2.1 Introduction

The non-conventional fuel becomes the researcher's priority because it is a renewable energy source that is environmentally friendly, non-toxic, biodegradable, and readily available. The rising demand for conventional fuels has prompted people to consider alternative fuels that can partially replace current demand. In recent years, the development of alternative fuels has garnered worldwide attention due to the deteriorating environmental quality resulting from increased emissions from the combustion of petroleum-based fuels and unexpected price fluctuations of imported crude oil.

2.2 NO$_X$ Mitigation Techniques

The increase in NOx emissions is the major problem associated with the use of biodiesel blends. This section summarizes relevant research to orient the reader with reviews of the various techniques to mitigate NO$_X$ emissions from CI engines' exhaust gas.

2.2.1 Exhaust Gas Recirculation (EGR)

D. Kawano et al. [52] chose B100 rapeseed oil methyl ester (RME) as fuel for CI engines, along with a high and low-pressure loop EGR setup. A rise in the high-pressure loop (HPL) EGR rate lowered NO$_X$ emissions while having little effect on PM emissions. A rise in the amount of LPL EGR, NOx and smoke emissions is being reduced at the same time. S. Prakash and M. Prabhahar S. Prakash and M. Prabhahar [37] conducted an investigation on a diesel engine using a 20% biodiesel blend and varying recirculation (EGR) rates (10%, 20%, and 30%). They monitored and estimated the rate of released heat and pressure inside the cylinder. According to the outcome of the experiments, a Pongamia biodiesel blend of 20% and a 20% EGR rate lowered the BTE, raised the specific fuel consumption, and reduced NOx emissions as the EGR% increased, as shown in. Figure 2-1[37]. Other pollutants, such as carbon monoxides, hydrocarbons, and smoke, have risen with the rise in EGR%. We observed a decline in the pressure inside the cylinder and HRR as the rate of EGR for the biodiesel increased.

Elavarasan G et al. [36] have prepared mustard oil biofuel blends by mixing them with diesel in the proportions of 5%, 10%, and 15%. The investigations were performed

with a CI engine at various loads, and the emissions were matched to those of a diesel-fueled engine. The outcomes revealed that with the rise in the mix, smoke, hydrocarbons, and monoxide output reduced while nitrogen oxide discharge increased.

The increase in oxygen concentration in the mixture explains the improved igniting method and a reduction was also observed in smoke, hydrocarbons, and monoxides. Furthermore, with the help of 10% exhaust gas recirculation, a downtrend of 12 percent in NOx emissions was obtained. Although employing EGR in a CI engine to minimize NOx emissions is an effective technology, it has several disadvantages, including a significant increase in smoke, HC, CO, and fuel usage, as well as a drop in thermal efficiency unless properly tuned.
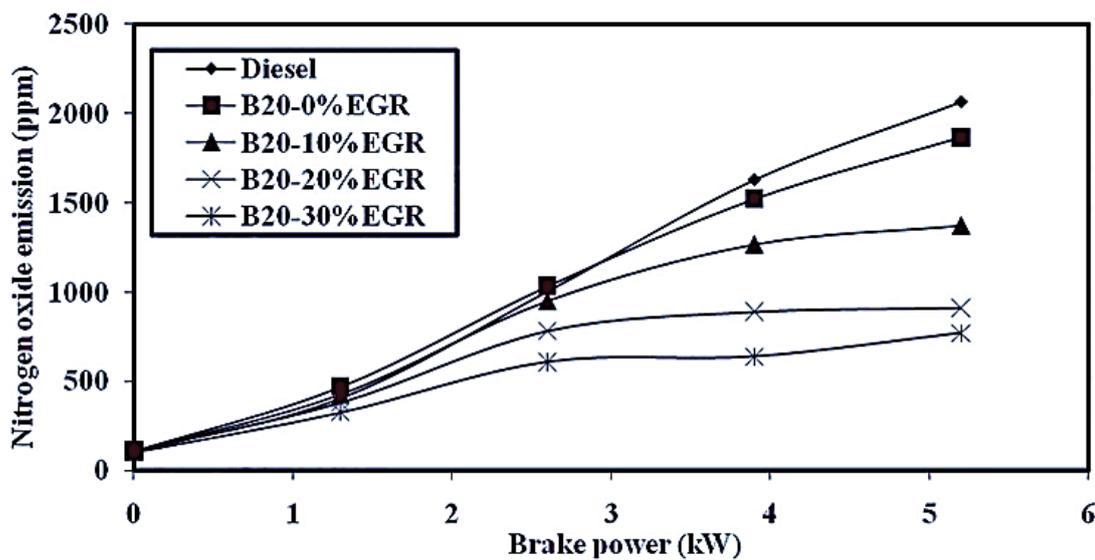

Figure 2-1: NOx Vs BP for various EGR%

MSD15 blend of mustard feedstock is prepared by D kawano et al [36]. The experiment was done without EGR and with 10% EGR. It has been found that NOx has decreased by 12% in the case of 10% EGR, but carbon monoxide, hydrocarbons, and smoke exhaust rise compared to non-EGR tests.

Özer Can et al [53] examined the effect of EGR on emission, combustion and performance parameters of the single-cylinder diesel engine at various engine loads and various EGR percentages (5, 10, and 15). A soybean biodiesel-diesel (B20) fuel blend was used for the experimentation. At a 15% EGR rate, BTE decreased by 3%, and specific fuel consumption increased by 6%. NOx and smoke emissions reduce by 55% and 15%, respectively. [53]

Mohd Hafizil Mat Yasin et al [54] experimentaly studied the effect of EGR on the parameters of the diesel engine. The author has used a blend of palm biodiesel and diesel

as fuel. The results showed a reduction in brake power, reduced NOx emissions, increased fuel consumption, and small increases in CO_2, CO, and particulate matter.

M. Gomaa et al. [55] study the effect of EGR on NOx and smoke emissions of a four-stroke DI engine fueled with jatropha and diesel blends. The author has used two blends, JB5 and JB20, along with various EGR rates. For the JB5 fuel blend and 5% EGR, reductions in NOx emissions and smoke emissions were observed at 27% and 17%, respectively. Furthermore, for the JB20 fuel blend, reductions in NOx emissions and smoke emissions were observed at 36% and 31%, respectively. On the performance side, the BTE decreases as the EGR% increases. The BTE of diesel fuel, JB5, and JB20 were reduced by 22.5%, 16.7%, and 8%, respectively.

M. Mani et al. [56] conducted the experiment on a single-cylinder CI engine using plastic oil biodiesel along with EGR. The result revealed a reduction in BTE as EGR% increased. Without EGR, the NOx emission decreased from 14.63 g/kWh to 8.56 g/kWh, while with 20% EGR, it increased from 10.897 g/kWh to 8.56 g/kWh. As EGR% increases, CO emissions also decrease.

A. Paykani et al. [57] examined the impact of exhaust gas recirculation (EGR) on the emission and performance characteristics of the compression ignition (CI) engine. The engine was powered by a combination of canola oil biodiesel and diesel blends, specifically B20 and B50. It has been noted that the brake thermal efficiency declines with an increase in the percentage of exhaust gas recirculation (EGR), while the reduction in NOx emissions occurs.

K. Venkateswarlu et al. [58] performed a test to investigate the combined effect of EGR and cetane improver ethyl hexyl on the emission and performance parameters of a mono-cylinder, 4-stroke CI engine. They used blends of Jatropha biodiesel and diesel (B20, B30, and B40). The experimentation results revealed that as EGR% increases, thermal efficiency increases and specific fuel consumption decreases. When it comes to exhaust emissions, NOx emissions decrease by 33% at a 20% EGR rate, whereas CO, HC, and smoke emissions increase as EGR% increases.

V.Manieniyan et al [59] conducted an empirical investigation on a diesel engine consist of single cylinder along with the implementation of EGR. The researchers examined the influence of EGR on the engine's performance and emission characteristics. The Madhuca biodiesel and diesel blend is used for four EGR% (5, 10, 15, and 20). The result shows a reduction in NOx emissions with an increase in EGR%; no major change in brake

thermal efficiency was observed. Furthermore, CO, HC, and smoke emissions decrease as the EGR percentage increases.

Rachel L. Muncrief et al [60] implemented the EGR in the CI engine to reduce NOx and particulate emissions. The experiment was conducted on a Volvo VE truck WX64 with 275 HP power. The cottonseed oil biodiesel blends (B20, B50, and B100) as well as the soy biodiesel B100 blend were used to power the engine. The result revealed a reduction of 40% in NOx emissions with the EGR as compared to diesel fuel without the EGR, but the particulate matter increased.

Jeya Jeevahan et al [61] study the effect of EGR on the performance and emission parameters of the monocyllene CI engine, which was fueled by the B20 biodiesel-diesel blend. From the observations, it is revealed that the NOx emission reduces, but on the other hand, CO, CO_2, and HC increase.

S. S. Gill et al [62] tried to reduce NOx as well as soot particles by implementing the EGR with a filtration facility, which will filter the soot particle before it enters the cylinder. The author has used a single-cylinder CI engine. The author has experimented with Rapeseed biodiesel and 10% and 20% EGR. The results revealed a reduction in NOx emissions compared to non-EGR, but in the case of EGR and EGR with filters, there was no substantial alteration in the NOx emission value. Furthermore, CO and HC emissions increase in all EGR cases compared to non-EGR.

2.2.2 Water Emulsion

Different experts have carried out studies on a range of emulsion fuels in CI engines. P. V. E. M. Parthasarathy et al.[41] the emulsified Nerium biodiesel is created by blending it with a tiny number of atoms of water in the proportions of 5-7%, 10-12%, and 15-18% by volume. A mixture of 60–62% diesel, 18–20% Nerium biodiesel, 15–17% water, and 3–5% surfactant gave higher BTE and bsfc values than the base fuel. These values were about 14% and 12.5%, respectively. In addition, the diesel, CO, NOx, smoke opacity, and HC emissions of the aforementioned fuel blend decreased by 43%, 6.5%, 13%, and 32%, respectively. The results showed that using emulsified gasoline in typical engines without any changes provides a considerable improvement and advantage.

S. Vellaiyan et al [63] studied the water-emulsified soybean biodiesel along with the alumina nano-additive and found it capable of being used as a fuel. As 10% water is added to soybean biodiesel, the specific fuel and energy consumption values increase approximately by 4.2% and 10.3%, respectively, compared to diesel-based engines.

Nitrogen oxides, hydrogen, monoxide of carbon, and smoke opacity are reduced by 21.3%, 16.6%, 16.8%, and 11.7%, respectively. The addition of aluminium nanoparticles to emulsified biofuel reduces pollutants like NOx and carbon, hydrocarbons, and smoke emissions while increasing CO_2.

O. A. Elsanusi et al.[64] studied the effect of water emulsion using canola biodiesel-diesel blends that were emulsified with three unique mixing proportions of water concentration (5%, 10%, and 15%). Increased water content in emulsions resulted in the rise of BTE and also a drop in EGT. The rise in water content in the emulsion lowered nitrogen oxides and smoke emissions significantly when compared to their bases, as shown in Figure 2-2[64].
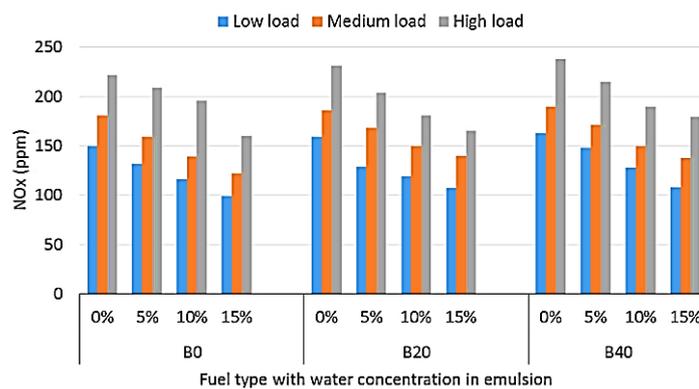

Figure 2-2: NOx emission Vs Water Emulsion %

CO emissions were found to be much greater in emulsion fuels with a higher water content, as depicted in Figure 2-3[64].
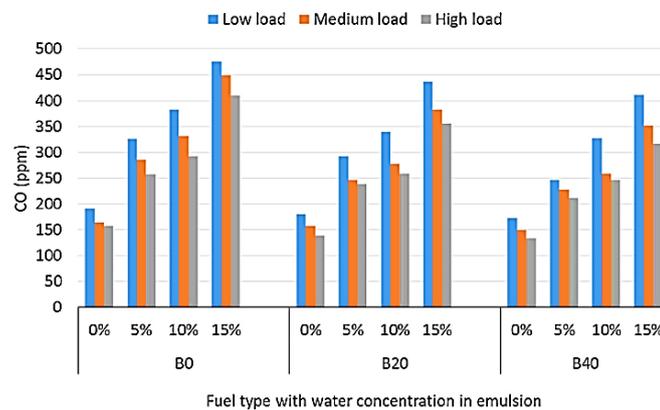

Figure 2-3: CO emission Vs Water Emulsion %

In general, having an aqua proportion in the emulsion makes the emulsification process expand faster and give more force, which improves the brake thermal efficiency. Nevertheless, there is a rise in BTE values and a decrease in the portion of nitrogen oxide-based emissions, but due to the lower temperature in the combustion process, there is a rise in CO and HC emissions. It also has issues with stability. Emulsified biodiesel requires an

emulsifier system to be installed on the vehicle. It comes at an extra expense. The emulsion can alter the physical properties of the fuel; hence, emulsified biodiesel could influence the fuel injection system's performance. [38].

Jiaqiang E et al. [65] conducted an investigation on a marine diesel engine with four cylinders to assess the engine's emission and performance parameters. The engine was fueled by a water-diesel-biodiesel emulsion fuel blend. Rapeseed oil biodiesel B5 blend was used along with three different percentages (2%, 4%, and 6%) of water for the emulsion. Based on the data, it can be seen that the NOx and CO emissions decrease for the 2%, 4%, and 6% water emulsions as compared to diesel. Where CO_2 emissions increase with an increase in water percentage.

In their study, Dinesha P et al[66] examine how the combination of water emulsion and diethyl ether additives affects the performance, combustion, and emission parameters of a single-cylinder, four-stroke CI engine. The waste cooking oil biodiesel and span 80 surfactants were used to prepare the four varieties of fuel blends. 20% biodiesel, 5% water, and 3 different quantities of span 80 (2%, 4%, and 6%) were used. The data indicate a decrease in NOx, CO, and HC emissions in all the fuel blends compared to diesel fuel, where there is no major change in thermal efficiency, cylinder pressure, or heat release rate.

Z. A. Abdul Karim [67] tried to reduce the NOx and smoke emissions of a single-cylinder CI engine simultaneously. The fuel blend was prepared with 5% palm oil biodiesel, 9%, 12%, and 15% water for emulsion, and 5%, 10%, and 15% surfactant. The experiment was conducted at constant speed at various engine loading conditions. The result exhibited an 11.7% reduction in engine power for the water emulsion blends as compared to non-water emulsion blends. Furthermore, the heat release rate and cylinder pressure were higher in the case of water emulsion blends. The most significant reduction in NOx emissions was recorded in the case of 15% water emulsion, which reduces around 79% of NOx emissions and 23% of smoke opacity.

Ali Khanjani et al [68] used the waste fish oil biodiesel, diesel, and water blend in a mono-cylinder CI engine to investigate the effect of water emulsion on the performance and emission parameters. They fixed the engine speed at 1800 rpm under full loading conditions. The water content and biodiesel content in the fuel blend were kept at 1% to 7%. The surfactant used is in the range of 1-2%. The performance and emission parameters were comparable for the best fuel blend and diesel. The result exhibited a 7.86% reduction in engine power and a 9.52% rise in specific fuel; however, CO emissions were reduced by

42.86%, HC emissions were reduced by 34.02%, and NOx emissions were reduced by 25.53%.

N.S. Senthur et al [69] carried out an investigation to reduce the NOx and smoke emissions of a mono cylinder CI engine by blending eucalyptus oil, biodiesel, and water emulsion with diesel. The results revealed a 30% reduction in NOx emissions and a 32% reduction in smoke emissions, with no significant change in performance parameters.

2.2.3 Water Injection

V. Ayhan et al studied the effect of water injection inside the cylinder with a B20 fuel blend of sunflower oil, methyl ester, and diesel. A reduction in NOx emissions of 54-58% was observed, but on the other hand, rises in other emissions like CO, HC, and smoke were observed[70]. The methyl ester of residues of chicken frying oil (10%) was combined with diesel fuel (90%) and used as B-10 in the CI engine. Idris. Cesur et al. [71] injected the steam to mitigate NOx emissions values, which are generated by the use of biodiesel. At varied ratios, steam was introduced into the intake manifold. According to the study's findings, the largest reduction in NOx emissions was 13.7 percent. A. Parlak et al [72] studied the effect of steam injection at the inlet manifold for diesel-canola oil methyl ester blends as a fuel. The B10-S10 combo has been shown to reduce NOx emissions significantly. At 1200 rpm, B10-S10 reduced NOx emissions by 22%, while B20-S10 reduced NOx emissions by 18%.

Mahmoud Bady et al [73] performed the experiment to study the impact of water by injecting the water at the inlet and exhaust manifolds on the performance and emission parameters of the CI engine. An experiment was performed and the injection of 40 mg/cycle of water into both exhaust and intake manifolds done. The findings indicate that the implementation of exhaust manifold water injection enhances engine performance and combustion characteristics while also decreasing emissions in comparison to intake manifold water injection.

B. Tesfa et al [74] injected water into the inlet manifold of a four-cylinder CI engine to study the effect of water injection on emissions and performance characteristics. The rapeseed oil biodiesel-diesel fuel blend is used to power the engine. The performance and emission parameters were analyzed for three different flow rates of water injection (0, 30, and 50 cc/min). The result revealed a reduction in NOx emissions of 50% for the 50 cc/mm flow rate of water, but on the other hand, CO emissions increased by 40%. Whereas in the case of specific fuel consumption, it increases by 4%.

Christopher J. Chadwell et al [75] injected the water inside the cylinder along with the diesel from the injection nozzle and studied the effect of water on the performance and emission parameters. The author has used a six-cylinder Volvo D-12 engine. The flow rate of water injection was 0%, 10%, 20%, and 30% of the fuel injection. The experiment revealed a reduction of NOx emissions by 42% at a 30% water flow rate, but on the other hand, particle matter and specific fuel consumption increased.

K.A. Subramanian [76] experimented and compared the water emulsion and water injection into the inlet manifold technique to reduce the NOx and smoke emissions of the mono-cylinder, four-stroke CI engine. The ratio of 0.4:1 by mass has been taken for both the case water emulsion and the water injection. The result shows that in both cases, NOx reduction has been achieved, while water emulsion gives almost the same reduction as shown in Figure 2-4[76]. Whereas CO and HC emissions increased in both cases
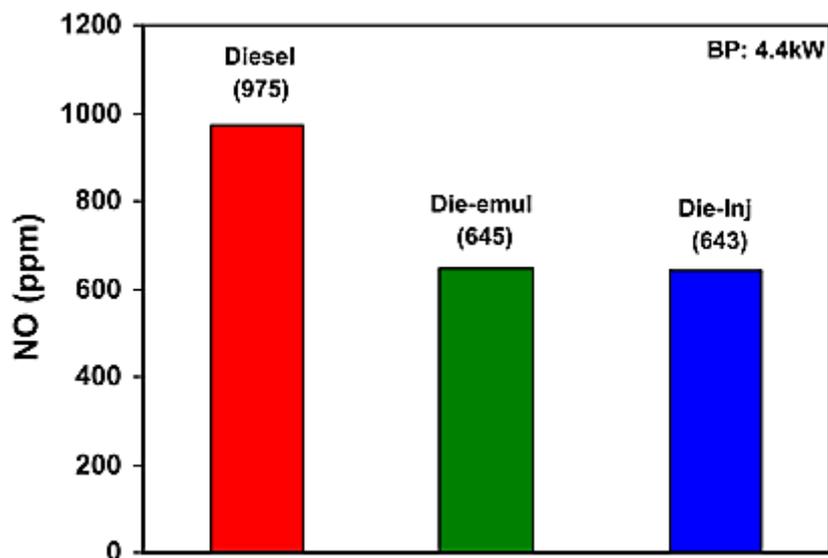

Figure 2-4: NOx emission, water emulsion Vs water injection

Water injection increased the engine's thermal efficiency by a small amount compared to water emulsion. The thermal efficiency decreased in both cases when compared with the diesel values.

Xavier Tauzia et al [43] investigated the effect of water on combustion and emission parameters in a four-cylinder CI engine by injecting water into the engine's inlet manifold. The water injection system has a Karcher K 2.01 high-pressure water pump, a pressure regulator, and a port fuel injector (PFI). Figure 2-5 shows the photograph of Spray from the PFI.

Figure 2-5: Spray photograph from the PFI injector

The water flow rate was kept at 2 to 4 times that of the fuel flow rate. Comparing the four different flow rates (100, 183.33, 316.67, and 350 cc/min), the results showed that NOx emissions went down as the water flow rate went up, as shown in Figure 2-6[43]. The graph shows a decrease in NOx emission in both cases as the dilution ratio (Dr) increases. On the other hand, particulate matter increases.
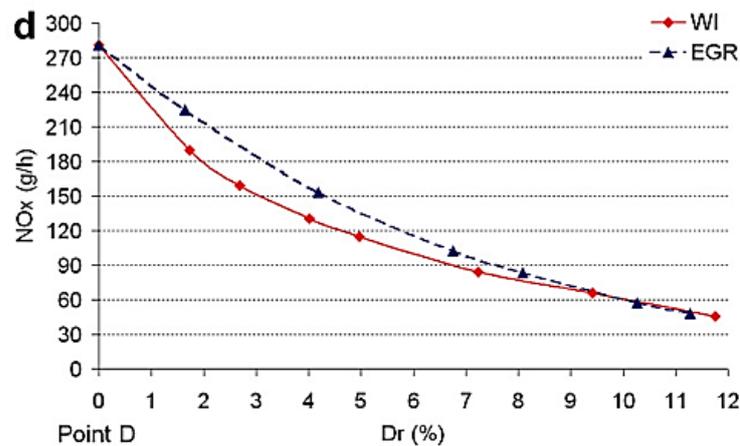

Figure 2-6: NOx Vs Dilution% for water emulsion & water injection

Guven Gonca and Bahri Sahin [77] performed test on a single-cylinder compression ignition engine by injecting steam into the engine's inlet manifold and studying the effect on performance parameters. The findings indicated a decline in thermal efficiency and a rise in specific fuel consumption, but the author did not discuss the impact on the emission parameters. Guven Gonca [78] investigates the effect of the steam on performance and emission parameters by injecting steam into the inlet manifold of the engine. The steam was injected at full load, and the results were analyzed. The result shows a reduction in NOx emissions and a rise in thermal efficiency.

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The Table 2-1 shows some of the research work done to reduce NOx emission through water and steam injection technique

Table 2-1: Effect of water injection on performance and emission parameters

Fuel Used	NOx	Other Performance and Emissions parameters	Ref.
Rapeseed oil methyl esters	↓	↑BSFC, ↑BTE, ↑CO,	[74]
Diesel	↓	↑BSFC	[75]
Diesel	↓	↑CO	[76]
Diesel	↓	↑BSFC, ↑BTE, ↑CO,	[43]
Steam Injection			
Diesel	↓	↑BSFC, ↑BTE	[77]
Ethanol-Diesel Blend	↓	↑BSFC	[78]

2.2.4 Fuel Additives

Thiyagarajan Subramanian et al. [79] studied the effect of additives on NO_X emissions using camphor oil biodiesel. The BTE increases by 31.7% as compared to diesel with the 10% diglyme (DGE) additives. Eugenol (EU) and acetone (A) are the bio-additives. Compared to diesel, we observed a reduction in NO_X emissions of 24.6% and 17.8%, respectively, with 10% EU and 10% A. On the other hand, CO and HC emissions increased.

The oxidation feature of biodiesel causes its quality to deteriorate. By adding appropriate antioxidants, we can rectify this problem and increase the fuel's oxidation stability. Natural antioxidants compensate for the shortcomings of antioxidants based on synthetic structure. The R. Senthil et al. [80] conducted the research in a test rig using jamun oil methyl ester (JOME) and adding Albizia Lebbeck (AL), a natural leaf extract. It is concluded that JOME20 at and around 1000 ppm AL reduced NOx emissions by up to 8–9% as compared to diesel. Biodiesel's oxidation stability is also observed to be greatly improved.

G. R. Kannan et al. [81] carried out an investigation on the effect of metal-based additives on emissions and performance parameters for CI engines fueled with waste cooking oil biodiesel. The experiment was conducted by adding 20 µmol/L ferric chloride additives, which decreased NO_X emissions and increased CO_2 emissions. Table 2-2 displays the researcher's efforts to decrease NOx emissions using fuel additives.

Table 2-2: effect of additives on performance and emission parameters

Biodiesel	Additive	NOx	Other Performance and Emissions parameters	Ref.
Jatropha oil	Magnesium (AL-Mg)	↓	↓BSFC, ↑BTE, ↓CO, ↓HC	[82]
	Cobalt oxide (CO$_3$O$_4$)	↓	↓BSFC, BTE (No change), CO (No change), ↓HC	
Tall oil	Magnesium (Mg)	↑	BSFC (No change), ↓CO, ↓HC	[83]
	Molybdenum (Mo)			
Mahua oil	Diethyl Ether (DEE)	↓	↑BSFC, ↓BTE,	[84]
Palm oil	BHA (butylated hydroxy anisole)	↓	↓BSFC, ↑BTE, ↑CO, ↑HC	[85]
	BHT (butylated hydroxytoluene)	↓	↓BSFC, ↑BTE, ↑CO, ↑HC	
Cottonseed oil	L-ascorbic acid	↓	↑BSFC, ↓BTE, ↓CO, ↓HC	[86]

2.2.5 Selective Catalytic Reduction (SCR)

M.Kowshik Dhev et al. [87] conducted the experiment by using the SCR technique to reduce NO$_X$ emissions. Various concentrations of urea solution, ranging from 30 to 35%, were used for the experimentation. Two different concentrations of urea, 35% and 32.5%, were injected with a titanium dioxide catalyst, resulting in a NO$_X$ emission reduction of 47.9% and 68.5%, respectively.

C. Solaimuthu et al.[88] carried out the experiment on a CI engine fueled with mahua biodiesel to reduce NO$_X$ emissions using the SCR technique. The findings indicate a 20% decrease in NO$_X$ emissions., but also got a penalty in terms of engine performance.

HongJuan Ren et al.[89] studied the SCR technique to reduce NO$_X$ emissions for the compression ignition CI engine powered by a mixture of diesel fuel and biodiesel derived from waste cooking oil. An average 75% reduction was observed for NO$_X$ emissions.

S.Sundarraj et al. [90] use the SCR technique to analyze the emission and performance parameters of a CI engine running on a jatropha biodiesel-diesel blend. The use of titanium dioxide as a catalyst resulted in a maximum 74% reduction of NO$_X$ emission at a 32.5% urea concentration.

B. Jothithirumal et al. [91] investigated the effects of various catalysts used in the SCR technique. The engine runs on a blend of neem oil biodiesel and diesel. The researcher used zinc, sulfate, NaCl, potassium, and silicate catalysts in the SCR. The results indicate

that the combination catalyst of zinc, sulfate, and NaCL achieved the highest reduction of NOX emission, at 52%. 50% of NOX emissions were observed in the case of potassium catalyst, and 20% in the case of silicate, as shown in Figure 2-7[91]. Due to back pressure and clogging problems, the OEM industry's Selective Catalytic Reduction (SCR) technique is not suitable for application in small engines[92].
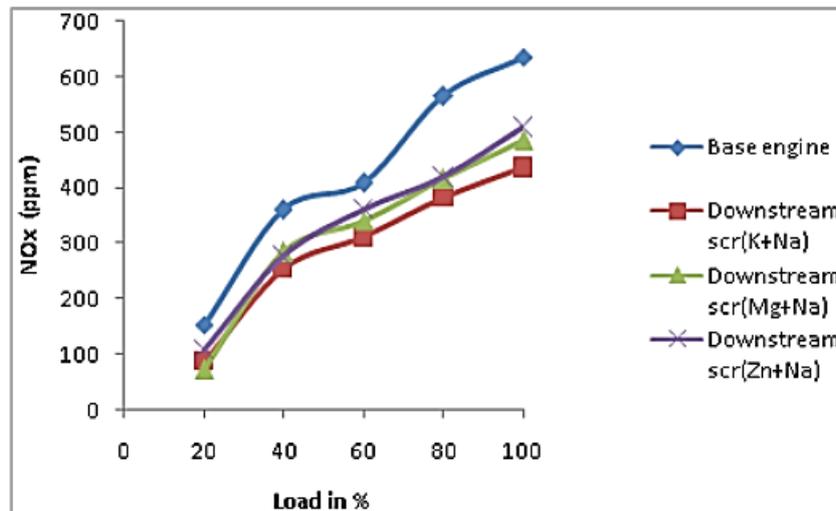

Figure 2-7: NOx Emission Vs Load for Various catalysts

There is no major change observed in thermal efficiency Whereas CO_2 emission increases with load for all kinds of catalysts.

2.2.6 Selective Non-Catalytic Reduction (SNCR)

Fewer researchers have implemented this method for diesel engines to mitigate NOX. Kemal Masera et al.[92] injected distilled water and urea water into the exhaust line at a 375 ml/min flow rate. The engine was filled with diesel-biodiesel blends prepared from waste cooking oil, chicken fat, and cottonseed biodiesel. Diesel and biodiesel reduced CO and NOX emissions by 10% and 6%, respectively.

Thiyagarajan et al. [93] injected four chemical absorbents into the downstream of the CI engine, namely monoethanolamine (MEA), diethylamine (DEA), anhydrous ammonia, and succinic acid. For all absorbents, the chemical injection flow rate was kept fixed at 1 kg/hr. The highest NOx and CO_2 emission reduction (10% and 15%) was observed in the case of diesel + MEA; however, some panellists received it in the case of fuel.

S. Vedharaj et al [94] investigate the performance and emission parameters of the CI engine coated with a thermal barrier and fueled with a B50 fuel blend of kapok methyl ester biodiesel and diesel. The coated engines improved brake thermal efficiency by 9%

compared to non-coated engines. The CO and HC emissions were recorded higher in the case of a non-coated engine as compared to diesel fuel. Furthermore, the NOx emissions decreased by 13.4% by using the urea-based SNCR system, as shown in Figure 2-8[94].

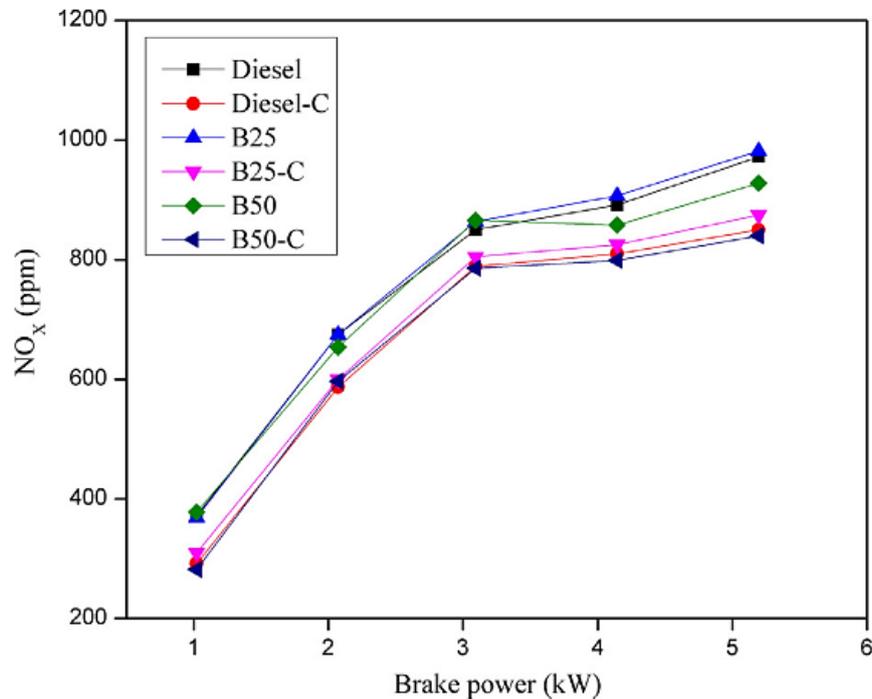Table 2-3 summarizes some of experimental investigations that utilize SNCR technology to reduce NO_X.

Figure 2-8:NOx Emission Vs Load for coated & non-coated engine

Table 2-3: Effect of SNCR Technique on NOx emission

Fuel	NO_X Reducer	NO_X	References
Diesel	Methylamine	↓ 70%	[95]
Diesel	Methylamine	↓ 80%	[96]
Furnace Coal based	NaOH	↓82.07 %	[97]
	Na_2CO_3	↓81.36%	
	CH3COONa	↓81.8%	
Furnace Coal based	HCOONa, CH_3COONa, $NaNO_3$, and Na_2CO_3	↓	[48]

2.3 Effect of Compression Ratio and Injection Pressure.

Experiments were conducted on diesel engines to study the effects of varying the compression ratio, and adjusting the injection pressure, using both diesel and biodiesel fuels. The following study presents research findings on the impact of

compression ratio and fuel injection pressure on the performance and emissions of diesel engines.

2.3.1 Effect of Compression Ratio

Some researchers investigated the effect of varying compression ratios on various IC engine parameters. Variable compression ratio is a technique for varying a diesel engine's compression ratio. It allows the dead center above the piston to modify the combustion chamber's volume.

K. Sivaramakrishnan[98] et al explored the performance and emissions of VCR engines and compared them with regular diesel when powered with Karanja blended with diesel (80-20%, 75-25%, and 70-30%). Researchers conducted experiments for CR ratios of 15:1, 16:1, 17:1, and 18:1. Researchers have investigated the impact of CR on fuel consumption, BTE, and emissions. Biodiesel-diesel performance was assessed experimentally using response surface methods. The blend's BTE increases as the CR increases. At full capacity and CR 18, B25 recorded the highest BTE of 30.47% among all blends, 5% more than diesel. Various blends showed a reduction in HC compared to diesel. As the CR increased, the specific fuel usage decreased. When compared to diesel, Karanja oil blends provide higher combustion pressures at high CR because of the ignition delay and heat release value. B25 at CR 15 provided the minimum NOx, and as the compression ratio increases, the NOx also increases.

Pali Rosha and Saroj Kumar Mohapatra [99] worked on different compression ratios on a mono-cylinder DI engine powered by a palm biodiesel (B20) blend. The author aimed to analyze the impact of different CR (18:1, 17:1, and 16:1) on various engine properties by running an engine with a 20% palm biodiesel blend. The author reported a delay in ignition duration, a rise in peak pressure in the cylinders, and an increase in brake thermal efficiency as the compression ratio increased from 16:1 to 18:1. At 3.5 bar BMEP, the brake thermal efficiency data in B20 fuel were 28.9, 30.8, and 33.8% at 16:1, 17:1, and 18:1 CRs, respectively. Furthermore, HC emissions increase with an increase in engine load and decrease with a rise in fuel blend%. The CO emission reduces to 1.4 bar bmep, then increases to the full load condition.

Raising the CR from 16:1 to 18:1 resulted in a 35.8% reduction in smoke opacity emissions. Oxides from nitrogen generation increased by 41.1%, as shown in Figure 2-9[99]. As a result, we concluded that blend B20 showed effective results for a higher compression ratio of 18. B20 at CR 16 produced the minimum NOx emission

Jatinder Kataria and S.K. Mohapatra [100] conducted an experimental study on a VCR diesel engine powered by biodiesel extracted from waste cooking oil, with heterogeneous catalyst considerations. The result revealed a rise in BTE with a rise in load. The highest thermal efficiency recorded was for B40 with CR 17.5 at full load, which is more than diesel. We observed a significant reduction in brake-specific energy consumption when using biodiesel. We observed an inverse reduction in CO and HC emissions for high CR values.
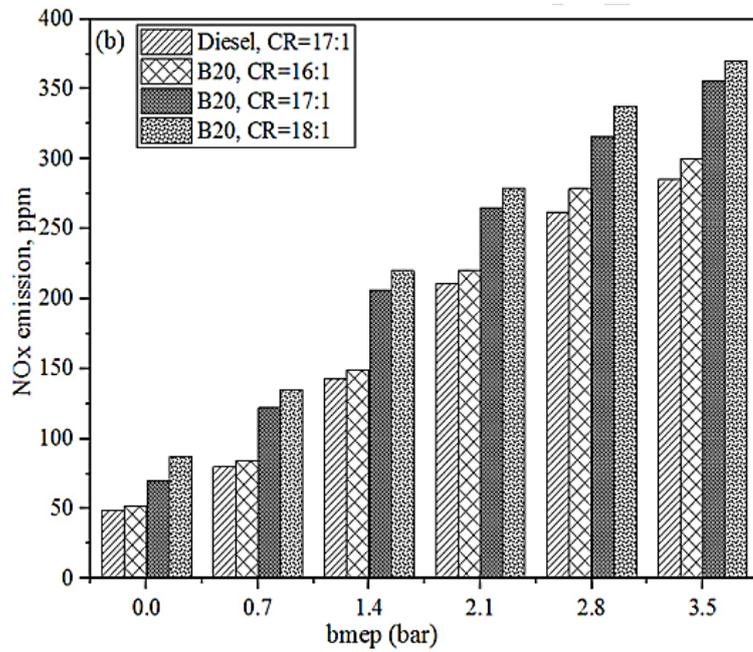

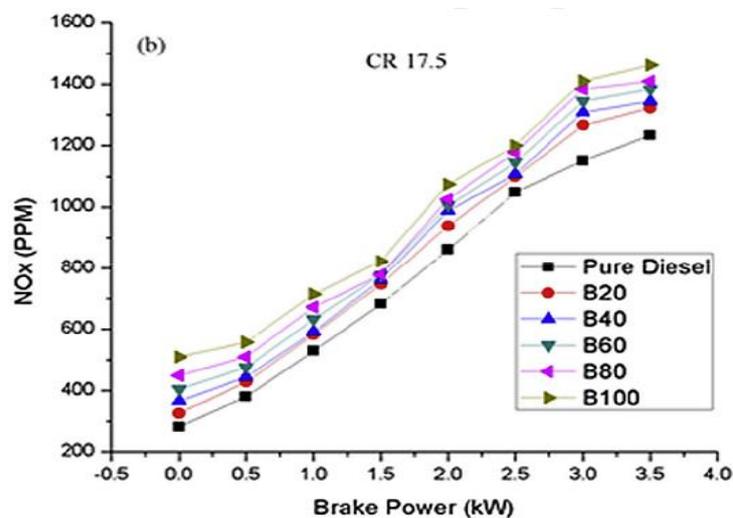Figure 2-9:NOx Vs bmep for B20 fuel blend at various CR

Figure 2-10: NOx Vs Brake Power for various Fuel Blends

Table 2-4: Effect of Compression Ratio

| Sr. No | Fuel | CR | Outcome | | Author & Year | Ref. |
			Thermal Performance	Emission		
1	Karanja biodiesel B20, B25, B30,	15,16, 17,18	BSFC, ↓ BP, BTE, CP↑	SMOKE↓ CO, HC, ↓ NO_X↑	K. Sivaramakrish nan-2017	[98]
2	PALM B20	16,17, 18	BSFC, EGT↓ ID, BP,BTE↑	SMOKE↓ CO, HC↓ NO_X↑	Rosha P, Mohapatra SK, Mahla SK Energy-2019	[99]
3	Waste cooking Oil B20, B40, B60, B80, B100	15, 17.5	BP, BTE↑ BSFC↓	SMOKE ↓ CO, HC↓ NO_X↑	Jatinder Kataria, S.K. Mohapatra-2018	[100]
4	Jojoba methyl Ester Biodiesel	18,20, 21.5, 22,23	BSFC, EGT↓ CP, BP↑ BTE↑	NO_X, ↓ CO, HC, ↓	Meshack Hawi, Ahmed Elwardany-2019	[101]
5	Biodiesel (palm oil) + fuel (methanol) BM5, BM10, BM15	16,17, 18	BSFC, EGT↓ CP, BP↑ BTE↑	SMOKE↓ CO, HC↓ NO_X↑	Y. Datta Bharadwaz, B. Govinda Rao-April-2016	[102]
6	(Jatropha biodiesel and turpentine oil) JBT50, JBT70, JBT90, JB	15.5, 17, 18.5, 20	BSFC, EGT↓ BP, BTE, ↑ CP, ↑	SMOKE, ↓ CO, HC, ↓ NO_X ↓ CO_2 ↑	Pankaj Dubey, Rajesh Gupta, Renewable energy-2017	[103]

The NOx emission increases with the rise in load of the engine and also increases as fuel blend% increases, as shown in Figure 2-10. The Table 2-4 below shows researchers' investigations into the effect of compression ratio on various CI engine parameters.

2.3.2 Effect of Injection Pressure

Many researchers conduct analytical studies for various fuel injection pressures on IC engines for various parameters.

Murat Kadir YESILYURT [104] carried out the experimental work of varying IP on a CI engine powered by waste cooking oil biodiesel (WCOB) and its 5–30% (v/v) mixing proportion in diesel fuel. Observations were analysed for 6 varieties of fuel injection pressures (170–220 bars), 11 different engine speeds (1000–3000 rpm), and full load conditions to find out the best pressure for favorable results. The study demonstrated that a diesel engine could use fuel blends without any modifications. Upon careful consideration

of all the findings, we discovered that 210 bar is the optimal fuel pressure for injection in WCOB and fuel blends.

V Channapattana and Abhay [105]A Pawar aimed to study experimentally the effect of fuel injection pressure (180-240 bar) on a single-cylinder VCR engine powered with Honne biodiesel-diesel blends . The compression ratio was set to 18 instead of the designated 17.5 CR value. The comparative performance of blended fuel in relation to diesel showed that the BSFC of Honne biodiesel is 0.042 kg/kW hour higher than that of diesel fuel at an injection pressure of 240 bar. The study shows the differences in thermal performance parameters at various IPs ranging from 180 bar to 240 bar in 30 bar incremental steps while keeping a constant CR of 18 and a full load of 12 kg.

The injection time was maintained at a constant value of 23° before top dead center (bTDC). Honne biodiesel (B100) emits the least amount of hazardous substances when compared to all other blends. Moreover, the escalation of IP leads to a corresponding surge in nitrogen oxide (NOx) emissions. As the proportion of blend grows, the emissions of NOx also increase, as demonstrated in Figure 2-11[105]. The B-20 blend provides best thermal performance compared to other Honne biodiesel blends, but it produces higher amounts of exhaust pollutants[105].

Pankaj Shrivastava and Tikendra Nath Verma experimented with B20, B40, and B100 Roselle biodiesel blends by changing the fuel injection pressure (180-260 bars) at various engine loading conditions (25-100%). The results showed that rising injection pressure deteriorates the ignition delay period, smoke emissions, and thermal efficiency. Increasing the injection pressure resulted in higher BSFC, cylinder pressure, CO_2, and oxide of nitrogen emissions. [106] Table 2-5 shows researchers' investigations into the effect of injection pressure on various CI engine parameters.
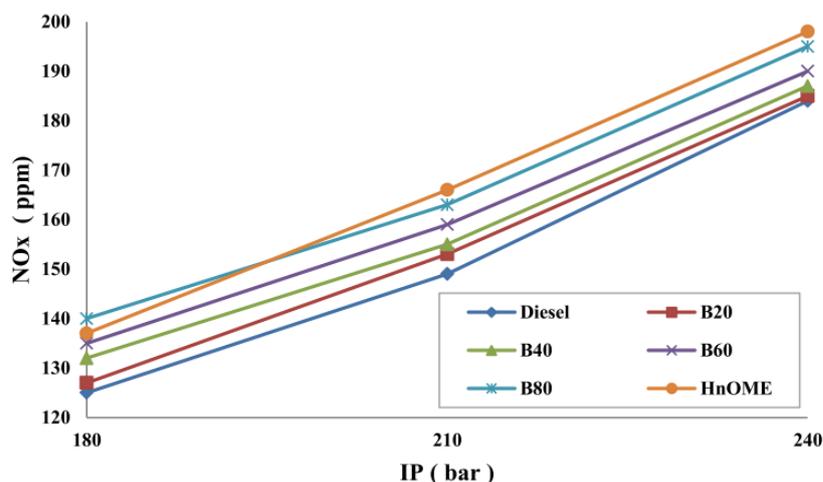

Figure 2-11: NOx Emission Vs Injection Pressure for various fuel blends

Table 2-5:Effect of Injection Pressure

Sr. No	Fuel	IP (bar)	Outcome		Author
			Thermal Performance	Emission	
1	Waste cooking Oil Biodiesel	170,180,190,200,210, 220	BSFC ↓ BP,BTE↑	SMOKE HC↓ NO_X,CO_2↑	Murat Kadir YESILYURT-2018 [104]
2	Honne Biodiesel B20, B40, B60 B80, B100	180,210, 240	ID↓ BP, BTE, ↑ BSFC, EGT↑	CO, HC↓ SMOKE↑ NO_X, CO_2↑	V Channapattana, Abhay A Pawar, -2015 [105]
3	Roselle Oil RB20, RB40, RB100	180,200, 220,240, 260	BP, BTE, ID↓ BSFC,↑ EGT, CP ↑	CO, HC↓ SMOKE NO_X, CO_2↑	PankajShrivastava, Tikendra N Verma-2020 [106]
4	Waste cooking Oil Biodiesel	220,240,260,280,300	BSFC, ID↓ BP, BTE, ↑ CP↑	CO, HC SMOKE↓ NO_X, CO_2↑	G.R. Kannan, R. Anand-2012 [107]
5	Honge Oil and its blend B10, B20, B40, B80, B100	205,220,240,260,280,	BSFC, EGT, ID↓ BP, BTE ↑ CP↑	CO, HC↓ SMOKE NO_X, CO_2↑	N R Banapurmath , P G Tewari, and R S Hosmath-2009 [108]
6	Pongamia oil methyl ester (POME20)	185,200,210,220,230	BSFC, ID↓ BP, BTE↑ CP ↑	CO, HC↓ SMOKE ↑ NO_X, CO_2↑	S.Jaichandar,K .Annamalai-2013 [109]

2.4 Summary

An extensive literature analysis has been conducted to examine the different approaches adopted for lowering NOx emissions, as well as the impact of compression ratio and fuel injection pressure on key parameters of the CI engine. The literature review's outcome is

- Fossil fuel sources are finite and decreasing day by day. Energy is the key to any country's development. In this context, renewable energy sources are the alternative to fossil fuels. India is an agriculture-based country having wide potential of renewable energy.

- Many researchers found that the CI engine powered by biodiesel and its blends gives lower CO, HC, and smoke emissions but emits higher NOx emissions as compared to fossil fuel.

- The exhaust gas recirculation technique decreases NOx emissions drastically, but on the other hand, CO, HC, and smoke emissions increase. Brake thermal efficiency decreases with an increase in EGR%, and specific fuel consumption increases. The installation of the EGR attachment incurs the cost of operation and maintenance of the same.

- The past study on water emulsion revealed that it reduces NOx emissions effectively but also reduces engine power and increases fuel consumption. The stability of a blend of water-diesel and biodiesel is critical to mitigate NOx emissions.

- Numerous researchers have conducted experimental investigations on water injection at the inlet manifold and inside the cylinder of a CI engine. This technique reduces NOx emissions remarkably but also gives a penalty in terms of brake thermal efficiency and specific fuel consumption. Increases CO and HC emissions. There has been very little research on injecting water on the downstream side of the CI engine.

- Previous studies reveal that the fuel additives effectively reduce NOx emissions, improve thermal efficiency in some cases, and increase CO and HC emissions in major cases.

- Selective-catalytic reduction is an effective NOx mitigation technique because it is a post-combustion treatment that does not disturb the engine's performance and combustion parameters, but in some cases, CO_2 emissions increase. In general, the SCR technique is more effective in power plants and large-scale furnaces because storage of ammonia is required besides the injection point. Previous studies have demonstrated the direct use of urea; however, in this scenario, the conversion of urea into ammonia requires the hydrolysis process, resulting in additional costs.

However, the back pressure and clogging issues make it less suitable for small engines.

- Many researchers have studied the selective non-catalytic reduction technique to mitigate NOx emissions. In most cases, this technique reduces the NOx emissions effectively but also increases the CO emissions. This technique works specifically for the temperature range of the emission gases. We cannot achieve the desired result if we do not inject chemicals at a suitable temperature range.

- Researchers have investigated the effect of various compression ratios on the performance and emission parameters of the CI engine fueled with diesel and biodiesel blends. According to research, NOx emissions increase as the compression ratio rises for all kinds of biodiesel-diesel blends, whereas thermal efficiency increases as the compression ratio rises.

- Many researchers have studied the effect of fuel injection pressure on the performance and emission parameters of the CI engine. The study reveals that NOx emissions decrease and thermal efficiency increases as fuel injection pressure increases.

The Limitation and effectiveness of NOx emissson mitigation technique are summaries in Table 2-6.

Table 2-6:Limitation and effectiveness of NOx emissson mitigation technique

Name of the NO_X Mitigation Technique	Effectiveness	Limitations
Exhaust Gas Recirculation	• NO_X emission can be reduced up to 30 to 50% with rise in EGR%	• Brake thermal Efficiency and other pollutants, such as carbon monoxides, hydrocarbons, and smoke, have risen with the rise in EGR%.
Water emulsion	• NO_X emission can be reduced up to 30 to 50% with rise in water%	• Reduces the engine power due to lower temperature in the combustion chamber. • There is a rise in CO, CO_2 and HC emissions as water% increases. • It also has issues with fuel stability. • Emulsified biodiesel requires an emulsifier system to be installed on the vehicle. It comes at an extra expense. • Emulsified biodiesel could influence the fuel injection system's performance.

Water Injection	• NO$_X$ emission can be reduced up to 30 to 50%	As water % increases in the fuel, • Other emissions like CO, HC, smoke and Fuel consumption increases while thermal efficiency decreases.
Fuel Additives	• NO$_X$ emission can be reduced by 10-30% • Brake thermal efficiency increases by 5-10%	• CO_2 and smoke emission increases. • Specific fuel consumption increases.
Selective Catalytic Reduction (SCR)	• NO$_X$ emission can be reduced up to 30 to 75%	• Due to back pressure and clogging problems, the Selective Catalytic Reduction (SCR) technique is not suitable for application in small engines. It is more effective in power plants and large-scale furnaces because storage of ammonia is required besides the injection point • Ammonia is toxic and flammable, and can be dangerous if it leaks. • For safety point of view, direct use of urea can be use by conversion of urea into ammonia through hydrolysis process, but this resulting in additional costs. • CO_2 emission increases with load for all kinds of catalysts.
Selective Non-Catalytic Reduction (SNCR)	• NO$_X$ emission can be reduced up to 30 to 80%	• CO emissions increases. • This technique works specifically for the temperature range of the emission gases. We cannot achieve the desired result if we do not inject chemicals at a suitable temperature range. • The exhaust system become more complex

2.5 Research Gap

Many investigators have extensively investigated the effect of water injection at the input manifold and within the cylinder to reduce NOx emissions. However, there has been limited experimental investigation into water injection at the exhaust manifold. Water injection on the downstream side is unlikely to affect the engine's performance or combustion parameters. This empirical investigation aims to examine the effect of water injection on nitrogen oxide (NOx) emissions by introducing water at the downstream of the compression-ignition engine.

2.6 Objectives

The objectives defined for the present study are as follows:

1. To prepare the biodiesel using the transesterification process.

2. To quantify the NOx for various combinations of compression ratio, injection pressure and biodiesel-diesel blends at various loading conditions on single-cylinder diesel engines fueled with diesel biodiesel blends.

3. To carry out an experiment by injecting the water at the exhaust manifold of a CI engine fueled with diesel biodiesel blends.

4. To investigate the effect of water injection on NOx emission.