

A proposed EGR technology setup to reduce NO_x emissions from biodiesel fuelled CI engines using biodiesel

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ABSTRACT

With the increase in pollution due to burning fossil fuels and soaring prices of fossil has compelled us to adopt alternative fuels which are environment friendly in nature as well as cheap to the pockets of the consumers. Biodiesel, a type of diesel fuel made of long-chain fatty acid esters produced from plants or animals, is one of the acceptable substitutes. When using biodiesel fuel in automobiles, it is blended with regular diesel fuel. Biodiesel reduces the formation of pollutants such as particulate matter, soot but it contributes to rise in nitrogen oxides (NO_x) emissions as a result of a surge in combustion chamber temperature. Increase in NO_x concentration causes breathing problem, cancer and ultimately lead to death. The area of research here includes the proposed system of exhaust gas recirculation to reduce NO_x emissions from biodiesel fuel.

Keywords: biodiesel, NO_x emissions, exhaust gas recirculation

INTRODUCTION

Diesel fuel is in high demand in agriculture, industrial, and transport sectors. With the surge in price of conventional diesel, the transportation cost also affects and with this, it also affects the economies of the consumables that reach to the common people (Abde et al., 2019; Islam et al., 2014). This price hike affects the budget of common people especially in developing economy like India.

As there is a considerable increase in automobile on roads and industries, the exhaust emissions from diesel engines such as CO_x, SO_x, nitrogen oxides (NO_x), and other pollutants such as smoke are also on rise due to which pollution is increasing and it is degrading the atmosphere. It is represented that the vehicles and industry plays a prime role in unregulated as well as regulated emissions. The emissions from exhaust engines play a significant role in climate change. In general, diesel engines play a prime role in to operate in marine and land transport.

So, one of the method to reduce the harmful emissions from diesel fuel is to blend the diesel fuel with biodiesel as use of biodiesel reduces emissions such CO_x, SO_x, particulate matter, smoke, etc. However, there is a surge in the quantity of NO_x emissions using biodiesel which can be reduced using various setups like exhaust gas recirculation (EGR), LNT, water injection, etc. (Sharma et al., 2020).

Biodiesel

An alternative fuel to regular diesel fuel, which is mostly made from vegetable or animal fats, is biodiesel. Usually, lipids like tallow (animal fat), soybean oil, or another type of vegetable oil are chemically reacted with alcohol to create methyl, ethyl, or propyl ester (Mohan et al., 2021). Because biodiesel is a drop in biofuel, it can be used with diesel engines that are currently in use. Diesel and biodiesel can be combined at various ratios or used separately. It has certain environmental advantages as compared to conventional diesel. However, there is on disadvantage that it contributes to increase in NO_x emissions (Verma & Sharma, 2015). Therefore, it becomes necessary to lessen the level of NO_x emissions coming from biodiesel to the levels of diesel combustion so that the biodiesel is universally accepted.

Biofuel produced from the oil is extracted from karanja, jatropha, mahua and animal fats. The biofuel is produced by the transesterification procedure. Vegetable oil is mixed with methanol to accomplish this procedure. A catalyst is needed in this process in order to speed up the chemical reaction between the vegetable oil and methanol. An alkaline catalyst is employed in the production of biodiesel (McCarthy et al., 2011).

Method of Biodiesel Production

Biodiesel can be produced from vegetable oils, animal fats, or used cooking oil (Kathirvelu et al., 2017) (**Figure 1**).

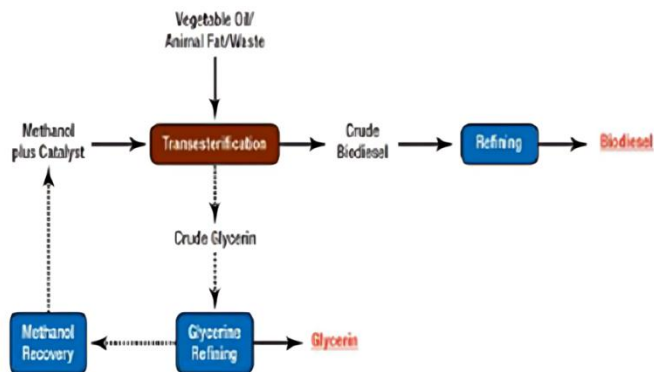


Figure 1. Diagram showing the production process of biodiesel (Source: Authors' own elaboration)

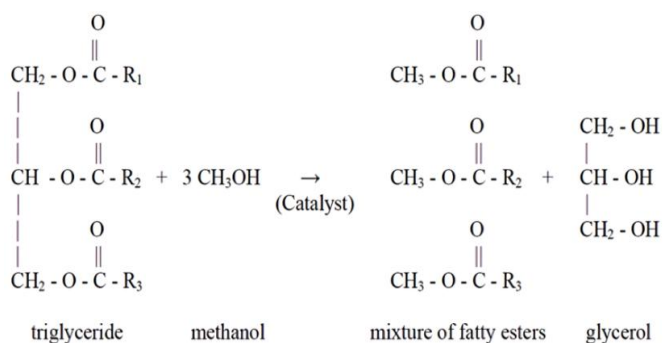


Figure 2. Biodiesel production from fats and oils (Source: Authors' own elaboration)

The fuel is produced by a process called transesterification, which converts fats and oils into biodiesel and glycerin (a byproduct). About 100 pounds of oil or fat are mixed with 10 pounds of a short-chain alcohol (usually methanol) and a catalyst (usually potassium hydroxide [KOH] or sodium hydroxide [NaOH]) to produce 100 pounds of biodiesel and 10 pounds of glycerin (or glycerol). Glycerin, some sugar, is a common co-product used in the manufacturing of pharmaceuticals and cosmetics (Kumar et al., 2021) (Figure 2).

What is NO_x

Nitric oxide (NO) and nitrogen dioxide (NO₂) are the two NO_x that are most important for air pollution, and together they are referred to as NO_x. These substances have an impact on tropospheric ozone and contribute to smog and acid rain. NO_x gases are typically created when fuels, like hydrocarbons, burn in the air. This reaction occurs notably at high temperatures, like in automobile engines. Lightning naturally also produces NO_x emissions. Excess temperature inside the combustion chamber becomes one of the key reasons for NO_x formation. NO_x is a chemical compound consisting of nitrogen and oxygen that is created when fuels like gas, oil, diesel, and organic materials burn at high temperatures and combine with one another

Mechanism of NO_x Formation

The main type of NO_x emissions from combustion is NO. At temperatures higher than 1,300 °C (2,370 °F), NO is produced in air up to the oxygen limit, or roughly 200,000 parts per million, according to the Zeldovich equations. Below 760

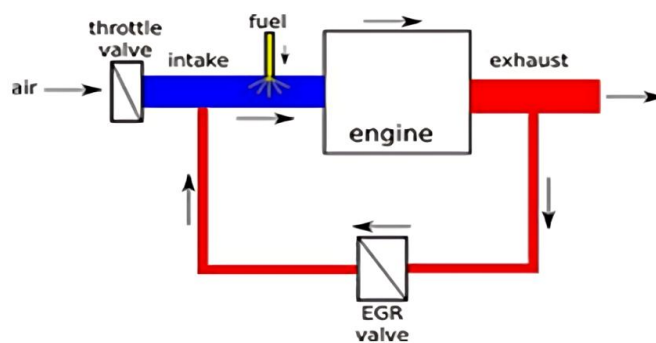
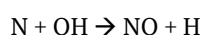
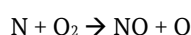
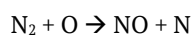


Figure 3. EGR setup (Source: Authors' own elaboration)

°C (1,400 °F), NO is either not produced at all or is produced in much smaller amounts. When the mixture is on the side of the stoichiometric ratio that is fuel-lean, combustion NO is produced more prominently and is air-fuel ratio dependent (Elkelawy et al., 2019; Islam et al., 2025).

The equations for Zeldovich are as follows:



EXHAUST GAS RECIRCULATION

Recirculating exhaust gas is an effective way to lower engine NO_x emissions. It functions by returning a certain amount of exhaust gas to the engine cylinder. Recirculated gas and incoming air are mixed to lower the peak temperature of combustion and decrease the amount of oxygen available for burning. Typically, recirculation is accomplished by connecting the exhaust manifold to the intake manifold via pipework. The circuit's control valve controls and modulates the gas flow (Shrivastava et al., 2019) (Figure 3).

Working at EGR

The major components of exhaust are carbon dioxide (CO₂), N₂, and water vapor. This exhaust gas serves as diluent when a portion of it is cycled back to the combustion cylinder. As a result, the combustion chamber's O₂ concentration is likewise decreased. Compared to fresh air, the EGR has a substantially higher specific heat. EGR lowers the temperature rise for the same heat release by increasing the intake charge's heat capacity.

EGR% can be calculated as follows:

$$EGR\% = \frac{EGR \text{ volume} \times 100}{\text{Overall charge entrance into the cylinder}} \quad (1)$$

Components of EGR system are intake manifold, EGR valve, EGR cooler cooled by engine coolant, exhaust manifold, bypass valve for the second stage cooler, and EGR cooler cooled by air.

Comparative Review of NO_x Reduction Technologies

Table 1 shows the comparative summary of NO_x reduction techniques.

Table 1. Comparative summary of NOx reduction techniques

Technique	Working principle	Typical NOx reduction	Advantages	Limitations	Applicability to biodiesel
EGR	Recirculates part of exhaust gas to reduce combustion temperature	5-25%	Simple, low cost, easy integration	Slight PM rise, minor efficiency loss	Highly suitable
LNT	Stores NOx under lean conditions and reduces under rich phase	30-70%	High conversion efficiency	Catalyst cost, sulfur poisoning	Moderate
SCR	Uses ammonia/urea to convert NOx → N ₂ + H ₂ O	70-95%	Very effective	Expensive, complex	Ideal for heavy-duty engines
Water injection/emulsification	Injects water to lower peak flame temperature	20-50%	Reduces NOx and soot	Potential corrosion and stability issues	Feasible

LITERATURE SURVEY

Islam et al. (2025) investigated that increased NOx generation during combustion is caused by greater input temperature, in-cylinder combustion temperature and advanced injection time. They proposed that by the use of combinations of algae-based biofuels resulted in fewer NOx formations when compared with pure diesel fuel and found out that the engine had a satisfactory performance.

Kumar et al. (2021) investigated that higher BSFC was obtained using blends of soybean biodiesel and solketal. Solketal being added to biodiesel results in increased emissions of CO₂ and NOx for all blends. When using soybean biodiesel and its mixes instead of pure diesel, emissions of carbon mono-oxide (CO) levels were shown to be reduced. An increase in the percentage of Solketal fuels was likewise associated with a decrease in emissions of CO and THC.

Masera and Hossain (2021) investigated that the injection of urea-water resulted in a decrease in CO and NO emissions of almost 60% and 13% for diesel fuel and approximately 45% and 15% for biodiesel fuel, respectively. CO and NO emissions were also reduced by roughly 10% and 6% for diesel fuel and by roughly 9% and 7% for biodiesel fuel.

Zare et al. (2021) demonstrated a turbocharged cummins diesel powered common rail diesel engine & biofuel derived from coconut in blending ratio of 10% & 20%. Trends of Information on engine coolant, lubricating oil, exhaust, injection time, cylinder pressure, and heat release rate was employed. In comparison to the hot operation, the cold operation's NOx, NO₂, and NO₂/NOx ratios were 31-60%, or 1.14-2.42 times and 3-8% higher, respectively.

Mohan et al. (2021) proposed the design of experiments using NOx emissions and brake thermal efficiency as response variables. Multi-objective particle swarm optimization was utilized in the development and optimization of regression equations. The ideal working conditions for highest effectiveness and lowest NOx obtained by including 10% OA, when the engine is operating at 81% load and the compression ratio is 17.5.

Sharma et al. (2020) investigated that when compared to conventional diesel, the combustion of biodiesel often results in fewer exhaust emissions of particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC). The third- and second-generation fuels were found to have somewhat higher oxides of nitrogen emissions when compared to base diesel. For any biodiesel blend, including B10 and B20, NOx emissions are higher than those of diesel fuel.

Abed et al. (2019) compared and measured the CO, CO₂, NOx, and HC emissions from exhaust with that of conventional diesel fuel. When comparing biodiesel blends B10 and B20 (Jatropha, algae, and palm) to conventional diesel, the emissions of CO, HC, CO₂, and smoke were reduced. For all blends of biodiesel B10 and B20, there is an increase in NOx emissions as compared to diesel.

Elkelawy et al. (2019) performed test on castor biodiesel fuelled in 4-stroke, single cylinder diesel engine. The results show an improvement in the rate of CO conversion of 33.8% for the D50B50 (50% diesel+ 50% biodiesel) when compared with diesel. The biggest decrease in diesel-related emissions of HC was for the D30B70 (30% diesel+ 70% biodiesel) was around 4.18%. Blends of biodiesel had increased NOx emissions when compared with diesel.

Shrivastava et al. (2019) researched on the manufacturing of biodiesel from karanja & roselle by transesterification process. The data included exhaust gas temperature, indexing thermal efficiency, maximum pressure build-up rate, ignition delay by LA20 (i.e., 20% diesel & 80% roselle), brake thermal efficiency, and ignition delay. Reductions in smoke, NOx, exhaust gas temperature, and brake thermal efficiency were observed in the KB20 (20% karanja + 80% diesel). Thus, it would seem that LA20 and KB20 are the most significant possible diesel fuel substitutes.

Prabhu et al. (2019) researched on the effect of water injection & emulsification techniques over NOx emissions in biodiesel engines. A CI engine running on biodiesel produces comparatively superior performance and lowers pollution; but it increases NO emissions. In biodiesel engines, the water injection approach can cut NOx emissions by 37-50%. As water and biodiesel are combined, the NOx content is lowered by 10-60% as compared to regular diesel.

Serrano and da Silva (2018) investigated that a CI engine powered by biodiesel produces pollution reductions and comparatively superior performance; but the emissions of NOx tends to increase. In biodiesel engines, the water injection approach can cut NOx emissions by 37-50%. The emulsification of water and biodiesel decreases the NOx to 10-60% when compared with standard diesel.

Manikandan et al. (2020) prepared and tested four fuel mixtures, i.e., in a diesel engine, pure diesel, biodiesel (MME100), or a mixture of biodiesel and carbamide (10 and 20% by volume). There is a noticeable decrease in smoke and NOx emissions when biodiesel is mixed with carbamide (MME90C10 and MME80C20) has been observed.

Table 2. Summary of past biodiesel–EGR studies

Reference	Fuel/blend	Engine	Method	NOx reduction	Findings
Palash et al. (2013)	B20 biodiesel	CI	EGR	5-25%	EGR effective at moderate rates
Manikandan et al. (2018)	MME biodiesel	Research engine	EGR + carbamide	12-20%	Smoke reduced significantly
Masera and Hossain (2021)	Biodiesel + urea	4-cycle diesel	SCR + EGR	13-45%	Combined systems most efficient
Mohan et al. (2021)	Pongamia ester	Single-cycle	EGR + optimization	18%	Optimal at 10% EGR
Present study (simulated)	B20 karanja	Single-cycle CI	EGR (10-20%)	20-25%	Balanced NOx–efficiency trade-off

Kathirvelu et al. (2017) researched that by using wasteland for the cultivation of *Jatropha* seeds from fish and fish waste have led to conservation of resources and its blending with diesel engines has led to reduction in emissions. These mixtures don't require any significant engine modifications to be used as diesel engine fuel. For both blends, NOx emissions were found to be marginally higher whereas CO, unburned HC, and PM emissions were reduced at all loads.

Nalgundwar et al. (2016) examined the functionality and emission properties of various biofuels used in fleet of locomotives used in Indian railways. Mixtures of two distinct kinds of biodiesel, specifically palm (*elaeis guineensis*) and *jatropha* (*jatropha curcas*), in a single-cylinder DI engine was assessed. An average increase of 5.3 % and 9.2% in NOx emissions were noted at lower biodiesel sample mixes, D90JB5PB5 and D80JB10PB10, respectively. The average decrease in carbon emissions were found to be 7.1%, 17.7% and 14.5% with samples with varying percentages of biodiesel (10%, 20%, and 30%).

Gharehghani et al. (2017) examined the output and comparison of parameters such as combustion, diesel fuel's performance and exhaust emissions with biofuel made with leftover fish oil. Regardless of engine load, more thermal efficiency of about 2.92% & 1.1% lower combustion loss was observed by using biodiesel. CO emissions tend to reduce around 5.2%-27% while UHC tends to reduce around 11.6%-70%. . Due to high content of oxygen in biodiesel, there has been an average increase of 7.2% in CO₂ emissions while increase in NOx emissions around 1.9% to 12.8% using biodiesel blends.

Verma and Sharma (2015) examined how biodiesel affected the emissions and performance of diesel engines. The main issue with using vegetable oil directly in engines is discovered to be its higher viscosity, which is resolved by transesterification reaction, which turns it into biodiesel. Properties of biodiesel such as cetane value, flash point, and calorific value were found comparable to that of petroleum and diesel. The majority of the time, NOx emissions is raised but HC, CO, and PM emissions are lowered, according to emission data. The optimal blend for engines was determined to be B20, which is a blend of biodiesel and diesel.

Sanli et al. (2015) investigated the effect on the DI diesel engine's performance, combustion, and emission characteristics using waste frying oil based methyl and ethyl ester biodiesel fuel. Use of ester fuel led to increase in BSFC in contrast to diesel. Ester fuels emits lesser CO and hydrocarbon emissions but they tend to produce more NOx emissions. Higher thermal efficiency was observed in ester fuel as compared to Petroleum based diesel fuel.

Islam et al. (2014) examined the performance and emissions of diesel engines with castor biodiesel which is

blend with diesel and maximum up to 40% by volume. Transesterification process based on acid based catalyst and highest yield obtained was 82.5%. During emission test, B40 (40% biodiesel and 60% diesel) emitted minimum smoke when compared with 100% diesel. To lessen the tailpipe emissions and bsfc, the blend of castor seed oil (B20) might be a good fit alternate fuel to lower the air pollution.

Palash et al. (2013) examined the effects of NOx emissions on biodiesel combustion and the methods used in CI engines to reduce them. The burning of biodiesel results in increased NOx emissions, which are determined by several important parameters like physical and chemical properties, engine load circumstances, adiabatic flame temperature, ignition lag time, and injection timing length. In order to reduce NOx emissions, low-cost methods such as exhaust gas recirculation (EGR) and delayed injection timing are also useful. EGR helps with the reduction of NOx emissions by around 5-25%.

McCarthy et al. (2011) conducted a study on emissions and performance characteristics of various mixtures of biodiesel with utilizing an internal combustion engine and petroleum diesel. They used two kinds of biodiesel:

1. **Type A:** 80% tallow and 20% methyl ester of canola oil.
2. **Type B:** 70% leftover frying oil methyl ester and 30% chicken tallow.

Overall, type A was shown to create lower emissions than type B and diesel.

It was also shown that while some greenhouse gas emissions were lower than those of petroleum diesel, others were higher. When comparing diesel fuel to both biodiesels, specific fuel consumption rises as well.

Literature Summary

Table 2 shows the summary of past biodiesel-EGR studies.

Objective and Target Area

- To make biodiesel the best alternative to conventional diesel fuel by targeting NOx emission reduction.
- To develop an EGR system which will utilize the recirculation of the exhaust gases back to the system in order to reduce the temperature inside the combustion chamber thus preventing the creation of NOx emissions.
- To analyze the impact of biodiesel on NOx emissions by using EGR technology.
- To conduct engine performance and emissions of engine using biodiesel and equipped with EGR technology.
- To lower the NOx emissions originating from biodiesel: Right now, the biggest concern using biodiesel fuel is the emissions of NOx from the engine using biodiesel

Table 3. Research phases

No	Research phase	Details
1	Phase I	Identification of problem and selection of blend of biodiesel
2	Phase II	Blending of biodiesel and emission test on engine without EGR using analyzer
3	Phase III	Design of EGR system, emission test on engine with EGR using analyzer, and comparison of results

as a fuel. The biodiesel cannot be a popular alternative to conventional diesel fuel unless NOx emissions issues are addressed properly.

- Use of EGR technology with biodiesel as fuel: To recirculate a portion of exhaust gases during the end of exhaust stroke in order to reduce the combustion chamber temperature as it is one of the biggest contributors to the NOx emissions.

METHODOLOGY

Overall research will be carried out in following phases.

Table 3 shows the research phases.

Experimental Setup and Design Parameters

The proposed system employs a single-cylinder, four-stroke, vertical, water-cooled diesel engine (5 BHP@1,500 rpm, compression ratio 16.5:1). The biodiesel blend selected is B20 (20% biodiesel + 80% diesel) derived from karanja oil.

Instrumentation

- AVL DiGas 444 analyzer (NOx, CO, HC, CO₂ measurement)
- Thermocouples (EGT and intake air temperature)
- Burette fuel flow system
- Tachometer and load cell
- Calibration: Analyzer zeroed with N₂; thermocouples verified at 100°C.
- Test cycle: Steady-state at 1500 rpm and load increments of 0-100%.
- Control variables: Injection timing fixed at 23° BTDC; ambient temperature ~25°C.

Design of an Experimental EGR System for Diesel Engine

- This experimental test setup was created with the intention of examining and illustrating the impact of different EGR rates and other engine settings on the engine's exhaust emissions (Serrano & da Silva, 2018).
- Several components of this EGR system is to be designed (Prabhu & Ramanan, 2018).
- To gauge the volumetric flow rate of intake air to the engine, an air box is used.
- It is installed on the inlet pipe between the engine's input manifold and the air filter.
- The air box attenuates the variations in the air intake.
- The air box is equipped with a hole for measuring the air's volumetric flow rate.

Design Parameters

Air box

$$U = \frac{1}{40.94 \times 10^5} \left(\frac{n_v C V N^2 n^2}{T d^4 p^2} \right), \quad (2)$$

where V is the engine swept volume, C is volume of air box, N is RPM of engine, n is the total count of cylinders, p is number of induction strokes for every crank stroke (2 in case of 4-stroke engines), T is temperature (ambient), d is diameter of the orifice, U is a design parameter that establishes how well the air box dampens out oscillations, and n_v is the engine volumetric efficiency.

Recirculation system design parameters

1. Ratio of diameter: $\beta = D2/D1$

2. Rate of flow: $W = (\rho 2Y)U2A2$

$$Y = 1 - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{12})] \frac{\Delta P}{k P_1}, \quad (3)$$

where Y is expansion factor, which is based on absolute static pressure, adjusted for changes in the fluid's density as it passed through the orifice in the pipe, $\Delta P = P1 - P2$ (pressure difference across the orifice), $k = CP/CV = \gamma$ (for the EGR = 1.4), $\beta = D2/D1$.

$$U_2 = \frac{C \sqrt{2g \Delta h}}{\sqrt{1 - \beta^4}}, \quad (4)$$

where $U2$ is EGR velocity, C is discharge coefficient, Δh is pressure differential over the orifice plate, $A2 = \alpha(\pi D2^2/4)$ is orifice area, α is area multiplier (which takes into consideration the orifice plate's thermal expansion when it comes into touch with the hot EGR), $D2$ is orifice diameter.

One such component to consider in flow is the Reynolds number.

$$R_{eD} = \frac{u_1 D_1}{\nu}. \quad (5)$$

To read the value of β , the Reynolds's number must be ascertained.

For $R_{eD} < 10,000$, β lies between 0.2 and 0.5.

Specification of proposed setup

Table 4 shows the specification of proposed setup.

Figure 4 shows the engine used in setup.

Expected Results

The optimal EGR rate is around 10-15%, offering significant NOx reduction (~20-25%) with marginal efficiency loss (~3-5%). Beyond 15%, incomplete combustion may increase PM (**Table 5**).

Table 4. Specification of proposed setup

Variable	Value
Type of engine	Diesel
Number of stroke	Four
Cylinder	One
Bore diameter (mm)	80
Length of stroke (mm)	110
Compression ratio	16.5:1
Engine capacity (CC)	553
Position of cylinder	Vertical
BHP@1,500 RPM	5

**Figure 4.** Engine used in setup (Source: Authors' own elaboration)

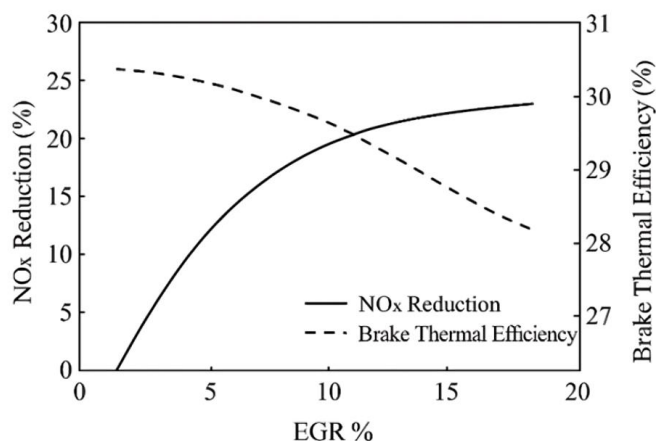
Figure 5 shows the simulation plot–EGR% (x-axis) vs. NOx reduction and BTE (dual y-axis graph).

DISCUSSION

- The simulation results are consistent with prior studies, confirming that moderate EGR rates can effectively suppress NOx by lowering in-cylinder temperature and oxygen concentration.
- However, higher EGR levels reduce the available oxygen for combustion, leading to minor efficiency losses and increased soot.

Table 5. Expected EGR performance results

EGR rate (%)	Simulated NOx (ppm)	Reduction vs. baseline (%)	Brake thermal efficiency (%)	Remarks
0	850	—	30.2	Baseline (no EGR)
5	740	12.9	29.8	Slight reduction
10	680	20.0	29.1	Optimum range
15	640	24.7	28.5	Efficiency drops slightly
20	620	27.0	27.9	Potential PM rise

**Figure 5.** Simulation Plot–EGR % (x-axis) vs. NOx reduction and BTE (dual y-axis graph) (Source: Authors' own elaboration)

- This trade-off emphasizes the importance of precise control through electronically actuated EGR valves. The incorporation of a cooled EGR circuit further enhances performance by stabilizing intake temperature.

CONCLUSION

- This study demonstrates that EGR technology can significantly mitigate NOx emissions in biodiesel-fuelled CI engines.
- Results indicate an expected 20-25% reduction in NOx at 10-15% EGR rates, with only a 3-5% decrease in brake thermal efficiency.
- EGR proves to be a cost-effective and practical approach for Indian small diesel engines operating on biodiesel blends. Future experimental validation will further optimize EGR cooling, valve actuation, and control strategies to maintain performance while ensuring compliance with European & Bharat Stage emission norms.

Future Scope

- Trials can be done using biodiesels by incorporating NOx emission reduction techniques, using cetane improvers and retarding injection timing.
- Trials can also be done by varying the injection pressures.
- Biofuel can be produced using bio catalysts.
- NOx emission reduction can also be achieved by varying the biodiesel, i.e., by using B50, B70 fuel etc.

- To reduce the combustion chamber temperature, a pilot injection of water droplets through a separate injector can be done to lower the NO_x emission.

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Ethical statement: The authors stated that the study is conceptual and simulation-based, focusing on the design and performance analysis of an exhaust gas recirculation (EGR) system for biodiesel-fuelled CI engines. Therefore, ethical committee approval and informed consent were not required for this study.

AI statement: The authors stated that generative AI tools were used solely for language editing, grammar improvement, and clarity enhancement. No AI tools were used for data generation, analysis, interpretation of results, or drawing scientific conclusions. The authors take full responsibility for the content of the manuscript.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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