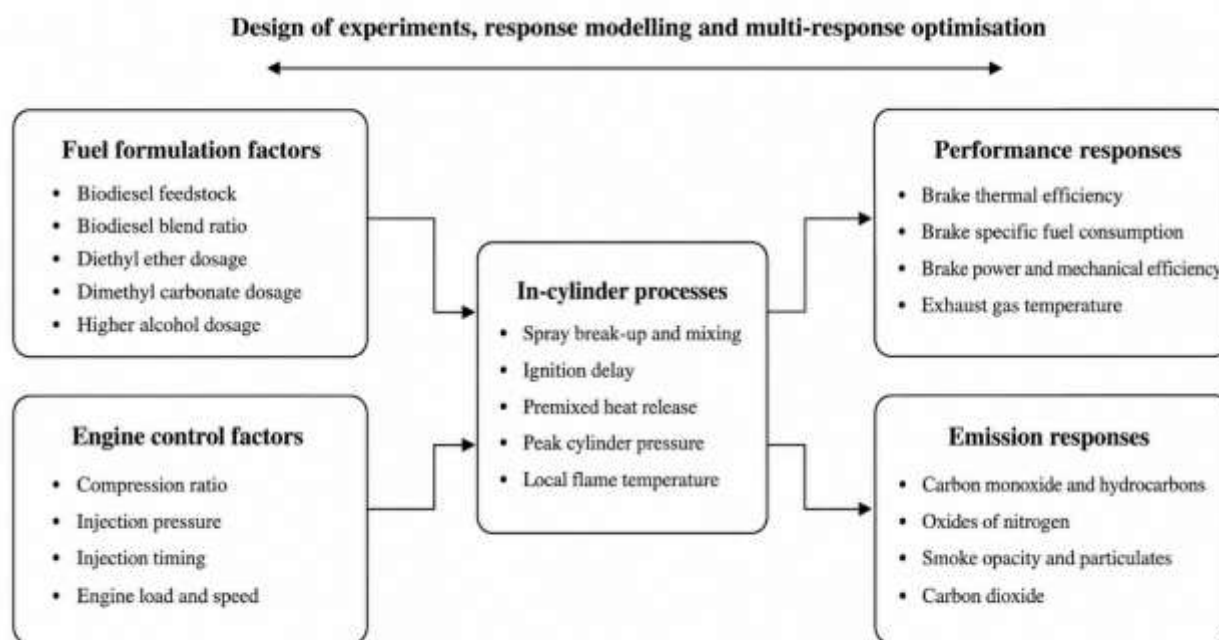


Fig. 1. Schematic relationship between fuel formulation factors, engine control factors, in-cylinder processes and the measured performance and emission responses. The diagram is a conceptual framework for organising the review and contains no measured data.

3. Combustion characteristics

3.1. Ignition delay

Ignition delay (the time between the start of injection and the start of combustion) determines how much fuel is mixed before premixed burn, and biodiesel blend presence has two effects that favor two different outcomes for ignition delay. The high cetane number of the ester decreases the chemical part of the delay, while its higher viscosity and boiling range lengthens the physical part, because injection into the combustion chamber is in the form of droplets, and atomization and evaporation are slowed by high viscosity and long chains.

But the measured data shows that the physical fraction may dominate. For the case of the waste cooking oil methyl ester, Muralidharan and Vasudevan found that the ignition delay is longer, maximum pressure rise is higher, heat release is lower and the mass fraction burnt is higher with MCE with higher CR (22:1) instead of diesel fuel (18:1) [3]. This is one reason why a hotter charge alone is not necessarily sufficient to reduce the delay period for a viscous ester, and why an optimum compression ratio must be determined experimentally for each fuel.

Nearly all additives have a cetane number i.e. acting on the delay, with a broad range. For example, the cetane number range between ethanol and DEE in Table 1 is 6.5 - 120 against 46 for diesel. [25] Ethanol, by itself, increases the delay. However, this can be counteracted using DEE in an ethanol-doped blend. The reduction in oxides of nitrogen has also been attributed to the lower ignition delay and higher enthalpy of evaporation of the blend [25]. It was however observed that DMC was added with a low cetane number to support a partially premixed low temperature operation, but this has an opposite effect of increasing

ignition delay [10]. As such it is unlikely that a single compression ratio is appropriate for all additive types.

3.2. Cylinder pressure and heat release

As compression ratio and injection pressure have different effects on pressure traces, if papers were to vary both compression ratio and injection pressure together, that would be a better test of the interaction between the two. Jindal et al. did this for Jatropa methyl ester and showed that increasing both together increased brake thermal efficiency, reduced brake specific fuel consumption, and reduced emissions which is evidence of an interaction between compression ratio and injection pressure [6]. Patil et al. extended the same idea by exploring the effect of nozzle geometry, compression ratio and injection pressure together in a single-cylinder direct injection engine [7]. Sayin and Gumus explored the effect of compression ratio and injection parameters on the performance of biodiesel-blended diesel [4].

The heat release curve is probably influenced by a slower rate of decrease of heat release rate and a higher mass fraction burnt of waste cooking oil methyl ester than diesel at a higher compression ratio. This might suggest slower mixing in early combustion and nearly complete late-cycle oxidation [3]. The timing of the fuel injection is used to control the combustion timing when the fuel has been switched. Accordingly, Çakmak and Özcan varied the two parameters together for their diesel-biodiesel-glycerol tert-butyl ether blend [33]. Barik et al., on the other hand, applied the same reasoning to their dual fuel engine with port-injected DEE and independently varied the compression ratio while the premixed energy fraction was separately tuned [24].

4. Engine performance

The engine efficiency can be expressed in terms of brake thermal efficiency, brake specific fuel consumption, brake power, mechanical efficiency and exhaust gas temperature. Tables 2 and 3 summarize the studies included with respect to the controlled and measured variables. Quantitative results of the subset of studies whose results were able to be verified in the primary source are shown in Table 4.

Table 2
Design characteristics of the reviewed studies on biodiesel blends containing an oxygenated additive.

Ref.	Fuel system	Engine and test configuration	Variables examined	Responses measured
[8]	Diesel + DEE at 8, 16 and 24 vol%	Single-cylinder four-stroke HSDI engine, three loads	DEE volume fraction and load	Fuel consumption, smoke, NO _x , CO, HC
[9]	Diesel–Aegle marmelos biodiesel–DEE	Single-cylinder VCR DI CI engine	CR 16–18, IP 210–250 bar, IT 21–25° bTDC	Performance and emissions
[10]	Diesel + DMC	DI diesel engine, partially premixed low temperature mode	DMC share and combustion mode	Smoke, NO _x , combustion

Ref.	Fuel system	Engine and test configuration	Variables examined	Responses measured
[11]	Biodiesel/diesel + 1-butanol or n-pentanol	CI engine	Alcohol identity and blend share	Combustion, performance, exhaust emissions
[12]	Diesel–Aegle marmelos biodiesel–DEE	VCR DI CI engine	CR, IP and IT	Performance and emissions
[13]	Palm biodiesel–DEE–diesel ternary blends	Diesel engine	Operating parameters and blend ratio	Performance and emissions
[18]	Waste cooking sunflower oil biodiesel + DEE	Single-cylinder diesel engine	DEE fraction and load	BTE, BSFC, combustion, CO, NO _x , HC, smoke
[19]	Jatropha biodiesel–diesel + DEE	VCR diesel engine	Load, compression ratio and DEE dosage	Performance and emissions
[20]	Biodiesel + DEE + water emulsion	CI engine	DEE dosage and emulsion condition	Combustion performance and emissions
[21]	Neem biodiesel with butanol, pentanol or DEE	Single-cylinder diesel engine	Oxygenate identity and blend share	Performance and emissions
[22]	Diesel–Pongamia biodiesel + n-butanol and DEE	Diesel engine	Alcohol and DEE addition	Performance and emissions
[23]	Mahua biodiesel + DEE	DI diesel engine	Blend and engine parameters	Performance and emissions
[24]	Upgraded biogas–biodiesel dual fuel with port-injected DEE	DI diesel engine in dual fuel mode	Compression ratio and DEE port injection	Performance and emissions
[25]	Biodiesel–ethanol + 5 vol% DEE	Two-cylinder DI engine, CR 18:1, 1700 rpm, loads 2.7–8.1 kW	DEE introduction into the base blend	BSFC, BSEC, efficiency, NO _x , CO, THC
[26]	Cottonseed biodiesel + DEE	DI diesel engine	DEE addition and load	Performance and emissions
[27]	Prosopis juliflora biodiesel B20 + 5 ml DMC	Single-cylinder CRDI engine, IP 600 bar, IT 21° bTDC, CR 16	DMC addition and 20% EGR	Performance, combustion, NO _x , smoke, CO, HC
[28]	Diesel + DMC + straight vegetable oil	Diesel engine	DMC and vegetable oil share	Power, BSFC, smoke

Ref.	Fuel system	Engine and test configuration	Variables examined	Responses measured
[29]	Corn oil biodiesel + DMC + carbon quantum dots	Diesel engine	Nanoparticle addition and DMC content	Combustion, performance, emissions
[30]	Biodiesel + ethanol or butanol	Diesel engine	Alcohol identity and concentration	Combustion, performance, emissions
[31]	Moringa oleifera biodiesel + hexanol or ethanol	CI engine	Alcohol identity and blend share	Performance, combustion, emissions
[32]	Cottonseed oil and its biodiesel + n-butanol or DEE	HSDI diesel engine	Additive identity and blend share	Combustion and emissions
[33]	Diesel–biodiesel–glycerol tert-butyl ethers	DI diesel engine	Compression ratio and injection timing	Combustion and emissions
[34]	Biodiesel + 2-ethylhexyl nitrate	Diesel engine	Process parameters and blend ratio	Multiple performance and emission responses

Entries describe what each study controlled and measured, as stated in its title, abstract or bibliographic record. Numerical outcomes are given in Table 4 only where they could be verified against the primary source.

4.1. Effect of compression ratio

A higher compression ratio improves cycle efficiency and raises charge temperature, which should favor a fuel that is hard to vaporize, but the measured picture is more qualified than that expectation. At the compression ratios of 18:1 to 22:1 at half load, the thermal efficiencies of all the blends of waste cooking oil methyl ester and their respective specific fuel consumptions were inferior to that of diesel, though the best of the blends of waste cooking oil methyl ester were at forty per cent. This implies that for some blends, this gap is ameliorated and not necessarily closed with the use of a variable compression ratio engine. The variable compression ratio rig is locating at what point that gap is smallest to minimize clearance.

This is reflected in the ranges of compression ratios for the various studies. The ranges are 14-18 for waste cooking oil biodiesel [16], 16-18 for diesel-biodiesel-DEE blend [9], 17-18 for dual fuel rice bran biodiesel engine [17] and 18-22 for waste cooking oil methyl ester [3]. No optimal number was found from various studies, as the optimum value correlated with fuel and not the engine itself.

4.2. Effect of injection pressure and timing

It has been shown that injection pressure improves performance because it acts as a better atomizer, which supports evaporation and fuel-air mixing since smaller droplets evaporate more quickly. The study that provides the clearest evidence for an interaction with compression ratio was conducted by Jindal et al., who found that an increase of both gave the highest brake thermal efficiency and the lowest brake specific

fuel consumption and emissions for Jatropha methyl ester. [6] Sayin and Gumus examined this pair of factors with biodiesel-diesel blend [4], while Patil et al. also included the nozzle geometry as a variable. [7]

Injection pressures in the reviewed literature have ranged from 210 to 250 bar in a mechanically injected VCR engine [9] to 600 bar in a CR one [27]. Because injection pressure, injection timing and compression ratio affect the combustion phasing, these parameters have tended to be varied together in a factorial experiment in later works [9,12,33]. Krishnamoorthi and Malayalamurthi varied all three on a diesel-biodiesel-DEE blend, getting a compromise performance and emissions by validation [9].

4.3. Effect of blend ratio and additive dosage

Since specific fuel consumption (SFC) closely depends on fuel heating value, soybean methyl ester for example having a heating value about twelve per cent lower than that of diesel on a mass basis [25], more fuel is needed to do the same amount of work. Direct measurements of SFC with biodiesel blends have confirmed these results [3]. Being an energy-based efficiency, brake thermal efficiency is less sensitive to this and can also change either direction depending on the burning characteristics of the blend.

Adding an oxygenate changes both, and both of the DEE studies agree on the low dose effect. By adding 5% DEE in a biodiesel-ethanol blend, engine thermal efficiency could be increased by 0.5% to 2% relative to the blend due to lower viscosity, higher cetane number, and a higher oxygen content [25]. On the other hand, dosing a diesel-biodiesel-bioethanol ternary mixture at this rate considerably reduced fuel consumption and improved brake thermal efficiency, according to testing with the B20 mixture [18]. This cannot be increased indefinitely, however, as the heating value of the resulting fuel mix decreases with increasing additive content. The larger fractions assessed by Rakopoulos et al. were assessed for fuel consumption and emissions [8]. For DMC the benefits are greater than the heating value alone, so with a triple mix up to forty per cent of the fossil diesel could be replaced without loss of power or specific fuel consumption [28].

Table 3

Design characteristics of the reviewed studies concerned mainly with engine control parameters and biodiesel feedstock effects.

Ref.	Fuel system	Engine and test configuration	Variables examined	Responses measured
[1]	Several biodiesel feedstocks blended with diesel	Generator diesel engine at varied load	Feedstock source and load	Combustion, performance, emissions
[2]	Shorea robusta biodiesel	VCR engine	Engine operating factors	Performance and heat losses
[3]	Waste cooking oil methyl ester, B20 to B80	Single-cylinder VCR engine, 1500 rpm, 50% load	CR 18:1 to 22:1 and blend ratio	BTE, BSFC, combustion pressure, CO, HC, NO _x
[4]	Biodiesel-blended diesel	DI diesel engine	Compression ratio and injection parameters	Performance and emissions

Ref.	Fuel system	Engine and test configuration	Variables examined	Responses measured
[5]	Mahua biodiesel blends	Single-cylinder four-stroke diesel engine	Compression ratio and ignition timing	Performance
[6]	Jatropha methyl ester	DI diesel engine	Compression ratio and injection pressure	BSFC, BTE, CO, CO ₂ , HC, NO _x , smoke opacity
[7]	AOME biodiesel	Single-cylinder DI diesel engine	Nozzle geometry, CR and injection pressure	Performance and emissions
[14]	Tomato seed oil biodiesel	Diesel engine with an accompanying CFD model	Fuel type and operating condition	Combustion performance
[15]	Waste fried oil methyl ester blend	CI engine at several compression ratios	Compression ratio and blend ratio	Performance and emissions
[16]	Waste cooking oil biodiesel, B10 to B50	Diesel engine	CR 14 to 18, blend ratio and speed	Performance and emissions
[17]	Rice bran biodiesel with biogas in dual fuel mode	VCR dual fuel diesel engine	Compression ratio 17 to 18 and load	Performance, CO, HC, pilot fuel saving

5. Engine emissions

5.1. Carbon monoxide and hydrocarbons

As CO and unburned hydrocarbon are products of incomplete oxidation, both reflect improvements in mixing, temperature, and air (oxygen) supply. Two of the reviewed studies isolated the effects of compression ratio on CO and unburned hydrocarbon during combustion. Raising it from 17 to 18 in a rice bran biodiesel-biogas dual fuel engine reduced carbon monoxide by 17.67 per cent, and hydrocarbons by 17.18 per cent on average [17]. Lower levels of hydrocarbons and carbon monoxide are reported relative to diesel for waste cooking oil methyl ester blends in the range 18:1 to 22:1 [3], so the mechanism is likely be strong and not specific to either engine or fuel type.

Five per cent DEE addition had an effect on the CO emissions, reducing them by a factor of three to fourteen per cent at medium and high load. This led to an increase in total hydrocarbons by up to thirty-seven per cent; this was because of the high volatility and high enthalpy of evaporation of the mixture which reduced the combustion temperature [25]. The same weakening was observed for the two species in the ternary DEE blend Naik et al. studied: CO decreased and hydrocarbons increased too [18]. In contrast, when DMC was tested with exhaust gas recirculation, both species increased due to a reduced flame temperature [27]. However, carbon monoxide and hydrocarbons must be treated as two separate responses, even though both are products of incomplete oxidation.

5.2. Oxides of nitrogen

The formation of oxides of nitrogen is a function of flame temperature, oxygen availability, and residence

time; therefore, NO_x tends to increase with combustion completeness. Increasing the compression ratio from 18:1 to 22:1 resulted in an increase in oxides of nitrogen emissions and a simultaneous decrease in carbon monoxide and hydrocarbon emissions from waste cooking oil methyl ester blends [3]. This opposition between the two sets of species is the main limitation of optimizing the compression ignition engine for one objective.

As oxygenated additives reduce or increase the response by adding oxygen to the charge and cooling both charge and mixture by evaporation. The DEE studies reported a reduction of three to thirteen per cent, for a five per cent addition to a blend of biodiesel and ethanol, due to the reduction in ignition delay and the increased latent heat of evaporation of the blend [25]; and a return to baseline, for a ten per cent addition to a diesel-biodiesel ternary blend [18]. DMC was also used along with exhaust gas recirculation for reducing the oxides of nitrogen at the cost of an increase in carbon monoxide and hydrocarbons [27], and it was used deliberately to achieve an optimal smoke and oxides of nitrogen balance in the PMLT mode [10].

5.3. Smoke

For better atomization, more locally available oxygen for combustion and no easy mechanism for fuel molecules to aggregate into soot, it is expected that the smoke generated in the fuel-rich regions of the spray would be eliminated. All three processes appear in the verified results, and increasing the compression ratio and injection pressure reduced the smoke opacity in addition to the other regulated emissions for *Jatropha* methyl ester [6]. In diesel-biodiesel blend fuels, the addition of DEE reduced smoke when compared to a base blend fuel [18]. DMC, which does not have a carbon-carbon bond, reduced smoke emissions both in a partially premixed low temperature combustion mode [10] and in exhaust gas recirculation [27]. When blended in a combination use with straight vegetable oil, it was shown to reduce exhaust emissions [28].

Smoke is the only one for which the oxygenated additives and the engine control parameters act in the same direction and so it tends to be the least contentious outcome in the literature. It is also the most sensitive to the measurement basis since opacity, filter smoke number and mass concentration are not directly interconvertible without additional information.

Table 4

Quantitative outcomes that could be verified directly against the primary source of the cited study.

Ref.	Comparison and conditions	Reported outcome	Verification
[3]	Waste cooking oil methyl ester B20–B80 against diesel; single-cylinder VCR engine, 1500 rpm, 50% load, CR 18:1 to 22:1	Thermal efficiency of all blends lower than diesel and specific fuel consumption higher; B40 gave the highest thermal efficiency among the blends; longer ignition delay, higher maximum rate of pressure rise, lower heat release rate and higher mass fraction burnt at higher CR; CO and HC reduced and NO _x increased.	Publisher abstract

Ref.	Comparison and conditions	Reported outcome	Verification
[6]	Jatropha methyl ester across combinations of compression ratio and injection pressure	The combined increase of compression ratio and injection pressure raised brake thermal efficiency and reduced brake specific fuel consumption while giving lower emissions.	Publisher abstract
[17]	Rice bran biodiesel with biogas in dual fuel mode; compression ratio raised from 17 to 18	Carbon monoxide reduced by 17.67% and hydrocarbons by 17.18% on average.	Publisher record
[18]	Ternary diesel / waste cooking sunflower oil biodiesel / DEE blend; DEE near 10% against the base B20 blend	Specific fuel consumption reduced and brake thermal efficiency increased; CO, NOx and smoke decreased while HC increased.	Supplied verified extraction
[25]	B76E19DEE5 against B80E20; two-cylinder DI engine, CR 18:1, 1700 rpm, loads of 2.7, 5.4 and 8.1 kW	NOx reduced by 3–13%; CO reduced by 3–14% at 5.4 and 8.1 kW; THC increased by up to 37%; engine efficiency increased by about 0.5–2%.	Full text (open access)
[27]	B20 Prosopis juliflora biodiesel with 5 ml DMC and 20% EGR; single-cylinder CRDI engine, IP 600 bar, IT 21° bTDC, CR 16	The combination of DMC and EGR reduced NOx and smoke while increasing CO and HC.	Publisher abstract
[28]	Diesel / DMC / straight vegetable oil triple blends against diesel	Up to 40% of the fossil diesel was replaced without compromising power or specific fuel consumption under the tested conditions, with lower exhaust emissions.	Supplied verified extraction

Studies for which only the bibliographic record, scope and controlled variables could be confirmed are listed in Tables 2 and 3 but are deliberately omitted here. Their numerical results should be added to this table once the full texts have been consulted.

6. Design of experiments and modeling approaches

Because these four factors may also interact with each other, and a full factorial for the design of experiments, at three levels for four factors, would require eighty-one runs (before replication), statistical design is used to minimize experimentation and also to probe into interactions that the one-factor sweeps cannot. Most of the studies surveyed are parametric in nature, but a few others are formal optimizations.

6.1. Screening designs

Taguchi orthogonal arrays rank the factors based on impact on a signal-to-noise ratio with a fraction of

the design. Early utilizations include Uslu and Aydın for ternary blends of palm biodiesel, DEE and diesel [13] and Simşek et al. for a blend of biodiesel and 2-ethylhexyl nitrate in a multi-objective design [34]. This reasoning runs into one serious problem: orthogonal arrays alias interaction terms with main effects, so the apparent importance of a factor may be due to its aliasing with an interaction. If a screening result does not include the aliasing structure, the variable importance cannot be inferred from it.

6.2. Response surface methods

Once these key factors are determined, response surface methodology fits a second-order model containing curvature and an interaction. Using a factorial response surface design of compression ratio, injection pressure and injection timing against a diesel-biodiesel-DEE blend Krishnamoorthi and Malayalamurthi found a tradeoff between performance and emissions that is adequately validated [9]. The same fuel system then underwent a full response surface analysis, involving analysis of variance, desirability functions and confirmation runs [12]. The confirmation run is the acid test that tells you whether your model is useful or just a fitted surface; a predicted optimum has no standing until it has been reproduced at the recommended setting under the same measurement protocol.

6.3. Multi-response and data-driven methods

Since engine optimization is multiconstrained, efficiency and NO_x emissions usually vary in opposite directions for the engine configuration of interest. Therefore, in a grey relational analysis, the responses are normalized according to the direction of their performance (maximum or minimum) and the normalized values are combined to form the grey relational grade. Rai and Sahoo employed the Taguchi-grey method to optimize performance and heat losses for VCR engine fueled with *Shorea robusta* biodiesel [2]. However, the direction of normalization must be specified in advance, as ranking will be affected by this.

Artificial neural networks are useful when prediction rather than explanation is required. Naik et al. trained a neural network on data for ternary DEE blends and interpolated between experiments [18]. While neural networks are able to model non-linear behavior, they do not have coefficients on the design variables. Therefore, a response surface model is also used. As CFD needs to solve for large quantities that cannot be measured (e.g. in-cylinder temperature distribution and species fields), Karami et al. have combined in-engine measurements with CFD results of a tomato seed oil biodiesel engine [14]. Only after this step can the computational analysis be input with an experimentally determined pressure trace and heat release rate. Fig. 2 illustrates a staged sequence of methods where the output from one stage becomes the input for the next.

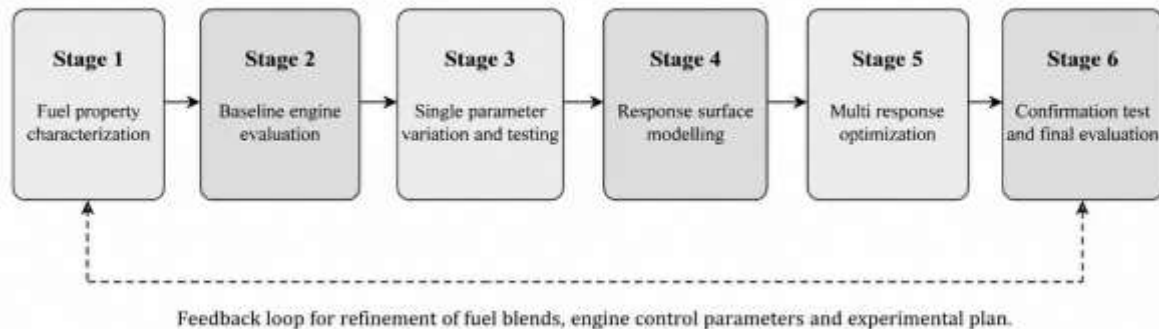


Fig. 2. Schematic staged experimental and modeling programme for optimizing fuel formulation and engine calibration together. The diagram is a proposed workflow and contains no measured data.

7. Limitations of the evidence base

Referred to in Table 4 are seven out of a total of thirty-four studies. The relation of seven to thirty-four is the statistically determined finding of this review. It does not reflect the quality of the experiments reported in it, but can be accounted for by four specific barriers.

In the first, the baseline against which the blend was compared was pure diesel, or a biodiesel blend with the same proportion of ester, or some other additive, so reported increases are not directly comparable. Note that there are two validated DEE results, one for biodiesel-ethanol blend [25] and one for B20 [18], both expressed as a percentage increase. While the result is likewise positive in both cases, the percentages of increase are not directly comparable due to differing baselines used.

The second is the reporting of an additive as a fuel formulation, or fuel composition. This is used as a volume in milliliters [27] or as a mass, or as part of the base blend in the fuel. Due to the dose dependent effect of oxygenate, depending on the basis, an unknown could also change the interpretation. The same applies to measured properties. Due to only one of the studies considered [25] providing an entire set of single-source property data for its substances, the only data provided in Table 1 are those given in that study, and not data from other sources.

The third is that emissions can be expressed in parts per million or grams per kilowatt hour (g/kWh), as a volume percent, as a smoke opacity or as a filter smoke number (FSN). Conversions from one to the other require knowledge that may not be available. Uncertainty is given less consistently; however, instrument accuracy, repeatability, and number of replicate runs, must be known before differences of only a few per cent between two blends are accepted as real. Several of the numbers in Table 4 fall within the ranges where this is a problem.

Fourth, the treatment of interactions and confounded variables: compression ratio, injection pressure and injection timing are often varied independently although it has been shown that they interact synergistically [6]. If a designed experiment was used, the aliasing structure is rarely reported. Confirmation runs are sometimes omitted, but are good practice. The introduction of a second measure,

such as exhaust gas recirculation [27] or the addition of nanoparticles [29], does not allow any conclusions to be drawn about the additive alone, however clear the overall outcome.

Minimum information to be reported: the fuel formulation tested on a defined basis, its measured density, viscosity, calorific value, cetane number and oxygen content; the engine specification used and the full operating point including load, speed, injection timing, injection pressure and compression ratio; mean, spread and number of replicates of all responses; comparator towards which each measure of effect is reported; and the accuracy of each measurement instrument. If a second measure is added to the tested additive, a condition isolating each measure of effect must be defined, as otherwise the contribution of each cannot be separated.

8. Conclusions

This review includes a discussion about how the compression ratio, injection pressure, injection timing, biodiesel blend ratio and oxygenated additive dosage factors may cause variations in the performance of a compression ignition engine which may be related to variable compression ratio studies. A total of 34 studies are included in this review and classified according to study design with quantitative data extracted from primary sources when available.

In the verified subset, higher compression ratio reduced CO and hydrocarbon emissions, and increased NO_x emissions, by 17 percent per one-step change in CR for a dual fuel engine. Higher compression ratio did not bring biodiesel blends up to the diesel efficiency. In the range of 18:1 to 22:1, diesel thermal efficiency was higher than all of the waste cooking oil methyl ester blends reported. Specific fuel consumption was lower for diesel, too. The strongest evidence for optimizing compression ratio and injection pressure simultaneously is that the effect of changing the two together is greater than that of changing either alone.

Moderate diethyl ether additions improved performance and reduced carbon monoxide, oxides of nitrogen, and total hydrocarbons in both verification tests, and total hydrocarbons in both tests. Dimethyl carbonate reduced oxides of nitrogen and smoke if exhaust gas recirculation was also present but increased carbon monoxide and hydrocarbons. It replaced a large fraction of fossil diesel in a triple blend without any power or fuel economy sacrifice. Carbon monoxide and hydrocarbons are not a single group and do not respond likewise to oxygenate addition, and this confusion is often made in the literature.

The problem was not the amount of material but its transferability. Of the thirty-four studies reviewed, results from only seven could be checked against the original source at the depth that would allow direct comparison. With consistent baselines, explicit additive units, complete single-source fuel property tables and published uncertainty and conditions isolating each additive, the rest of this literature could be quantitatively combined. Until then, the direction of each effect is better supported than its magnitude.

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