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Review

Enhancing Performance and Emission Characteristics of Biodiesel-Operated Compression Ignition Engines through Low Heat Rejection Mode and Antioxidant Additives: A Review

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ABSTRACT: Depending on the heat content and compression ignition (CI) engine combustion, biodiesel is a viable substitute fuel. Biodiesel is an oxygenated, safe, sulfur-free, biodegradable, and renewable fuel. It may be utilized in CI engines in any combination with diesel fuel without requiring the engine to be significantly modified. Many research studies have been made with several biodiesels as diesel substitutes, including *Pongamia pinnata*, *Jatropha curcas*, *Mangifera indica*, and *Madhuca longifolia*. The topic of the current review is the potential of renewable fuels to outperform diesel fuel in terms of performance, combustion, and emission characteristics. In the present study, CI engines are fueled with biodiesels made from *Man. indica*, *Mad. longifolia*, and pongamia seed oil. Adopting low heat rejection (LHR) mode CI engines and adding an antioxidant agent in addition to the biodiesel blends may resolve the issue of these biodiesels' poorer performance and increased NO emission. Both these additions may provide positive approaches in both performance and emission.

1. INTRODUCTION

Compression ignition (CI) engines are widely utilized in light, medium, and heavy duty vehicles, load transporters, and power generation because of their improved fuel economy and capacity for low burn operation. In addition, the lean burn capacity reduces carbon monoxide and hydrocarbon output compared to petrol engines. The major pollutants in CI engines are CO, HC, NO_x, particulate matter, and smoke. These are harmful and often interact with other pollutants, leading to ozone depletion, global warming, photochemical smog, and acid rain, disturbing the ecological balance.

The rigorous emission standards for CI engines are difficult to meet because of the high amounts of particulate matter and nitrogen oxide (NO_x) emission. The diffusive combustion chamber temperature and dissociation are to blame for the high levels of particle output. Due to their compromise, it is challenging to simultaneously control the particulate matter and NO_x emission in a CI engine. Apart from the emissions, fossil fuels will deplete too shortly and the world will face a fuel crisis. To meet the demand in the future, it is crucial to choose an alternative fuel to diesel.

The world energy supply has relied heavily on nonrenewable fuels sourced from crude oil, of which it is estimated that 90% is used for transportation and energy production. It is known that emissions from the combustion of these fuels are the principal causes of environmental issues, and many countries have passed legislation to arrest their adverse effect on the environment consequent to the rapid increase in population. Worldwide energy demand is increasing, and crude oil reserves could be depleted at the current consumption rate. A long-chain alkyl (methyl, propyl, or ethyl) ester mixture of vegetable or animal fat is called "biodiesel". Lipids and alcohols are often chemically combined to create biodiesel. With some simple diesel engine changes, it may be utilized either alone or in combination with diesel. The choice of biodiesel depends on its availability in a particular area, on the heating value, and on other physical properties.

India is the leading producer of biodiesel in the world, and it may be gathered and obtained from nonedible oils such as *Jatropha curcas*, *Pongamia pinnata*, *Azadirachta indica*, *Madhuca longifolia*, *Ricinus communis*, *Linum usitatissimum*, *Schleichera oleosa*, etc. Some of these oils produced even now are not being properly utilized. India focuses on *J. curcas* and *P. pinnata*, which can grow in arid wastelands. Oil contents in the *J. curcas* and pongamia seeds are around 30−40%.

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2. BIODIESEL

Biodiesel is the most promising alternative fuel among other alternate fuels for CI engines because of its availability and simplicity in processing and distribution. This section reviews the various studies conducted about the feedstocks for biodiesel preparation, processing, performance, and emission studies using biodiesel as fuel in a CI engine. Nadaf studied the application of pongamia biodiesel in a CI engine on the basis of performance and emission characteristics.[1] The experiments were conducted with 5, 10, and 15% pongamia biodiesel as a substitute for diesel fuel. It was seen that the 10% blend had the optimum brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE).

Sivakumar investigated the production and working characteristics of pongamia biodiesel (PBD) in a direct injection compression ignition (DICI) engine. The BTE of the PBD is lower than that of diesel at various brake mean effective pressures (BMEPs) because of the combined effects of increased viscosity and a decreased calorific value.[2] Due to its greater oxygen concentration and peak in-cylinder gas temperature, PBD emits more brake specific nitrogen monoxide (BSNO) than diesel. Navada used an additive to conduct an experimental investigation of the performance and emission characteristics of the *Mad. longifolia* methyl ester. It used neat diesel and neat *Mad. longifolia* biodiesel and mixed them with 5, 10, and 15% dimethyl carbonate as additives.[3] Diesel has a higher BTE than neat *Mad. longifolia* biodiesel. The fraction of *Mad. longifolia* biodiesel and BTE both slightly rise as an outcome of the use of additives.

Bora examined how the performance and emissions of CI engines were affected by various mixes of pongamia methyl ester (PME) B20, B40, B60, B80, and B100. PME biodiesel has a little greater NO_x emission than petroleum diesel.[4] PME blends feature a shorter delay time and a slower premixed combustion heat release rate. Bora et al. concluded that PME may be utilized as an environmentally benign and alternative fuel for CI engines. Experimental analysis of the combustion, emission, and performance properties of PME mixes was conducted by Pasri.[5] The CO and HC emissions of PME were reduced to a maximum of 8.2 and 8.9%, respectively, compared to diesel. It is also mentioned that there is a considerable reduction in oxides of nitrogen. The BSFC of PME increased by 4.2%, and the BTE reduced by 2.4%. It was found that the ID period of PME is lower than that of diesel, and it decreases with the increase in the proportion of biodiesel.

The performance and emission behavior of methyl ester *Mangifera indica* oil (MEMSO), used in diesel engines, were studied by Yadav.[6] All of the mixes had lower BTEs and smoke and HC emissions than diesel under all load circumstances. Additionally, because of their reduced calorific value, MEMSO blends' BSFC is greater than diesel's. However, compared to diesel, NO_x emissions are greater and get worse as the biodiesel content rises.

Mad. longifolia oil ethyl ester (MOEE) was the subject of a performance and emission research performed by Mohammed in a DI diesel engine.[7] It was discovered that, while the specific fuel consumption (SFC) is higher than that of diesel because to its lower calorific value, the BTE of MOEE is somewhat lower. Additionally, it was discovered that the smoke, NO_x, CO, and HC emissions of MOEE are lower than those diesel at all load conditions.

Moreira examined the performance and emission characteristics of several mahua *Mad. longifolia* methyl ester/diesel mixes in multicylinder turbocharged diesel engines.[8] With an increase in the percentage of biodiesel, there is a decrease in the BTE and a rise in the BSFC. Because biodiesel contains oxygen, *Mad. longifolia* methyl blends have lower HC and CO emissions than diesel. The greater exhaust gas temperature (EGT) and more oxygen present in biodiesel, which promote the generation of NO_x, cause NO_x emissions to rise as the biodiesel mix percentage rises.

Mad. longifolia biodiesel's efficiency and emission characteristics in a DICI engine were studied by Geng. It was discovered that all of the fuel attributes of *Mad. longifolia* biodiesel, except for the calorific value, are within the range set by international regulations.[9] With an increase in the percentage of biodiesel mix, it is shown that the BSFC increases and the BTE decreases. *Mad. longifolia* alkyl esters including methyl, ethyl, and butyl esters have been experimentally tested for their performance and emission characteristics in a diesel engine by Senthil. *Mad. longifolia* alkyl esters use more fuel per unit of energy than diesel. Alkyl esters also have lower CO, HC, and NO_x emissions than diesel fuel.[10]

The performance and emission characteristics of *P. pinnata* methyl ester (PPME) and its blends on the performance and emission characteristics of the diesel engine have been studied by Slavova-Kazakova.[11] The performance and emission properties of biodiesel with various fatty acid compositions were studied by Tamil Selvan.[12] A higher cetane index is shown to shorten the ignition delay. Pongamia biodiesel has a slightly higher BTE than diesel and other biodiesels compared to other fuels, as well as slightly higher NO_x and lower CO and HC emissions.

In their study, Jain et al. examined the impact of *P. pinnata* biodiesel on diesel engine emissions.[13] At all loads, the NO_x output from B100 and its mixes exceeds that of diesel, with a maximum increase of around 14%. Engine noise is reduced by at least 2.5 dB for B100 at maximum load, and all biodiesel blends are quieter than diesel at all loads. The combustion, performance, and emission properties of the various *Annona muricata* methyl ester (AME) and diesel mixes were studied by Kongkaoroptham.[14]

However, A20 is quite close to diesel. The BTE of the blends is lower than that of diesel. In a naturally aspirated DICI engine, Thbayh examined the combustion and exhaust characteristics of diesel blends containing *Aza. indica* oil methyl ester (NOME).[15] The oxygen concentration in the fuel may cause the NOME blends' increased NO_x emissions and decreased CO and smoke emissions. It is concluded that NOME may be utilized in a DICI engine as a renewable substitute for diesel fuel.

Karunanithi investigated the performance and emissions of *R. communis* biodiesel blends from 0 to 40% with diesel in a CI engine.[16] The B40 blend emits the least smoke when compared to the other mixtures. CO, HC, and PM emissions are reduced when the mix fraction is raised. The NO_x emission and SFC are shown to be rising at maximum load. Deng investigated the production of biodiesel from *Aza. indica* oil methyl ester (NOME) and evaluated the fuel's effectiveness and emission characteristics in diesel engines.[17] Gonçalves found that adding water to diesel–biodiesel blends can improve engine performance and reduce emissions. The best performance was achieved with a diesel, biodiesel, and 5% water blend.[18] It was found that using RCCI combustion in a biodiesel/natural gas engine can improve engine performance and reduce emissions. The best performance was achieved with a blend of biodiesel and natural gas injected in two stages. Rangaraj et al. found that using thermal barrier coatings and neural networks can improve pongamia water emulsion biodiesel's stability, performance, and emission characteristics in compression ignition engines. It was found that adding cerium oxide (CeO_2) nanoadditives to biodiesel—diesel—water emulsion blends can improve engine performance and reduce emissions.[19] The best performance was achieved with a blend of biodiesel, diesel, water, and 30 ppm CeO_2. Abdel Rahman found that blends of animal fat and vegetable oil biodiesels can improve fuel properties and combustion characteristics. These blends also help to reduce exhaust pollutants.[20] It was found that 2-butoxyethanol can be effectively used as a biodiesel additive to improve fuel properties and to achieve better combustion and reduced pollution. Ballatore et al. found that adding hydroxy gas to biodiesel blends can improve combustion performance, fuel consumption, overall efficiency, and emissions.[21] It was found that adjusting the temperature and oxygen concentration can improve the combustion and microexplosion characteristics of mixed droplets of aviation fuel, biodiesel, and ethanol. Adding *tert*-butyl peroxide to biodiesel blends can improve performance and combustion characteristics while reducing emissions. Oh found that biodiesel blends can improve engine performance and reduce emissions. However, it was also found that biodiesel blends can increase NO_x emissions.[22] Load tests were conducted to determine the performance and emission behavior of various NOME and diesel mixes. It was discovered that, because biodiesel burns more efficiently than diesel, the BTE of the biodiesel mixes is higher than that of diesel. In a study, Abdulfatai compared high-oleic soybean diesel and biodiesel to high-oleic soybean exhaust emissions. Compared to diesel and commercial soybean biodiesel, high-oleic biodiesel emits less NO_x.[23] It was discovered that there are no appreciable differences between conventional and high-oleic biodiesel in terms of HC and smoke emissions.

Uduwana investigated the performance, emission, and heat release characteristics of diesel and soybean methyl ester in a DICI engine.[24] Additionally, it was discovered that the mixes' NO_x emissions are slightly greater than diesel's because of higher combustion temperatures. Furthermore, compared to other biodiesel blends, the diesel's premixed combustion phase heat release is slightly greater. In a CI engine, Vander Leek have explored experimentally and numerically the performance and emission characteristics of *J. curcas* methyl ester. The increased oxygen content of *J. curcas* and the higher combustion chamber temperature have been observed to cause biodiesel to emit more NO_x than diesel.[25]

Comparative performance and emission experiments employing various oil/biodiesel mixes with diesel in a CI engine were carried out by Elumalai. When compared to clean diesel fuel, the CO and smoke opacity of biodiesel blends from diverse origins dramatically decreased. Vegetable oil mixes, on the other hand, result in an increase in CO and smoke emissions. It is concluded that the NO_x emission of biodiesel and vegetables is higher with increasing mix proportions and is lower than that of diesel.[26]

The combustion properties of biodiesel based on polenta, *P. pinnata*, and *J. curcas* have been experimentally examined by Paparao in a single-cylinder diesel engine. According to reports, diesel fuel has a greater peak heat release rate than all other biodiesels because it ignites more quickly, causing peak heat release to occur sooner. It has been determined that biodiesel consistently has a lower ignition delay duration than diesel.[27]

Senthil examined the emission properties of biodiesel made from waste oil, rapeseed oil, and maize oil. All biodiesels emit more NO_x than diesel at all speeds due to their higher cetane numbers. The higher oxygen concentration of the fuel, which encourages fuel oxidation during combustion, leads to the conclusion that HC and CO emissions from biodiesel are lower than those from diesel.[28]

Citrus sinensis biodiesel (CSB) and diesel fuel were both researched by Balu for their effects on diesel engine emissions and performance.[29] It is established that the increased combustion chamber temperature with CSB leads to a large rise in NO_x emission. Senthur tested the *Helianthus annuus* oil methyl ester (SFME) performance and emission behavior of a diesel engine. It was discovered that employing SFME in both small and big engines results in a loss of torque and power.[30]

According to Parlak, biodiesel's increased viscosity and density limit its usage as the only fuel in CI engines. The greater cetane index of the biodiesel, which shortens the ignition delay time, increases NO_x from the engine.[31] Murugesan studied biodiesel's effect on combustion and diesel engine emission. It was concluded that biodiesel has lower CO, higher HC, and higher NO_x emissions due to advanced injection and combustion processes.[32]

The physical features, stability, performance, and emission characteristics of biodiesel were reviewed by Sharma et al.[33] It was discovered that, regardless of the feedstock, biodiesel emits less CO, HC, and PM than mineral diesel but NO_x emissions rise due to the biodiesel's higher oxygen content. Murali Krishna M studied the characteristics and feedstocks for manufacturing biodiesel. When biodiesel (B100) is used in diesel engines, NO_x emissions rise by an average of 12%, whereas PM, THC, and CO emissions fall by 48, 77, and 48%, respectively. The primary element affecting NO_x emission is the chemical makeup of fatty acid methyl ester (FAME), a biodiesel component. As the number of double bonds in FAME rises and its chain length reduces, NO_x emission increases.[34]

Parlak examined the effects of various biodiesel and diesel mixes (B5, B10, B15, B20, B25, B50, and B100) on the operation, emissions, combustion, and injection spray parameters of a diesel engine. Reports state that the higher cetane number reduces all blends' ignition delays and rates of pressure rise. Although NO_x emissions increase, the biodiesel blends significantly reduce CO, HC, and smoke emissions at all loads.[35]

Karthikeyan examined the emission characteristics of biodiesel (B100), diesel, and B20 mix in four separate engines. It was discovered that the impact of fuel on PM emission varied depending on the vehicle, with B100 and B20 emitting more pollutants than diesel for most cars. B100 emits fewer HC emissions than B20 and a lot fewer than diesel.[36] The biodiesel mix emits less CO than diesel.

Krishna examined the effects of biodiesel blends on the flow characteristics of *Croton megalocarpus*, *J. curcas*, and *Moringa oleifera* oils.[37] The biodiesel's characteristics, including kinematic viscosity, cloud point, and pour point, were assessed. It was discovered that adding 20% mix to various biodiesels dramatically lowered their pour and cloud points.

The use of biodiesel and additives can significantly affect the emission, combustion, and performance characteristics of a diesel engine. Here are the effects observed:

- Biodiesel reduces emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) compared to conventional diesel fuel.

- Biodiesel has a lower sulfur content, leading to reduced sulfur oxide (SO_x) emissions, which contribute to air pollution and acid rain.
- Biodiesel has a higher oxygen content, resulting in more complete combustion and reduced nitrogen oxide (NO_x) emissions, which are major contributors to smog and air pollution.
- Biodiesel has a higher cetane number, which improves combustion efficiency and reduces ignition delay, resulting in smoother engine operation.
- Biodiesel has a higher flash point, reducing the risk of engine knock or preignition.
- The higher viscosity of biodiesel can affect atomization and spray characteristics, potentially influencing combustion stability and efficiency.
- Biodiesel generally has slightly lower energy content than conventional diesel fuel, leading to a slight decrease in engine power and torque.
- Biodiesel's lubricating properties can improve engine durability by reducing wear on fuel system components.
- Biodiesel's higher lubricity may also improve fuel system efficiency and reduce maintenance requirements.
- Additives, such as antioxidants and stabilizers, can improve the oxidative stability of biodiesel, preventing the formation of gums and deposits that can affect fuel system performance.
- Additives can enhance the cold flow properties of biodiesel, reducing the risk of fuel gelling and improving cold start performance.
- Certain additives, such as cetane improvers, can further enhance combustion efficiency, improving engine performance and reducing emissions.

In their study of the environmental effects of using biodiesel as a fuel for road transport, Mittal et al.[38] found that combining biodiesel with kerosene or Fischer–Tropsch diesel can greatly minimize NO_x emission from biodiesel. Using biodiesel blends as fuel, Mittal described the PM emission from a heavy-duty engine. However, there is a rise in the concentration of fine and ultrafine particles when biodiesel is used.[38]

Buyukkaya examined biodiesel's efficiency, emissions, and combustion characteristics in DI diesel engines. Rapeseed biodiesel blends of 5, 20, and 70% were used in the studies. It was discovered that using less biodiesel in the mix improved performance and reduced emissions. Additionally, it was shown that using biodiesel caused greater NO_x levels.[39]

2.1. Summary. According to the literature review, several biodiesels were tried in the CI engine. According to reports, all biodiesels had lower brake thermal efficiencies, with 20% being the ideal blend. The NO_x emission rises for all biodiesel mixes, according to every study. At the same time, emissions like HC, CO, and smoke were significantly reduced under all circumstances. According to other reports, the CI engine most frequently uses biodiesels made from *Mad. longifolia* oil, *Man. indica*, *P. pinnata*, *J. curcas*, etc.

In terms of brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), and exhaust emissions of hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and smoke, a biodiesel fuel engine performs better than a diesel engine. Table 1 presents the effects of various biodiesel feedstocks on engine performance and emissions, compared to diesel fuel. The studies referenced cover multiple biodiesel types, each showing different impacts on performance and emissions.

Table 1. Effects of Biodiesel–Diesel Blends on Engine Performance and Emissions

	performance (compared to diesel)		emission (compared to diesel)				
biodiesel feedstock	BTE	BSFC	HC	CO	NO_x	smoke	ref
pongamia biodiesel	↓	↑	↑	↑	↑	↑	40
pongamia biodiesel	↓	–	↓	↓	↑	↓	41
Mad. longifolia methyl ester (MOME)	↓	–	↓	↓	↑	↑	42
pongamia methyl ester	–	↓	↓	↓	↑	–	43
pongamia methyl ester	↓	↑	↓	↓	↓	–	44
methyl ester *Man. indica* oil (MEMSO)	↓	↑	↓	↓	↑	↓	45
Mad. longifolia oil ethyl ester (MOEE)	↓	↑	↓	↓	↓	↓	46
Mad. longifolia methyl ester	↓	↑	↓	↓	↑	↓	47
Mad. longifolia biodiesel	↓	↑	–	–	–	–	48
Mad. longifolia alkyl ester such as methyl, ethyl, and butyl esters	↓	↑	↓	↓	↑	↓	49
P. pinnata methyl ester (PPME)	↓	↑	↓	↓	↑	↓	50
pongamia, rice bran, *H. annuus*, and palm oils	↑	↓	↓	↓	↑	↓	51
Ann. muricata methyl ester (AME)	–	–	↓	↓	↑	↓	52
Aza. indica oil methyl ester (NOME)	↓	↑	↓	↓	↑	↓	53
karanja biodiesel	↓ (3–5%)	↑	↓	↓	↓	↓	54
R. communis biodiesel	↓	↑	↓	↓	↑	↓	55
soybean methyl ester	↓	↑	↓	↓	↑	↓	56
J. curcas methyl ester	↓	↑	↓	↓	↑	↓	57
C. sinensis biodiesel (CSB)	↓	↑	↓	↓	↑	↓	58
biodiesel	↓	↑	↓	↓	↑	↓	59
biodiesel	↓	↑	↓	↓	↑	↓	60
corn oil, rapeseed oil, and waste oil	↓	↑	↓	↓	↑	↓	61

2.2. Low Heat Rejection (LHR) Engine. The evaluations in this area examine the impact of utilizing biodiesel in an LHR engine and the performance and emission characteristics of various coatings on diesel engine parts. Krupakaran examined how a thermal barrier coating affected the diesel engine's output and emission characteristics.[62] For improved coating adhesion over the substrate, the cylinder head, valves, and piston crown are coated with LHR materials such $CaZrO_3$ and $MgZrO_3$ utilizing plasma spray coating. Due to the greater in-cylinder temperature, the engine's BTE and SFC are significantly increased.

Büyükkaya examined how a thermal barrier coating (TBC) affected performance and emission traits. A coating of 350 μm of $MgZrO_3$ was applied to the piston crown, followed by a bond coat of 150 μm of NiCrAl. Due to a greater EGT, the coated engine's smoke emission decreased by around 40%, and its NO_x emission decreased by 9%.[63] The performance and emission characteristics of a mullite-coated LHR engine were studied by Haşimoğlu.[64] The piston crown, cylinder head, and valves were coated with a 0.5 mm layer of $3Al_2O_3{\cdot}2SiO_2$ (mullite) over a 150 μm layer of NiCrAlY bond coat (Al_2O_3 is 60%, SiO_2 is 40%). For the LHR engine at full load, there is a 2% increase in EGT and a 20.64% increase in NO_x emission.

Jagtap evaluated the impact of TBCs on turbocharged diesel engines compared to that of a normal diesel engine.[65] Due to the rise in combustion chamber temperature, the engine with a TBC has a lower BSFC and a greater BTE. The performance and emission properties of PSZ-coated combustion chamber surfaces, piston crown faces, valves, cylinder heads' top surfaces, and CI engine liners have been researched by Pandey. The NiAl bond coat serves as the foundation for the ceramic layers, comprised of ZrO_2 and applied by plasma spray coating.[66]

A coating of lanthanum zirconium oxide ($La_2Zr_2O_7$) was applied to the combustion chamber components and cylinder lining by Li, who then examined the performance and emission characteristics. The LHR engine's BSFC figures were around 7% lower than the original engine's.[67] The impact of a YSZ-coated piston crown on diesel engine performance and emission characteristics has been studied by Abedin. Additionally, it was discovered that residual gas lowers the inducted air density and TBC-coated engines have increased volumetric efficiency. It was found that greater NO_x emissions from coated engines are caused by higher combustion temperatures, which make it easier for oxygen and nitrogen to react during combustion.[68]

Rajendra Prasath examined how TBCs affected the efficiency and emissions of diesel engines. It has been observed that biodiesel with higher oxygen content emits more NO_x into the exhaust.[69] The performance and emission characteristics of the conventional diesel engine and the low compression ratio LHR diesel engine were compared by Periyannan. According to reports, the LHR engine's NO_x emissions are higher than those of a normal diesel engine at a higher compression ratio (CR) because the combustion chamber temperature is higher.[70] However, the LHR engine's NO_x emissions were reduced due to the CR reduction. Using biodiesel made from *J. curcas* seed oil, Paparao examined LHR engines' combustion, performance, and emission characteristics coated with partly stabilized zirconia.[71] According to reports, the LHR engine's NO_x emissions are greater than those of other engines due to the extremely high cycle temperature. Paparao found that jatropha biodiesel blends with cetane improver can reduce smoke emissions. This is a promising finding, as smoke emissions are a major concern with diesel engines. It was found that hydrogen fuel can improve combustion performance and reduce emissions in a compression ignition engine. This is a very promising finding, as hydrogen is a clean-burning fuel that has the potential to reduce emissions from diesel engines significantly. It was found that *n*-butanol and isobutanol can improve combustion performance and reduce soot emissions in a diesel engine. These findings are also promising, as *n*-butanol and isobutanol are renewable fuels that biomass can produce. Researchers conducted experiments to study the spray and combustion characteristics of a dual-fuel collision of biodiesel and *n*-butanol. It was found that the collision of biodiesel and *n*-butanol can improve the spray atomization and mixing and reduce soot emissions. The combustion, performance, and emission characteristics of LHR engines running on different biodiesel and vegetable oils were examined by Abedin.[68] Due to a greater combustion chamber temperature, it has been observed that LHR engine emission characteristics have greatly improved except for NO_x for all fuels. In a diesel engine, the combined effects of LHR coating and combining diesel fuel with vegetable oils have been studied by Ellappan. The piston, exhaust, and intake valves were coated with zirconium oxide (ZrO_2) using a plasma spraying process to apply thermal insulation.[72] However, the coated engine's greater combustion temperature causes the biodiesel blend's NO_x emission to be higher. Liu examined the combustion and emission characteristics of diesel B100 and B20 fuel in a CI engine with a TBC coating.[73] At maximum load, the BTE of the B20 blend is enhanced by 1.96%, while the BSFC is increased by 4.2%. Compared to an uncoated engine, the coated engine has a peak in-cylinder pressure approximately 4.48% higher and a peak heat release rate 2.26% lower. Zhao examined how TBC affected the efficiency and emission characteristics of a biodiesel and diesel blend made from used cooking oil. Except for NO_x emissions, biodiesel decreases HC, CO, and smoke emissions from coated and uncoated engines.[74] Due to the high in-cylinder temperature, coated engines also have increased cylinder pressure and heat release characteristics.

De Freitas et al. examined how an Al_2O_3 TBC of the engine affected its efficiency and emission characteristics while it was powered by pongamia methyl ester (PME).[75] They applied 200 μm of Al_2O_3 with nanoceramic material to the piston crown face, cylinder head, cylinder liner, valves, and other engine components using the plasma spray coating technique. With diesel, it utilized 20, 40, and 100% PME.

Comparative studies of the performance and emission characteristics of fly ash coated diesel fueled with pongamia and rice bran oil methyl ester blends have been conducted by Hosseinalizadeh.[76] Diesel and biodiesel both reduce HC and smoke emissions more effectively. Due to the biodiesels' greater oxygen content, NO_x emissions from all these fuels and their mixes are higher than diesel ones. Additionally, the combustion experiments revealed that the biodiesel's ignition delay was shortened due to coating the engine parts.

Muniyappan used nerium biodiesel and its mixes to study an LHR engine's performance and emission characteristics.[77] At full load, the BTE of the coated engine is 3.8% more than the BTE of the uncoated engine. Except for NO_x emissions at all loads, the different emissions for the coated engine with methyl ester of nerium oil (MEON) are lower. In a 450 μm thick layer of a yttria-stabilized zirconia (Y_2O_3–ZrO_3) coated diesel engine, Elkelawy employed palm oil methyl ester (POME). POME mixes with diesel in a coated engine have increased heat loss in engine coolant and exhaust gas under both partial and full loads.[78] Using the plasma spray coating approach, Hoseini coated diesel engine pistons with 0.5 mm of titanium oxide and examined the performance and combustion characteristics of PME B20 and B100. The NO_x emission rises by 15% with a coated engine, but CO and HC exhaust emissions are decreased.[79] Ng employed LHR coating to investigate if vegetable oil blends were appropriate for usage in a diesel engine.[80] The results showed that the power output and torque of the biodiesel-coated engine increased while the BSFC value decreased. The exhaust emissions of the blends, including CO, HC, and smoke opacity, are decreased in both coated and uncoated engines, although the NO_x emissions are higher than those of diesel fuel.

Yaşar conducted an experimental investigation of the performance and emission characteristics of diesel fuel and cotton methyl esters in an engine with a ceramic coating. Because biodiesel contains more oxygen than diesel and engine coatings raise combustion chamber temperatures, NO_x emissions from biodiesel blends are greater than those from pure diesel.[81] In a semiadiabatic diesel engine, Zhu examined the performance, emission, and combustion characteristics of cottonseed (CSOME) and *Aza. indica* kernel oil (NKOME)

Table 2. Effects of LHR on Engine Performance and Emissions

		performance (compared to diesel)			emission (compared to diesel)				
biodiesel feedstock	type of coating material	BTE	BSFC	EGT	HC	CO	NO_x	smoke	ref
biodiesel	$CaZrO_3$ and $MgZrO_3$	↑	↓	–	–	–	–	–	88, 89
$_{bi}$odiesel	$3Al_2O_3{\cdot}0.2SiO_2$ (mullite)	↑	↓	↑	↓	↓	↑	–	90
biodiesel	lanthanum zirconium oxide ($La_2Zr_2O_7$)	↑	↓	–	–	–	↑	–	91
biodiesel	YSZ	↑	↓	–	↓	↓	↑	–	92
J. curcas seed oil biodiesel	partially stabilized zirconia	↑	↓	–	↓	↓	↓	↓	93
various biodiesel and vegetable oils	PSZ	↑	↓	–	–	–	↑	–	94
vegetable oils	zirconium oxide (ZrO_2)	↑	↓	–	↓	↓	↑	↓	95
waste cooking oil biodiesel	88% ZrO_2, 4% MgO, and 8% Al_2O_3	↑	↓	–	↓	↓	↑	↓	96
pongamia methyl ester (PME)	Al_2O_3	↑	↓	–	↓	↓	↑	↓	97
pongamia and rice bran oil methyl ester	fly ash	↑	↓	–	↓	↓	↑	–	98
nerium biodiesel	partially stabilized zirconia (PSZ)	↑	↓	–	↓	↓	↑	↓	99
palm oil methyl ester (POME)	yttria- stabilized zirconia (Y_2O_3– ZrO_3)	↑	↓	↑	↓	↓	↑	↓	100
PME	titanium oxide	↑	↓	–	↓	↓	↑	–	101
vegetable oil blends	ZrO_2	↑	↑	–	↓	↓	↑	–	102
cottonseed (CSOME) and *Aza. indica* kernel (NKOME) oils	LHR coating	↑	↑	–	↓	↑	↑	–	103
methyl ester of *Mad. longifolia* oil (MEMO)	Al_2O_3	↑	↓	↑	↓	↓	↑	↓	104
Ann. muricata methyl ester (AME)	88% ZrO_2, 4% MgO, and 8% Al_2O_3	↑	↓	–	↓	↓	↑	–	105
carburetted methanol and crude *J. curcas* oil	LHR coating	↑	↓	↓	–	–	↑	–	106

methyl esters.[82] According to some reports, biodiesel's increased viscosity and subpar atomization in LHR engines result in higher CO and HC emissions than diesel. As a result of the oxygen in the fuel and the LHR engine's greater combustion temperature, it is also claimed that NO_x emissions from biodiesel with LHR engines are higher than those from diesel. Methyl ester of *Mad. longifolia* oil (MEMO) and its mixes with diesel were used to power an Al_2O_3-coated diesel engine, according to Boschen.[83] The LHR engine's NO_x emissions are primarily caused by a rise in combustion temperature brought on by the ceramic coating. Due to the greater oxygen content of the fuel and coating on the engine parts, conventional and LHR engines utilizing biodiesel produce more NO_x.

The performance and emission characteristics of LHR engines running on biodiesel were assessed by Li et al. According to their findings, biodiesel's BTE is lower than diesel's, and it is even better when LHR coating is applied while utilizing both fuels.[84] Due to its increased engine power and torque at low speeds, biodiesel has been suggested for low-speed diesel engines. Pineda-Camacho examined how TBC affected the operation and emission characteristics of the diesel engine powered by *Ann. muricata* methyl ester (AME). It was discovered that, when compared to other test fuels, B20 had the lowest BSFC at all loads. Compared to the uncoated diesel engine, the BTE for B20 mix is somewhat higher in the LHR engine. However, the coated engine produces more NO_x than the uncoated engine for all test fuels due to the increased combustion chamber temperature.[85]

Chung assessed the efficiency of medium-grade LHR diesel engines running on carburetted methanol and crude *Jatropha*.[86] Shishov et al. assessed the efficiency of medium-grade LHR diesel engines running on carburetd methanol and crude *J. curcas* oil.[87] They came to the conclusion that, while the LHR engine emits more NO_x than a normal engine, the NO_x emission has decreased due to the use of ethanol.

2.3. Summary. The literature review reveals that many experimental studies are carried out using various ceramic materials as coating materials in a diesel engine, such as alumina, cerium oxide, partially stabilized zirconia, aluminum, titanium, and yttria-stabilized zirconia, but very few literature studies have been done using lanthanum as a coating material in CI engines. The BTE of the engine is enhanced and the SFC is decreased when the LHR engine is used. Additionally, it raises the peak in-cylinder pressure and combustion temperature of the diesel engine, which raises NO_x. Most studies have demonstrated that the LHR engine has improved combustion even when running on biodiesel.

Table 2 shows the effects of low heat rejection on the performance and emissions of biodiesel fuel engines compared to diesel engines.

2.4. Antioxidant Additives. Biodiesel is prone to oxidation due to unsaturated and polyunsaturated fatty esters, which will undergo oxidation during storage. The oxidation of biodiesel results in the formation of fuel-degrading compounds with different physicochemical properties. The antioxidant addition results in the improvement of the oxidation stability of the biodiesel. The antioxidant will also potentially suppress the NO_x emission when mixed in a small proportion with biodiesel and diesel. The present section will give a clear view of the recent research on antioxidant additives and biodiesel in CI engines.

Saini investigated the effect of antioxidant additives on NO_x emission using biodiesel. Ten antioxidant additives were considered for investigation: ascorbic acid 6-palmitate, 2-ethylhexyl nitrate, 2,2′-methylenebis(6-*tert*-butyl-4-methylphenol), α-tocopherol, TBHQ, PG, diphenylamine, BHA, BHT, and citric acid. It was found that most of the antioxidants significantly reduce NO_x emission.[107]

Akkarawatkhoosith have synthesized epoxidized cardanol (ECD) and evaluated its antioxidative properties with vegetable oils and biodiesel by using pressurized differential scanning calorimetry (PDSC) and the Rancimat method. Cardanol is a product obtained from cashew nut shell oil. Thermogravimetric analysis (TGA) of cardanol and ECD shows that the decomposition temperature of ECD is higher than that of cardanol.[108]

Yusuff investigated the impact of antioxidants on NO_x emissions from diesel engines running on *J. curcas* biodiesel. About 0.025% by volume of biodiesel was mixed with

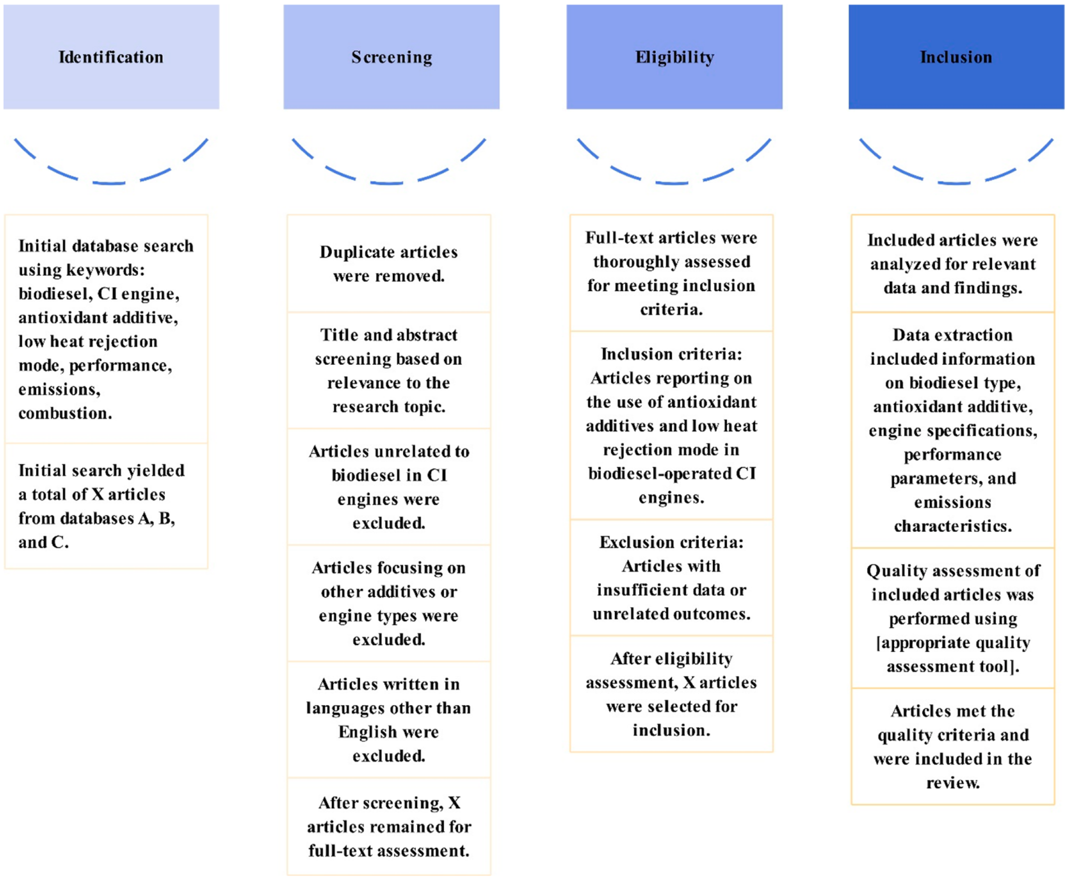

Figure 1. Selection process for literature review.

antioxidants like L-ascorbic acid (vitamin C), tocopherol acetate (vitamin E), butylated hydroxytoluene (BHT), *p*-phenylenediamine (PPDA), and ethylenediamine (EDA). The outcome demonstrated a considerable reduction in NO_x at all loads for all antioxidant additions.[109]

Gozmen Şanli studied the effect of antioxidant additives on NO_x emission from a mango oil biodiesel fueled engine. Among the antioxidants tested, the phenolic-derived additive showed a maximum reduction of NO_x emission compared to those of DEA and TBHQ. It was also seen that addition of antioxidants is insignificant in BTE and SFC but increases in CO, smoke, and HC emissions.[110]

Lee et al. examined the effect of adding different antioxidants on the performance and emission behavior of the canola oil methyl ester (COME)−diesel blend. It was also found that the oxidation stabilities of the antioxidants are in the order TBHQ > BHA > BHT > EHN. B20 has higher NO_x emissions than diesel when the antioxidant additive proportion is below 500 ppm.[111]

Ezekoye assessed the effects of *N*,*N*′-diphenyl-1,4-phenylenediamine (DPPD), *N*-phenyl-1,4-phenylenediamine (NPPD), and 2-ethylhexyl nitrate (EHN) on performance and emission behavior using a 20% blend of *Calophyllum inophyllum* biodiesel with diesel. B20 has a higher BSFC and a lower BTE when compared to diesel.[112] It can be proven that additive positively reduces NO_x emissions, but at the cost of increasing CO and HC emissions. Researchers investigated the suitability of preheated *Vateria indica* methyl ester (VIME) as an alternative fuel for a diesel engine. Preheating VIME could improve engine performance and reduce CO and HC emissions. Researchers conducted a chemical kinetics study on the combustion of ethanol/biodiesel/*n*-heptane. It was found that adding ethanol to biodiesel could improve the combustion characteristics of the fuel, leading to reduced emissions. Researchers investigated the effects of ternary blends of diesel/*n*-propanol/composite biodiesel on diesel engine operating parameters. It was found that ternary blends could improve engine performance and reduce NO_x emissions.

Uğuz investigated the oxidation stability and exhaust emissions of a 20% blend of *Moringa olifera* biodiesel with aromatic amine antioxidants. NPPD and DPPD increased the oxidation stability of the B20 mix up to induction times of 34.5 and 18.4 h, respectively. It was discovered that DPPD and NPPD reduced the blend's NO_x output by 7.4 and 3.04%, respectively.[113]

Paryanto used blends of lemongrass oil and diesel to examine the impact of antioxidant additives BHA and BHT on DICI engines' operation and emission characteristics. Antioxidants enhanced the BTE of the engine and marginally raised CO, HC, and smoke emissions, but they also significantly boosted the BSFC.[114] When it comes to boosting fuel stability and lowering NO_x emissions, BHA has been proven to be the better additive out of the two. Rashvand examined *Ann. muricata* biodiesel (MEAO) powered diesel engines' usage of antioxidant additives for NO_x reduction.[115] PPA is the most effective antioxidant ingredient for reducing NO_x compared to MEAO without additives, with a maximum NO_x reduction of roughly 42.15%. The following is a list of the different antioxidants' NO_x lowering effects: PPDA > AT > 1,4-dioxane > LA. The effects of natural and synthetic antioxidants on the oxidation stability, effectiveness, and emission characteristics of diesel engines operating on a 20% blend of sapota oil methyl ester were researched. In 2023, Ramalingam et al. found that LE and PY are the most effective antioxidants for improving the oxidation stability of biodiesel. Compared to diesel, B20 produces the least amount of pollutants overall, except for NO_x, whose emissions have been significantly reduced by the addition of LE[131].[116]

The impact of antioxidant additives on biodiesel's oxidation stability and combustion properties has been studied by Ryu.[117] The antioxidants are more effective in the following order: TBHQ > PrG> BHA > BHT > α-tocopherol. It was concluded that antioxidant addition had no impact on the combustion and performance of biodiesel. Kumar examined how BHT affected the *Aza. indica* biodiesel's oxidation stability, performance, and emission properties. The engine's BTE and BSEC remained unchanged. It is concluded that BHT can be employed to minimize NO_x and enhance biodiesel's oxidation stability.[118]

Pandey examined how antioxidant additions like BHA, BHT, and TBHQ affected how mixes of palm oil methyl ester and diesel burned. It was discovered that antioxidants successfully reduce NO_x emission.[119] In contrast, BHT and BHA both produce higher CO. Senthil et al. (2015) examined how AME's L-ascorbic acid (LA) addition affected the environment. The LA is combined in four ratios, including 100, 200, 300, and 400 mg. Compared to neat diesel at full load, the 200 mg proportion of LA reduced NO_x emission by approximately 23.38% and HC emission by 29.71%. The performance and emission parameters of the B20 blend of palm biodiesel at 1000 ppm concentration were examined by Sebayang et al. They have claimed that the antioxidants' phenolic hydroxyl groups interfered, resulting in a modest rise in BSFC and a decrease in NO_x production.[120] Thanikodi examined the performance and emission behavior of *J. curcas*—diesel blends concerning *N*,*N*′-diphenyl-1,4-phenylenediamine (DPPD) antioxidants. According to their experimental findings, adding antioxidants reduced NO_x emission at the expense of a minor decrease in brake power (BP) and an increase in BSFC.[121]

2.5. Summary. The literature review shows the investigation on various antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), *tert*-butylhydroquinone (TBHQ), 2-ethylhexyl nitrate (EHN), pyrogallol (PY), propyl gallate (PG), L-ascorbic acid (LA), and carotene antioxidant with biodiesel. All the antioxidants improved the oxidation stability of the biodiesel above the standard induction period of 6 h without affecting the physicochemical properties of the biodiesel by suppressing the free radicals. All the antioxidants showed a better reduction of the NO_x emission when it was fueled with biodiesel. Figure 1 shows the process of the literature review.

Table 3 depicts the effects of antioxidant additives on engine performance and emissions of biodiesel fuel engines as compared to diesel engines.

2.6. Summary of the Review of the Literature. According to the literature, neat biodiesel cannot be utilized in a diesel engine without any fuel or engine modifications. *Aza. indica* oil, *Man. indica* oil, *Mad. longifolia*, *P. pinnata*, and nerium are the feedstocks that are accessible in India. The majority of studies noted that using biodiesel increases NO_x emission since it contains more oxygen. Additionally, it is mentioned that the BTE has been consistently decreased for all biodiesels at all blend ratios. Adopting an LHR mode engine is one of the greatest methods to improve the efficiency of a CI engine powered by biodiesel. Studies showed that the LHR engine reduced NO_x pollution while increasing the BTE. Alumina

Table 3. Effects of Antioxidant Additive on Engine Performance and Emissions

		performance (compared to diesel)			emission (compared to diesel)				
biodiesel feedstock	type of antioxidant additive	BTE	BSFC	EGT	HC	CO	NO_x	smoke	ref
J. curcas biodiesel	L-ascorbic acid (vitamin C), α-tocopherol acetate (vitamin E), butylated hydroxytoluene (BHT), *p*-phenylenediamine (PPDA), and ethylenediamine (EDA)	–	–	–	–	–	decrease	–	122
soybean biodiesel	diethylamine (DEA), pyridoxine hydrochloride (PHC), and *tert*-butylhydroquinone (TBHQ)	–	–	–	increase	increase	decrease	increase	123
canola oil methyl ester (COME)	butylated hydroxyanisole (BHA), BHT, TBHQ, and 2-ethylhexyl nitrate (EHN)	–	–	–	–	–	decrease	–	124
Moringa olifera biodiesel	*N*,*N*′-diphenyl-1,4-phenylenediamine (DPPD) and *N*-phenyl-1,4-phenylenediamine (NPPD)	–	–	–	–	–	decrease	–	125
Calophyllum inophyllum biodiesel	DPPD, NPPD, and EHN	–	–	–	decrease	increase	decrease	increase	126
lemongrass oil	BHA antioxidant	increase	increase	–	increase	increase	decrease	increase	127
Ann. muricata biodiesel (MEAO)	PPDA, α-tocopherol acetate (AT), 1,4-dioxane, and L-ascorbic acid (LA)	–	–	–	–	–	decrease	–	128
sapota oil methyl ester	citric acid (CA), rosemary extract (RE), leaf extract (LE), and synthetic antioxidants such as pyrogallol (PY), propyl gallate (PG), and BHA	–	–	–	–	–	decrease	–	129
Aza. indica oil (MENO)	*p*-phenylendiamine	–	–	–	decrease	increase	decrease	increase	130
Ann. muricata biodiesel (MEAO)	L-ascorbic acid	–	–	–	–	–	decrease	–	131

(Al_2O_3), zirconia (ZrO_2), titanium oxide, partially stabilized zirconia (PSZ), magnesium oxide (MgO), fly ash, and other minerals are used as coating materials in CI engines. Lanthanum oxide has, however, received very little investigation as a coating material for CI engines. Lanthanum oxide reportedly has a lower thermal conductivity than PSZ and is more thermally stable. The in-cylinder gas temperature rises and less heat is lost to the coolant due to lanthanum oxide's lower thermal conductivity, potentially boosting the engine's BTE.

According to reports, the LHR coating elevates the in-cylinder gas temperature, increasing NO_x emission. The use of biodiesel would increase NO_x emissions even further. It has also been asserted that antioxidant addition is the best way to lower NO_x emissions using biodiesel. L-Ascorbic acid, *n*-butyl amine, pyrogallol, propyl gallate, BHA, BHT, TBHQ, and phosphorate cardanol are effective antioxidants to decrease NO_x emissions, according to the majority of research. The amount of phenolic groups the additive contains demonstrates its antioxidant activity. L-Ascorbic acid has four phenolic groups (OH) and is one of the many additives that is easily accessible and less expensive. Additionally, just a few investigations have been made, and current inquiries can try it.

2.7. Advantages of Using Low Heat Rejection (LHR) Mode in Biodiesel-Operated CI Engines. The advantages of using LHR mode in biodiesel-operated CI engines include the following:

- LHR mode in biodiesel-operated CI engines can enhance thermal efficiency by reducing heat losses through the engine's cooling system. This leads to improved fuel economy and increased overall engine efficiency.
- By minimizing the amount of heat dissipated through the engine's cooling system, LHR mode helps in reducing the thermal stress on engine components. This can extend the engine's lifespan and improve its durability.
- LHR mode often involves special coatings or materials that reduce friction between moving engine parts. This can reduce energy losses due to friction, improving engine performance and efficiency.
- LHR mode can promote better combustion characteristics in biodiesel-operated CI engines. By maintaining higher cylinder temperatures, LHR mode facilitates improved fuel atomization, more complete combustion, and reduced unburned fuel emissions.
- Implementing LHR mode in biodiesel-operated CI engines has shown potential for reducing emissions of pollutants such as NO_x and PM. The optimized combustion process and reduced heat losses contribute to lower emissions, promoting a cleaner and more environmentally friendly engine operation.

2.8. Disadvantages of Using Low Heat Rejection (LHR) Mode in Biodiesel-Operated CI Engines. The disadvantages of using LHR mode in biodiesel-operated CI engines include the following:

- Implementing LHR mode in biodiesel-operated CI engines requires additional components, such as special coatings, insulation, or modified cooling systems. This can increase the complexity of the engine design and may require more sophisticated manufacturing processes.
- Incorporating LHR mode typically involves additional expenses, such as using advanced materials, coatings, or engine modifications. These extra costs can make LHR mode less economically feasible, particularly for smaller-scale or cost-sensitive applications.
- LHR mode may not be universally applicable to all biodiesel-operated CI engines. The effectiveness of LHR mode can depend on factors such as engine design, operating conditions, and fuel properties. Thus, it may not yield significant benefits in all engine configurations or for all types of biodiesel fuels.
- While LHR mode can help reduce overall emissions, it may lead to a slight increase in NO_x emissions. The higher combustion temperatures associated with LHR mode can promote NO_x formation, necessitating the use of additional emission control technologies to mitigate this drawback.
- The use of LHR mode may require specialized maintenance procedures and monitoring to ensure optimal performance. Additionally, introducing new components or modifications may raise concerns about long-term reliability and durability, requiring careful attention and maintenance practices.

3. PRESENT WORK

This review aims to find any potential renewable fuels that might outperform diesel fuel in terms of efficiency, combustion, and emission characteristics. The current work uses biodiesels made from renewable sources including *Man. indica*, *Mad. longifolia*, and *P. pinnata* as diesel fuel alternatives. These biodiesels have the downside of reduced performance and increased NO_x emission and are frequently utilized in CI engines. These issues may be avoided by including LHR mode in CI engines and adding additives with biodiesel. The LHR engine will increase combustion, resulting in better performance, and adding additive will enhance the characteristics of biodiesel and dramatically lower NO_x emissions. Therefore, an effort is made to investigate the impact of *Man. indica*, *Mad. longifolia*, and pongamia biodiesels with LHR engines and additive with varying quantities on the engine's performance, combustion, and emission characteristics.

3.1. Materials and Methods. The present investigation focused on the production of biodiesel from various seeds like *Mad. longifolia*, mango, and *P. pinnata* seed, and it is considered as renewable based energy and is easily biodegradable.

3.1.1. Biodiesel and Biodiesel Blend Preparations. Based on a literature review, B20 (a blend of 80% diesel and 20% biodiesel) was utilized to operate the CI engine with few alterations. However, it still has issues with decreased performance and a rise in NO_x. Among three biodiesels, the MEMSO20 blend showed significant results in all aspects. Similarly, LA of 200 mg with MEMSO showed the best trends when the engine was operated in LHR mode. In the present analysis, MEMSO20 with 200 mg of LA and diesel in LHR and conventional modes was made. The graphs are plotted for BSFC, BTE, HC, EGT, NO_x, and smoke opacity with engine brake power. The influence of thermal barrier coating on the combustion components and the addition of 200 mg of LA with MEMSO are discussed elaborately.

3.2. Experimental Setup. A single-cylinder CI engine connected to an eddy current dynamometer underwent a load test to vary the load. A load cell fastened to the dynamometer arm has measured the load. The system is set up to measure the rate at which fuel and air enter the engine. The setup is offered to measure and regulate the flow rate of coolant water. The piston position is measured using a crank angle encoder, and the in-cylinder gas pressure is determined using a PCB piezoelectric pressure transducer. Engine exhaust emission is measured using an AVL 444 di-gas analyzer and an AVL smoke meter. The engine can operate on neat diesel at a constant speed of 1500 rpm to reach a steady state. The smoke meter and exhaust gas analyzer are turned on relatively early, so all its systems can stabilize before the experiment starts.

4. RESULTS AND DISCUSSION

4.1. Brake Specific Fuel Consumption. Figure 2 displays the deviation of BSFC versus BP for MEMSO biodiesel with LA and diesel in the LHR engine. MEMSO greatly enhanced the BSFC with LA in the LHR engine. Higher combustion chamber temperatures and LA enable efficient burning in the combustion chamber due to the additional oxygen present in the biodiesel. In the conventional engine, the BSFC for MEMSO is higher at all loads. This is caused by the biodiesel's reduced calorific value and lower combustion chamber temperature. The BSFC for the LHR engine with MEMSO20 with LA is 0.31 kg/kWh at maximum load, which is 0.09% less than the diesel in the LHR engine.

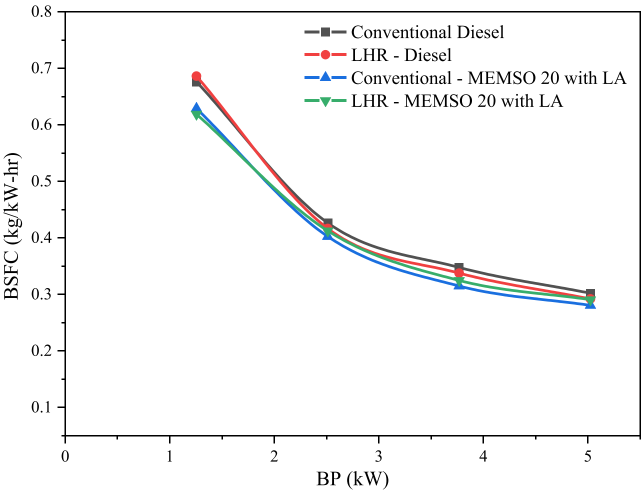

Figure 2. Deviation of BSFC versus BP for conventional and LHR engines (diesel and MEMSO20).

4.2. Brake Thermal Efficiency. The deviation of BTE versus BP for MEMSO biodiesel with LA and diesel in LHR and conventional engines is shown in Figure 3. It is seen from the figure that a BTE of the LHR engine is higher than that of a conventional engine. The engine is converted into LHR mode, which retains a high temperature in the combustion chamber. Further, the BTE of MEMSO in LHR is 31.7% at maximum load, 0.3% closer than the diesel with an LHR engine. Even though biodiesel is operated in the engine, the efficiency is improved by the combined effect of MEMSO, thermal barrier coating, and 200 mg of LA, which improves combustion. It is seen from Figure 3 that the BTE is higher for MEMSO in LHR mode when compared to that of diesel in conventional mode.

4.3. Exhaust Gas Temperature. The deviation of EGT versus BP for MEMSO biodiesel with LA and diesel in LHR and conventional engines is shown in Figure 4. It is seen from the figure that the EGT is higher for biodiesel in an LHR engine and it is also due to the heat retained in the combustion chamber, which is converted into useful work. Further, lower heating value, higher density, and high viscosity of biodiesel lead to poor atomization, increasing the EGT. The EGT of MEMSO20 with LA in LHR mode is 246 °C, which is 10 °C less when diesel is operated in LHR mode.

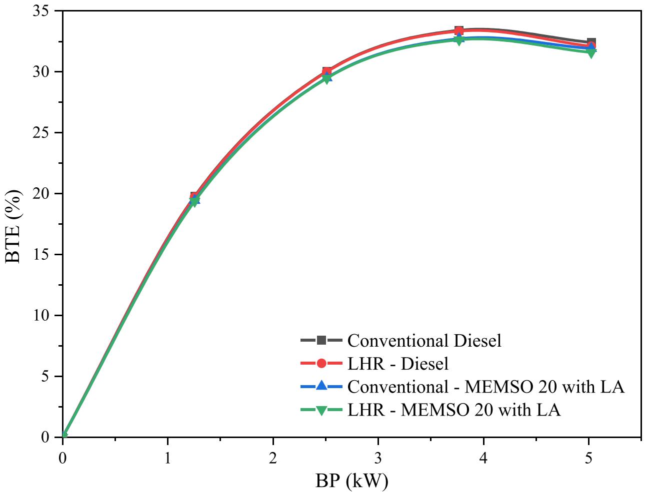

Figure 3. Deviation of BTE versus BP for conventional and LHR engines (diesel and MEMSO20).

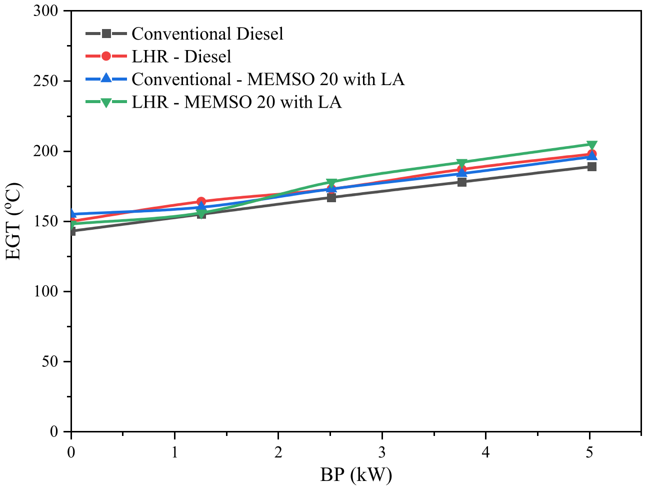

Figure 4. Deviation of EGT versus BP for conventional and LHR engines (diesel and MEMSO20).

4.4. Carbon Monoxide Emission. The deviation of CO versus BP for MEMSO biodiesel with LA and diesel in LHR and conventional engines is shown in Figure 5. The MEMSO operated in the LHR engine shows lower CO emissions than others. This is because MEMSO biodiesel and coating induce perfect combustion in the presence of excess O_2 and free radicals of LA in the fuel. At maximum load CO for MEMSO in LHR engine emission is 0.03%, 0.06% less than diesel in a conventional engine. Further, the combined effect of excess O_2, higher combustion chamber temperature, and LA in the fuel considerably reduces CO emission in the exhaust.

4.5. Hydrocarbon Emission. Figure 6 displays the variation of HC versus BP for MEMSO biodiesel with LA, diesel in the LHR engine, and the conventional engine. It has been noted that all loads using biodiesel operating in LHR had the lowest HC emission. Additionally, at all loads, diesel powered by conventional engines had the highest HC emission. The combined effects were from the heat barrier layer, the larger decrease of

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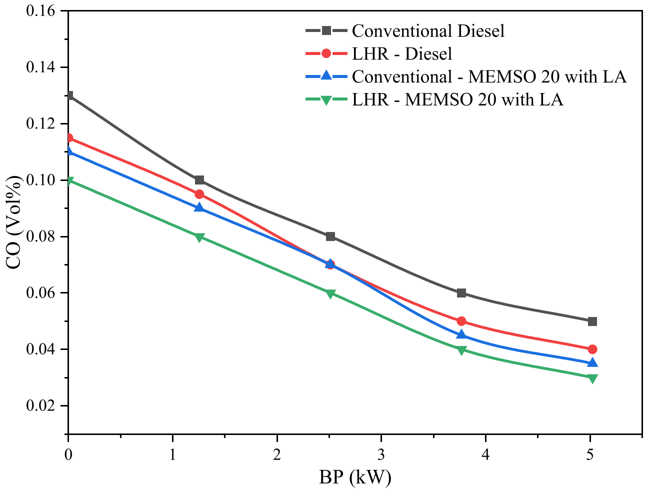

Figure 5. Deviation of CO versus BP for conventional and LHR engines (diesel and MEMSO20).

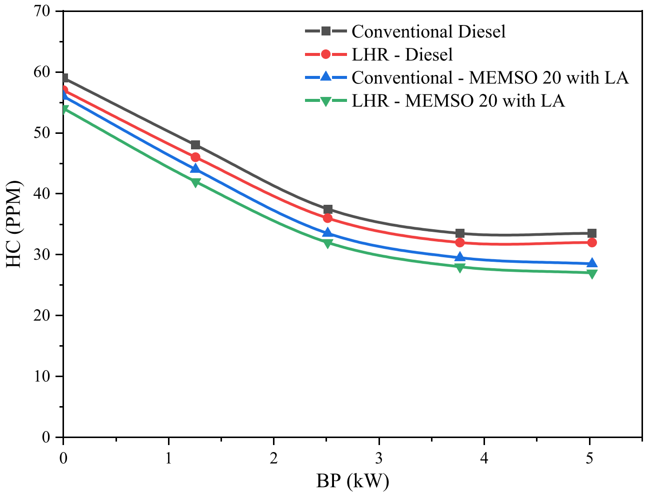

Figure 6. Deviation of HC versus BP for conventional and LHR engines (diesel and MEMSO20).

HC, excess of O_2, and LA present in the fuel. At 80% load, the HC emission is 22 ppm, which is 5 ppm lower than a conventional engine.

4.6. Nitrogen Oxide Emission. The deviation of NO_x versus BP for MEMSO biodiesel with LA and diesel in LHR and conventional engines is shown in Figure 7. It is seen from Figure 7 that NO_x emission is decreased considerably for the best combination at all loads. The engine is provided with a thermal barrier coating and is operated with biodiesel, which makes higher NO_x emissions, but adding LA with biodiesel significantly reduces NO_x at all loads. It is proved from Figure 7 that the addition of LA at the proportion of 200 mg exhibits suppression of NO_x at all loads because of more free radicals present in the combustion chamber. This trend is the same for all loads and may be due to the suppression of NO_x by the antioxidant activity. At 80% load, the NO_x emission is 396 ppm, 12 ppm lower than a conventional engine.

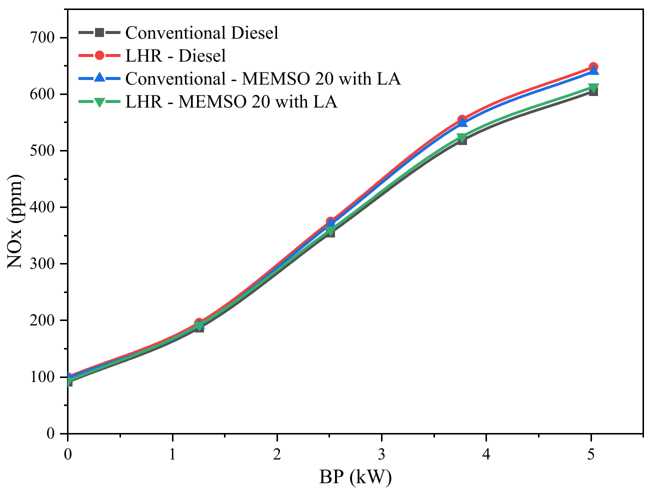

Figure 7. Deviation of NO_x versus BP for conventional and LHR engines (diesel and MEMSO20).

This review comprehensively examines the impact of biodiesel-operated CI engines on emissions, including particulate matter (PM) and particulate number (PN) emissions. The selected articles investigate the influence of various biodiesel types, antioxidant additives, and low heat rejection mode on PM and PN emissions in CI engines. The findings suggest that biodiesel blends, combined with appropriate engine modifications and antioxidant additives, can effectively reduce PM and PN emissions compared to conventional diesel fuel. This review highlights the importance of considering PM and PN emissions as crucial parameters in evaluating the environmental impact of biodiesel-operated CI engines and provides insights into the mechanisms and strategies for mitigating these emissions.

4.7. Smoke Opacity. The deviation of smoke opacity versus BP for MEMSO biodiesel with LA and diesel in LHR and conventional engines is shown in Figure 8. It is seen that smoke is significantly reduced for the best combination at all loads. At maximum load, the smoke opacity for the best combination is 36 HSU, which is 40 HSU lower than the conventional engine. This is because excess of oxygen present in biodiesel causes better combustion, coating on engine components makes more heat available in the engine, and the presence of LA additive in the fuel provides better combustion. Therefore, a significant reduction of smoke opacity is achieved.

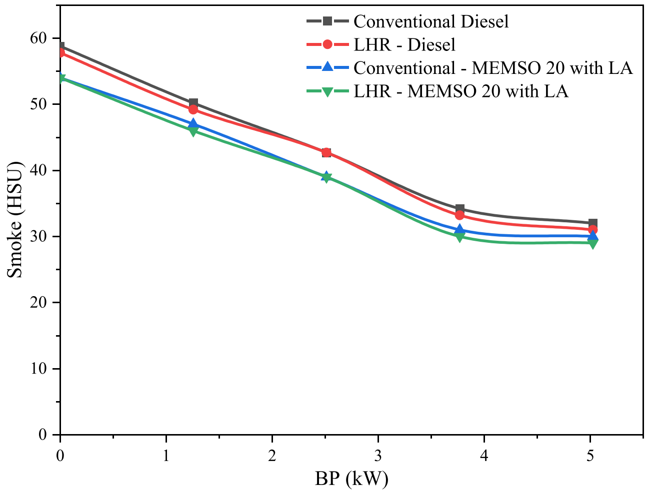

Figure 8. Deviation of smoke opacity versus BP for conventional and LHR engines (diesel and MEMSO20).

5. ECONOMIC VIABILITY

The economic viability of biofuels has been a persistent challenge for researchers and industry stakeholders. Several factors contribute to this challenge, including the high costs associated with feedstock production, processing technologies, and infrastructure development. Feedstock costs vary depending on the type of biomass used for biofuel production. The availability and accessibility of a feedstock and its cultivation, harvesting, and transportation costs greatly impact the overall economics of biofuel production. Research efforts have focused on identifying cost-effective feedstock options, optimizing crop yields, and exploring alternative feedstock sources to mitigate these challenges. Processing technologies for biofuel production also play a significant role in determining economic viability. The efficiency of conversion processes, such as biochemical or thermochemical conversion, can significantly impact production costs. Research endeavors have focused on improving conversion technologies, enhancing energy efficiency, and reducing capital and operational costs to make biofuel production economically competitive. Government policies and regulations heavily influence the economic viability of biofuels. Supportive policies, such as tax incentives, grants, and mandates, can provide a favorable investment environment and encourage market growth. Additionally, stable and long-term policy frameworks are essential for attracting private investments and fostering technological advancements in the biofuel sector. Market dynamics, including fuel prices and demand, also influence the economic feasibility of biofuels. Fluctuations in fossil fuel prices can impact the competitiveness of biofuels as an alternative energy source. Increasing consumer demand for sustainable and renewable fuels presents opportunities for biofuel market expansion, but it also requires cost-competitive production to meet consumer expectations.

Infrastructure requirements pose significant challenges to the economic viability of biofuels. Establishing a robust distribution and retail infrastructure for biofuels involves substantial investments. This includes storage facilities, transportation networks, blending infrastructure, and fueling stations. Overcoming these challenges requires collaborative efforts between industry stakeholders, policymakers, and infrastructure developers. To enhance the economic viability of biofuels, various strategies are being pursued. These include technological advancements to improve efficiency and reduce costs, diversification of feedstock sources, innovation in conversion processes, continuous policy support, and collaboration between research institutions, industry, and government entities. Additionally, exploring coproducts and value-added applications of biofuel production can create additional revenue streams, enhancing overall economic feasibility.

In conclusion, addressing the economic viability of biofuels remains a significant challenge for researchers and industry stakeholders. However, focusing on cost reduction, technological advancements, supportive policies, market development, and infrastructure expansion can enhance biofuels' economic feasibility and foster their sustainable integration into the global energy landscape.

6. POTENTIAL FUTURE DEVELOPMENTS

In the realm of biodiesel-operated CI engines, there is considerable potential for future advancements and developments in the use of antioxidant additives and low heat rejection (LHR) mode to optimize performance and reduce emissions. One potential avenue for future development lies in formulating advanced antioxidant additives. Researchers can continue to explore and develop additives with enhanced oxidative stability and antiaging properties specifically tailored for biodiesel blends. By improving the fuel's resistance to degradation, these additives can contribute to improved engine performance and durability. Another area of focus could be exploring synergistic combinations of antioxidant additives. By combining different additives, researchers can achieve additive interactions that enhance protection against oxidation and degradation. This approach may offer superior antioxidant performance compared to individual additives, further improving the stability and performance of biodiesel blends in CI engines. In terms of LHR mode, future developments may involve advancing materials and coatings used in engine components to withstand higher operating temperatures better. Researchers can explore innovative materials with improved thermal insulation properties, reducing heat losses and optimizing the combustion process in biodiesel-operated CI engines. Additionally, advancements in engine design and cooling systems can be pursued to enhance the efficiency of heat transfer and management in LHR engines. Integration with other emerging technologies, such as advanced combustion techniques and exhaust aftertreatment systems, holds promise for future developments. Combining antioxidant additives and LHR mode with technologies like homogeneous charge compression ignition (HCCI), selective catalytic reduction (SCR), or diesel particulate filters (DPFs) can further enhance the overall performance and emission control capabilities of biodiesel-operated CI engines. Furthermore, integrating advanced engine control strategies and real-time monitoring systems can provide valuable insights into the performance and emission characteristics of biodiesel-operated CI engines. This can enable more precise control of combustion parameters and facilitate adaptive optimization based on varying operating conditions, improving efficiency and reducing emissions.

7. EFFECT OF ANTIOXIDANTS ON THE ENVIRONMENT

Antioxidants play a significant role in the environmental impact of biodiesel-operated CI engines. Here are some effects of antioxidants on the environmental side:

- Antioxidants help improve the oxidative stability of biodiesel by inhibiting the formation of free radicals and preventing the oxidation process. By reducing fuel degradation, antioxidants contribute to lower emissions of harmful by-products that can have negative environmental effects.
- Antioxidants can minimize the formation of deposits and sediments in fuel systems and engine components. This leads to cleaner combustion and reduces the likelihood of engine malfunctions or performance issues, thereby promoting more efficient and environmentally friendly engine operation.
- The use of antioxidants in biodiesel blends can contribute to better emission control. By maintaining fuel quality and preventing degradation, antioxidants help ensure the combustion process is more complete and efficient. This results in reduced emissions of pollutants such as particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC), which are detrimental to air quality and can contribute to environmental issues.
- Antioxidants can also positively impact the lifespan and performance of exhaust aftertreatment systems, such as catalytic converters. By reducing the formation of deposits and maintaining fuel quality, antioxidants help prevent catalyst

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poisoning and degradation, allowing for more effective emission reduction and longer catalyst life. This, in turn, reduces the need for frequent catalyst replacement and associated environmental impacts.

- Antioxidants contribute to maintaining the fuel's energy content and quality, which can improve overall fuel efficiency. When biodiesel operates efficiently in CI engines, it reduces the consumption of fossil fuels, leading to reduced greenhouse gas emissions and a smaller carbon footprint. By optimizing fuel combustion and minimizing energy losses, antioxidants indirectly contribute to environmental sustainability.

8. CONCLUSION

This paper explores the impact of antioxidant additives and low heat rejection (LHR) mode on the performance and emission characteristics of diesel engines. The findings suggest the following:

- Biodiesel tends to decrease the brake thermal efficiency (BTE) compared to diesel due to its higher viscosity, which affects atomization.
- Biodiesel and its blends generally exhibit higher specific fuel consumption (SFC) than diesel due to differences in their calorific values, requiring more fuel to produce the same amount of power.
- Studies consistently show that biodiesel significantly reduces hydrocarbon (HC), carbon monoxide (CO), and smoke emissions compared to diesel. These improvements are attributed to biodiesel's higher oxygen content and lower levels of aromatic compounds.
- Biodiesel use typically increases nitrogen oxide (NO_x) emissions compared to diesel. Factors such as higher oxygen content, cetane number, reduced compressibility, changes in fuel injection characteristics, and elevated in-cylinder pressure contribute to this increase.
- LHR engines perform better than conventional compression ignition (CI) engines. They exhibit significantly reduced HC, CO, and smoke emissions compared to diesel across various loads. However, NO_x emissions in LHR engines are considerably higher.
- The stability of most biodiesel falls below the ASTM standard minimum induction time of 6 h due to the presence of mono- and polyunsaturated fatty acids. The addition of suitable antioxidant additives improves stability.
- Antioxidants enhance engine efficiency and emission traits without affecting NO_x emissions. They can reduce immediate NO_x emissions rather than thermal NO_x. When used with biodiesel, antioxidants have the potential to reduce NO_x emissions by up to 10%.
- Specifically, MEMSO20 with 200 mg of LA in an LHR engine demonstrates superior performance, including notable reductions in HC, CO, smoke, and NO_x emissions compared to a conventional engine. Thus, MEMSO20 shows promise as a viable alternative to diesel fuel in LHR-mode CI engines.
- Biodiesel can be directly substituted for diesel fuel in diesel engines, particularly with blends containing a moderate amount of B20 and including antioxidant additives, enhancing operating conditions. Economic and environmental considerations may further enhance their appeal. However, further research is needed to advance engine design and biodiesel supply.

In conclusion, using antioxidant additives and LHR mode in biodiesel-operated CI engines presents improved engine performance, reduced emissions, and enhanced stability opportunities. However, continued research and development are necessary to optimize engine design and further refine biodiesel production and supply to ensure long-term viability and sustainability.

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Notes

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NOMENCLATURE

CO = carbon monoxide
EGT = exhaust gas temperature
g/cm^3 = grams per cubic centimeter
g/kWh = grams per kilowatt hour
HC = hydrocarbons
ID = ignition delay
J/deg = joules per degree
kg/m^3 = kilograms per cubic meter
kJ = kilojoule
kJ/kg = kilojoules per kilogram
kW = kilowatt
m^2/s = square meters per second
ppm = parts per million
BTE = brake thermal efficiency
CSZ = calcia stabilized zirconia
CaO = calcium oxide
CO_2 = carbon dioxide
CO = carbon monoxide
COME = canola oil methyl ester
CN = cetane number
DI = direct injection
FFA = free fatty acid
GC−MS = gas chromatography−mass spectrometry
HSU = Hartridge smoke unit
HRR = heat release rate
ID = ignition delay
JA = Jamun blends
LHR = low heat rejection
LHRD = low heat rejection diesel
LHRWA = low heat rejection with NA additive

MgO = magnesium oxide
MMT = million metric tons
NA = natural leaf antioxidant
NiCrAlY = nickel−chromium−aluminum−yttrium
NO_x = oxides of nitrogen
PSZ = partially stabilized zirconia
PM = particulate matter
KOH = potassium hydroxide
PPDA = *p*-phenylenediamine
PG = propyl gallate

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