Emission Mechanism and Investigation of Biofuel Combustion Characteristics at Different Techniques Towards NOx Emission Reduction: an Overview

Abdelgader Agilah Gheidan, Mazlan A. Wahid and
Anthony Chukwunonso Opia

October 6, 2021

Emission Mechanism and Investigation of Biofuel Combustion Characteristics at Different Techniques Towards NOx Emission Reduction: An Overview

Abdelgader A.S. Gheidan[1, a)], Mazlan Bin Abdul Wahid[1, b)], Anthony C. Opia[1, c)]

[1]*High-Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*

[a)] *Corresponding author:* E-mail: gheidan015@gmail.com
[b)]*mazzlan@utm.my*

Abstract. In combustion, nitrogen oxide is one of the pollutants produced especially under fossil fuels. As a result of high emissions from fossil fuels, alternative fuel sources with less or free from emissions have evolved in response to the energy demand and environmental challenges associated with fossil products. In mitigating combustion emissions, a variety of technologies have been developed, including patronizing bio-fuel and flameless combustion applications. This paper gives an overview of bio-fuel benefits and flameless combustion as a solution to fuel emissions and the concepts that underpin it. The study found that biodiesel combustion produces low NOx emissions with optimal operation conditions using additives, water injection, utilization of De NOx and application of NOx adsorbed catalyst. However, influence by some parameters such as molecular structure and biodiesel properties, adiabatic flame temperature etc were discussed. According to the findings on NOx emission mitigation methods, exhaust gas recirculation (EGR) and delayed injection timing are both reliable and low-cost techniques. Among these strategies, EGR reduces NOx emissions in bio fuelled engines by regulating oxygen intensity and combustion maximum temperature while marginally lowering HC and CO pollutants at a 5–25 % EGR rate.

INTRODUCTION

Adequate power supply, globally is considered as one of the most significant parameters for sustainable evolution both for individual countries and the world economy. In this contest, the united nation (UN) has modelled a goal with aim of providing sustainable development for all the countries of the world through clean and affordable energy [1,2]. In achieving the goal, a promising solution will be through the innovation of technologies that promote clean energy and its accessibility, thus centered on renewable energy and flameless combustion [3,4,5]. It has been reported that the constant use of fossil energy for decades has a detrimental effect on the environment, and those effects associated with fossil products have generated a serious concern for the production of renewable energy all over the globe to replace them [6,7]. Simultaneously, the idea of sustainable state growth entails ongoing and systematic attempts to strengthen the current social and economic structure[8]. As a result, the use of renewable energy can increase the share of cleaner fuels in the economy generated by advanced technologies, which would help to solve these challenges as well [8,9,10]. Currently, some countries in the world have increased their renewable energy generation [11,12], for example, Germany's renewable energy for electricity generation has increased by 40% more than coal in 2018 [7]. Also in Malaysia, the generation of energy through renewable sources especially palm oil is something of great concern to the government and researchers [13]. Take Malaysia for example, the country generates over 103 million tons of biomass, from which agricultural waste, municipal waste and forest residues are the sources. In the area of agricultural Waste, about 91 % of biomass are produced with palm oil mill residues [14]. However, according to energy analysis, biomass fuel provision capacity factor is considerably low compared to the high target placed biomass in the area of power supply, sustainability and green economy [14,15]. In this regard, the need of upgrading fossil fuel through flameless combustion stands as a lifting opportunity in maintaining and keeping the ecosystem green.

.

BIOFUEL COMBUSTION PROCESS

The use of biomass fuel product (biofuels) have gained serious concern as an alternative source of fuels for transportation and mostly in energy generation [7,16]. The essential benefit from the use of biofuels especially in mitigating emission during combustion makes the class outstanding [11,17]. Though combustion is still associated with emissions and formation of some smoke particles like fossil fuel but in micro-level compared to traditional combustion using fossil products. Butanol appears to be a promising biofuel for developing a safe, reliable, and cost-effective combustion engine [18]. It is made by the fermentation of acetone, butanol, and ethanol (ABE), with a standard ratio of 3:6:1, also known as bio-butanol [19,20]. Smoke particles produced during biofuel combustion are dominated by carbonaceous nature, comprised of elemental carbon (EC) and organic carbon (OC) fraction, with soot or black carbon (BC) in some burning [17]. In the analysis of combustion constituents, observed that (OC) consist of thousands of individual organic compounds linked with numerous physio-chemical properties. The smoke aerosol produced from biofuel during combustion supplied with some new ideas on physical and chemical properties, including high molecular weight and organic compounds of polar [17]. The areas of biofuel burning considered in this study include forest/grassland fires, crop residues burning in industries and domestic application [11,21]. According to [4,21,22,23], the block structural constituents of biofuel are hemicellulose (20-40%), cellulose/biopolymers (30-50%) and lignin's (15-30%). More so, the hemicellulose comprises sugar monomers derived from galactose, glucose, arabinose, galacturonic, mannose, xylose and methyl glucuronic acid of polysaccharides [24,17]. The component of cellulose constitutes a linear polymer mostly from glucose monomers observed to be in fibre structures [21,17]. The combustion of these biomass constituents is of different stages such as heating, development of flame and smouldering stages [17,9]. During the combustion process, at a burning temperature of volatiles, a state of flaming commences, leading to energy generation for gasification of biofuel material, continuous until combustible volatile reduces below a temperature of propagation. The smouldering stage starts when there is oxidation in the biofuel substrates as shown in Table 1. However, the particles/gas in chemical species with the formation of the smoke of large or small range depending on the nature of biofuel, condition of combustion.

TABLE 1. Combustion phases and the features of the processes [9,17]

Burning Stage		**Mechanism**	**Mechanism features**
Flamming phase	Solid state	Dehydrating mechanism	Volatile constituents are dispersed into the bulk material inner layer
		Pyrolysis mechanism	Begins at about 400 K Lower than 450 K the operation is endothermic Above 450 K the process is exothermic and decomposition occur
		Glowing burning	Begin within 800 K, with oxygen content. Leading to oxidization of char.
	Gas Phase	The Flame	The discharged volatiles turn to combustion output of less molecular weight
Smouldering phase		Smoldering mechanism	A minimum-temperature state occurs at low oxygen concentrations of about 5%

During combustion, emissions from biofuel irrespective of the little generated affect the ecosystem. The application of modified techniques in controlling the effects of the utilization of biofuel in combustion. Jose et al., [25] demonstrated the emission control from the use of vegetable oil biofuel (rapeseed oil (VRpO), one refined, sunflower oil (RSfO) and sunflower (VSfO), the measurement was done using the oil properties (C_3-Amin, C_6-Amid, C_6-Amin and C_6-Amid) thus shows the significant impact in emission control. Analysis on CO and NO emission from biofuel [25] observed that NO_x CO and CxHy concentrations are lower (fall within the accepted range) than the established limit by European legislation. Fig. 1 shows the emissions (CO, NOx and CxHy) effects and combustion characteristics for the three biofuel oils depending on the different operating states for the burner.

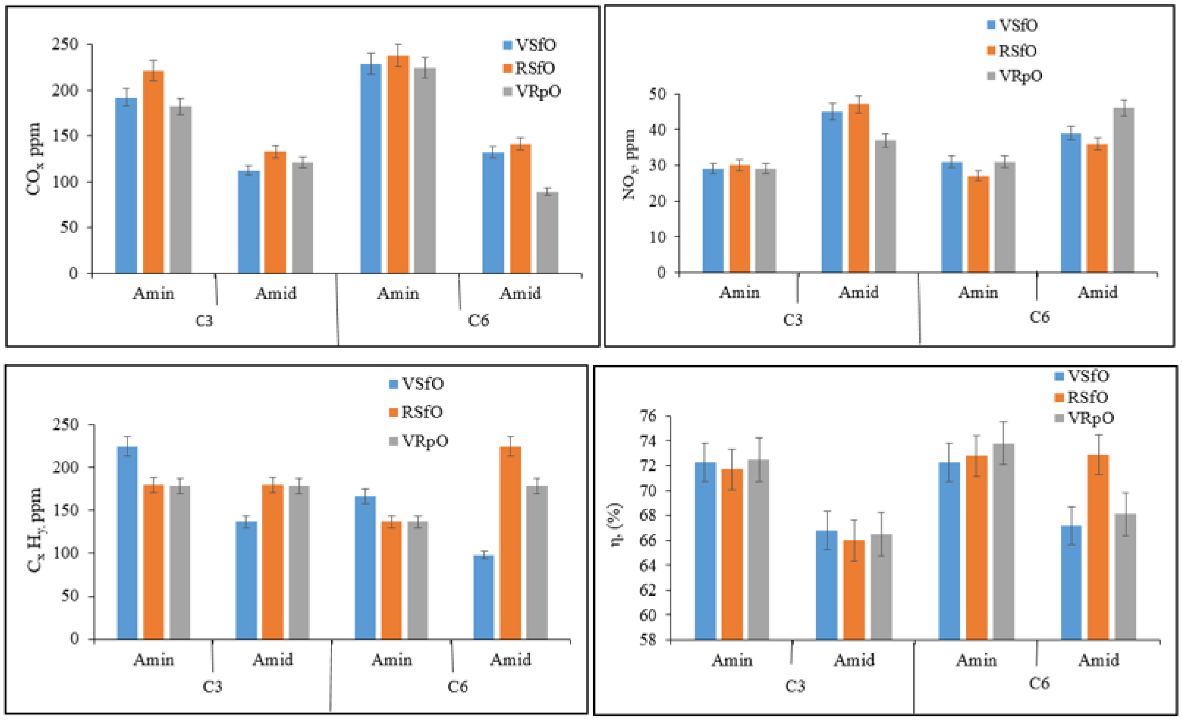

FIGURE 1. Combustion emission from various biofuels and combustion conditions (airflow and fuel flow of each Vegetable Oil) [25].

The investigation shows that CO emission increases with reduced airflow in all the biofuel used, however, NOx changes with inverse reduction when airflow was reduced. Since no organic nitrogen constituents in the biofuel and NOx component are produced from the nitrogen and oxygen in the air. Stated that as airflow increases at the combustion chamber, NOx rises. In addition, VRsfO, VSfO and VRpP, CxHy emission behaves differently [25]. In the production of biofuel, an appropriate method of producing bio-butanol using (ABE) as a biofuel is believed to be a suitable technique because it eliminates the recovery stage, saving both money and energy [18]. A minor variation in molecular structure between (ABE) and butanol does not have a major impact on important combustion properties such as thermal efficiency and combustible gases [18]. Table 2 compares the properties of various biofuel components to those of traditional petroleum-based fossil fuels. Since ABE is made at a volumetric ratio of 1:6:3, the butanol content is the most important element in its composition.

TABLE 2. Some important constituent's properties of biofuels compared to fossil towards its benefits.

Properties	**Diesel**	**Gasoline**	**Ethanol**	**Butanol**	**Acetone**	**ABE** [32]	
	[26]	[27,28]	[27,29]	[26,30]	[31]	6:3:1	3:6:1
Chemical formula	C_{12} - C_{25}	C_4 - C_{12}	C_2H_5OH	C_4H_9OH	C_3H_6O	$C_{3.2}H_{7.2}O$	$C_{3.5}H_{8.4}O$
Oxygen content (wt.%)	-	-	34.78	21.62	27.59	26.52	24.73
Lower heating value (MJ/kg)	42.70	43.40	26.80	33.10	29.60	30.37	31.42
C/H atom ratio	0.44 (n-heptane)	0.44 (octane)	0.33	0.40	0.50	0.45	0.42
Density at 288 K (g/mL)	0.82–0.86	0.77	0.795	0.81	0.79	0.80	0.80
Stoichiometric AFR	14.30	14.70	9.02	11.21	9.54	9.99	10.49
Octane number	20–30	88-99	108	96	117	109	102.7
Auto-ignition temp (°C)	>250	300	420	343	465	425	389
Viscosity at 413 K (mm^2/s)	1.90–4.10	0.49	1.08	2.63	0.35	1.11	1.79
Cetane number	40–55	0-10	5–8	25	-	-	-
Latent heat at 298 K (kJ/kg)	270	380–500	904	582	518	576	595
Solubility in water (g/L) at 25 °C	Immiscible	Immiscible	Fully miscible	73	Miscible	-	-

FORMATION OF NOX DURING COMBUSTION PROCESS

Nitric oxide (NO), nitrogen dioxides (NO) and nitrous oxide are the three main nitrogen oxides present in the atmosphere. Nitrogen oxides are constituents of contaminants and pollutants. Recent research has focused on reducing NO and general NOx emissions in combustion systems. The reaction zone is where the majority of NO is made. The subsequent oxidation to NO2 takes place away out from the combustion zone in a post-burn phase [5,33,34]. The majority of N_2O is released by combustion sources. The combustion process produces four types of NO: prompt NO (Fenimore mechanism), thermal NO (Zel'dovich mechanism), fuel NO or N_2O of fuel. The following section discusses the key characteristics of each NO formation process.

PROMPT NOX

Fenimore describes a nitrogen oxide formation process called prompt NO occurrence, which forms in fuel-rich systems[35,5]. The flame zone is where prompt NO is found, and it contains hydrocarbon species as well as nitrogen from the atmosphere. Due to the very early presence of the flame at the flame front, this NO forming process is commonly referred to as "prompt"[36,5]. The rate at which fuel and air mix determine the formation mechanism. The reactions that lead to the formation of prompt NO are as follows:

1. Cyanide formation during the reaction between nitrogen and hydrocarbon molecules (HCN).

$$CH_n + N_2 \rightarrow HCN + N \qquad (1)$$

2. Reaction between HCN hydrogen abstraction and oxy cyanogens forming ammonia radicals (NH, NH2).

$$HCN + O \rightarrow NCO + H \qquad (2)$$

$$NCO + H \rightarrow NH + CO \qquad (3)$$

3. Formation of NO from ammonia radicals.

$$NH + H \rightarrow N + H_2 \qquad (4)$$

$$N + OH \rightarrow NO + H \qquad (5)$$

THERMAL NOX

The direct oxidation of nitrogen species results in the formation of thermal NO [37,38,5]. The following are the three main reactions in the thermal NO generation mechanism:

$$N_2 + O \leftrightarrow NO + N \qquad (6)$$

$$N + O_2 \leftrightarrow NO + O \qquad (7)$$

$$N + OH \leftrightarrow NO + H \qquad (8)$$

The formed N and O through the chain propagating process are known as the Zel'dovich process [37,38], as shown in Equations (6) and (7). Temperatures above 1500 °C have a significant effect on the formation of thermal NO. Because of the high activation energy, the rate of formation raises rapidly as the temperature increases.

Nitrous oxide (N_2O)

Another form of NO, nitrous oxide (N_2O), is important for two reasons. For starters, NO, especially N_2 O, is a significant greenhouse gas that contributes to global warming [5,39]. N_2O has a global warming potential of 310 times greater than CO_2. Secondly, N_2 O is a result of the intermediate process in the formation of NO. The chemical reaction equations for N_2 O (fuel mechanism) and NOx formation are as follows.

$$O + 2N + M \leftrightarrow N_2O + M \qquad (9)$$

$$H + N_2O \leftrightarrow NO + NH \qquad (10)$$

$$O + N_2O \leftrightarrow 2NO \qquad (11)$$

FUEL NOX

Nitrogen constitutes fuels, like some liquid and solid fuels, are a popular source of fuel NO. Combustion NOx is produced by the oxidation of nitrogen in the fuel [5,36]. High oxygen concentration during fuel burning chemically bonds nitrogen to the carbon, resulting in fuel NOx. The nitrogen bound to the fuel is released as a free radical during combustion, eventually forming free N_2 or NO. The stoichiometric ratio between air and fuel determines the production of fuel NOx[40,41].

APPROACH IN REDUCING NOX EMISSION IN BIOFUEL COMBUSTION

Biofuel NOx reduction can be done in two ways; pre-combustion and post-combustion treatment approaches. To keep the ecosystem green through the use of clean fuels both biofuel and fossil products, different post and pre-combustion treatment methods have been globally adopted in modern technologies [42,43]. Application of different fuel additives, water injection, injection timing retardation, exhaust gas recirculation (EGR) and water fuel emulsion is the most use in pre-combustion treatment towards NOx emission control [43].

ADDITIVES APPLICATION

The use of different combustion additives like oxygenated fuel (methanol and ethanol), antioxidant, vegetable oil blended diesel, cetane number enhancer etc, significantly control NOx emission if used in combustion operation. According to [42,44], the application of ethanol as an additive in biodiesel reduces the formation of NOx due to the generation of low heating value. On the other hand, NOx emissions can be reduced using a cetane number enhancer by reducing ignition delay of an engine and premixed combustion, thus burn less fuel. In this condition, the combustion temperature could be reduced and suppresses the formation of NOx. The performance of cetane improvers like 2-ethylhexyl nitrate in minimising NOx formation is most effective with biodiesel. It was recorded that 2-ethylhexyl nitrate as a fuel additive can improve soy-based biodiesel to about 20% with a substantial reduction in NOx emissions. More so, additive of antioxidant through the formation of free radical including chain-breaking reaction, chelating with transition metal catalyst, scavenging radicals are capable of reducing prompt NOx. Researchers have presented that the inclusion of additives and some effective combustion catalyst yielded good combustion characteristics especially in the area of NOx reduction. Some effects from the use of additives in fuel to reduce emissions are summarized in Table 3.

TABLE 3. Some summary of some additives, fuel and results applied in combustion for NOx reduction.

References	Additive	Fuel	Engine condition	Result
[42]	Mg and Mo	TOME60	DE, DI, 1C, with variation in the speed at full load	CO decreased by 56.42% and Smoke decreased by 30.43%. Reduced NOx discharged measured.
[45]	About 20% ethanol Antioxidant p-phenylenediamin	SOME80 JME	1C, 4S, DI DE NOx↓ 1C, 4S, WC, DE, 4.4 kW power	NOx lowered by 12%, CO lowered by 16.67%, CO_2 reduced by 18.75%, SO_2 lowered by52% NOx lowered by 43.55% while increase on CO & HC obtained against to pure Biodiesel
[46]	1% of ODA	POME20	IDI,4C, 50 N/m load @ 2250 rpm	NOx lowered by 22.69%, CO and HC decreased
[44]	BE-1 5% diethyl ether blended B25 BE-2 5% ethanol with B25	B30	4S, 1C, DI engine DE at speed of 2000 r/min	NOx decreasing rate increased to lower (BE-1› B30› BE-2)
[47]	Mn and Ni	TOME60	Pure DI DE at full load	Decrease in NOx for (TOME60Ni › TOME60Mn), CO minimised to about 64.28%, Smoke lowered to about 30.91%.

Note: in this study, ODA = octylated diphenylamine ant oxide, DI = direct injection, DGMBE = diethylene glycol mono butyl ether, DGMME = diethylene glycol mono methyl ether, DE = diesel engine.

APPLICATION OF WATER INJECTION (WI) TECHNIQUE

WI into the burning chamber is another promising approach to reducing NOx emission during internal combustion. This approach uses two techniques; direct water injection to the combustor and inlet water injection [48,49]. Investigation on the impact of water injection and both water-fuel emulsion into combustion manifold on mitigating NOx emission, using a heavy-duty engine. This is done by changing the amount of injection water. The result from the investigation shows that NOx emission reduction by water-fuel was better compared to water injection, however, the two approaches yielded effective reduction compared to conventional diesel engine burning[48]. Tesfa et al.,[50,51] studied the effect of water injection on the emission of NOx and the performance of the internal combustion engine of direct injection. water injection reduces NOx emissions by around 50% while increasing CO emissions by about 40% [50]. NO emissions dropped dramatically at full load, from 1034 parts per million with base diesel to 645 parts per million with emulsion and 643 parts per million with injection. However, at component loads, injection reduces NO emissions less than emulsion. compared to the base diesel, smoke emissions are less with the emulsion (2.7 BSU) than that of water injection (3.2 BSU) (3.6 BSU). Compared to the emulsion, CO is lower with the water injection at low loads as shown in Fig. 2 (a) [51]. However, at high loads, it behaves similarly to the water–diesel emulsion. Owing, due to incomplete combustion and the use of richer mixtures, as well as less brake thermal efficiency, it is still higher than base diesel values. The explanation for this is still unknown. It has been recorded in the literature that at water to diesel ratio of 0.6:1, HC levels begin to decrease as opposed to 0.5:1, 0.4:1 and 0.3:1[51]. However, the use of emulsion is more efficient in reducing NO levels at given water to diesel ratio, as shown in Fig. 2 (b). When the injected amount of water is high, water injection often results in a substantial reduction in NO levels at high outputs [5,51]. As a result, it can be discovered that water close to the fuel is more efficient in regulating NO levels than water distributed evenly across the cylinder. Since both of the methods compared here are primarily used to monitor NO emission at high outputs, they appear to be equally accurate, as shown in Fig. 3 (a, b). NO emissions fell from 975 ppm with base diesel to 645 ppm with emulsion and 643 ppm with injection.

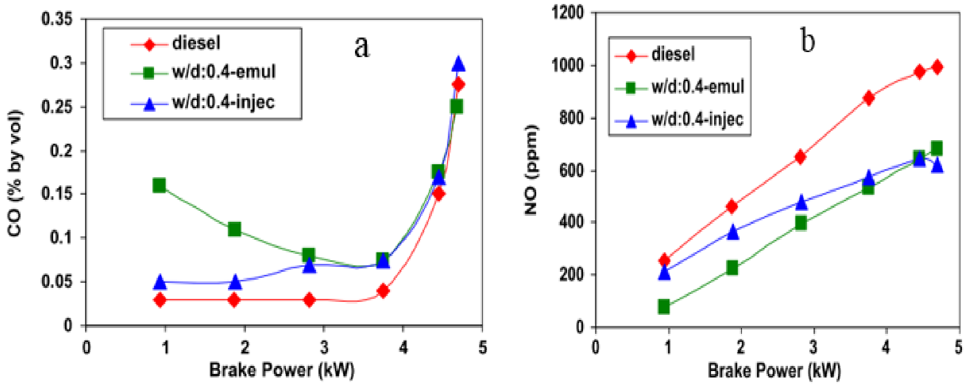

FIGURE 2. Result of CO emission (a), and NO emission applying injection and emulsion [51].

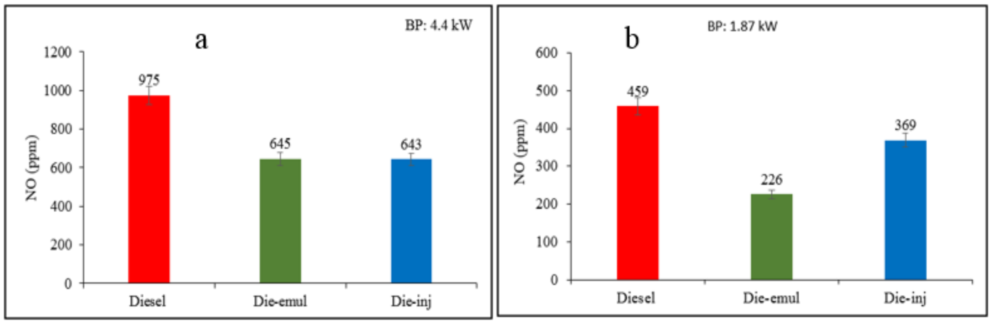

FIGURE 3. Result of NO emission using injection and emulsion at high load (a), and low 40% load (b)[51].

The analysis concluded that using diesel or water injection through inlet manifold provide less control on emission with the high release of heat ie has no effect on premixed combustion temperature been the key factor on NOx emissions [51]. A current investigation on the effect of different water injection timing towards emission variables and performance under hydrogen fuel in the compression engine was performed [52]. In the study, the technique uses injection from 20° before top dead centre to 20° after top dead centre for injection range of 40° crank angle (CA) and 20°CA. The result yielded the lowest NOx emission at underwater injection timing with a duration of 40° CA, however, produced high SO_2 and O_2 emissions.

INJECTION TIMING RETARDATION (IT)

Emissions from combustion can be reduced through injection timing retardation [53,54,55]. the presentation shows that emissions from 4-stroke and 2-stroke engines can control by injection timing retardation by placing the timing on 1-4,[56]. Also, Choi et al., [57] reported that both split injection and retardation minimizes premixed combustion thus exhibits excellent performance on NOx reduction, also that biodiesel produces low NOx emissions than fossil diesel with retardation in the timing. Observed that at high loads, oxygenated fuels had a major beneficial impact on reducing soot emissions with no impact on NOx emissions. Exhaust emissions on SOI retarding and advancing was conducted using a diesel engine with COME mixed [58]. The result reported that advancing the SOI produced the best outcome on CO and smoke for B100 while retardation mode on SOI yielded recommended results on CO_2 and NOx emissions under the fuel of B100 and B0 [59]. Since late combustion means a reduction in effective pressure, delaying SOI timing reduces NOx emissions [58]. Recently, Ye et al. [60] discovered that delaying the (IT) reduced NOx emissions for SME40 fuelled engines, while increasing injection pressure (IP) increased them, as seen in Fig. 4. Except for Mani and Nagarajan's presented some experimental findings was on the effect of delaying SOI timing are shown in Table 4.

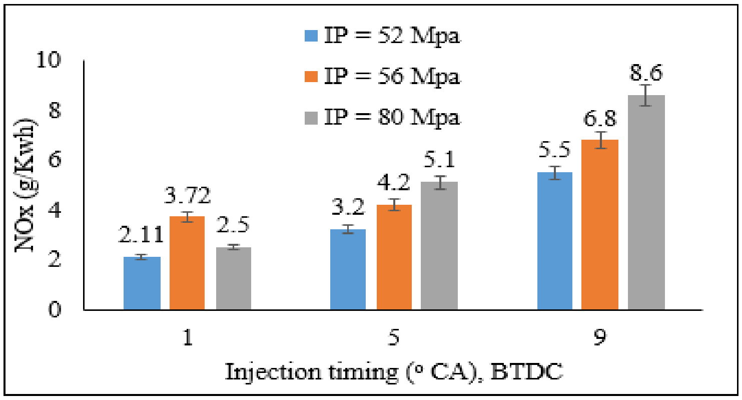

FIGURE 4. NOx discharge from different pressure at 25% load and injection timing using SME40 fuel [60]

TABLE 4. NOx emission results from retard injection timing on diesel and biodiesel fuel against original injection timing.

Ref	Engine model and type	Fuel type	SOI timing Fuel retard	NOx emissions	CO emissions	HC emissions
[61]	T/C LHR, TC, 6C, DI. Ford 6.0	Diesel	(2-4^{o} C) ORG 20^{o} CA BTDC	Lowered by 11%	-	-
[54]	Diesel engine	Pongamia oil methyl ester (PME)	SOI timing retard from original (ORG)	↓	↓	↓
[62]	E6-MS/128/76, 1C Ricardo	Diesel	4 ^{0}CA from ORG 38 ^{0}CA BTDC	Lowered by 40 %	-	-
[63]	MAN Diesel 2566, 4S, 6C, WC	ROME100 against diesel fuel	4 ^{0}CA ORG 23^{o} CA BTDC	Lowered by 25 %	Lowered by 25 %	Lowered by 30 %

APPLICATION OF NOX ADSORBENT CATALYST (NAC)

The NAC, also known as the lean-NOx trap method, is one of the most important NOx reduction techniques. That could be used by a variety of manufacturers in diesel engines and lean-burn fuel to minimize NOx formation [64]. The NOx adsorbed method works by storing NOx by the catalyst during periods of lean operation and then releasing it during periods of rich operation [65]. During this operation, incomplete combustion hydrocarbons react with NOx emissions to minimize them. An oxidation catalyst is used in a NAC system to convert all NO to NO_2, further stuck by inorganic material like barium oxide (BaO). Ultra-low sulfur diesel (ULSD) absorbent is now needed to increase the efficiency and reliability of new diesel emissions process mitigation [64,60]. Tatur et al.[66] used a NAC device to test the effects of biodiesel on a US light-duty tier 2 engine and pollution control. In a rich engine burning state, nitrate turns unstable, causing the stored NO_2 to be released. Because of the formation of sulphur compounds into stable sulphates, as well as NOx absorbent materials, NAC systems are extremely sensitive to a sulfur constituent, which gradually reduces the catalyst's efficiency.

UTILIZATION OF CATALYST OF DE NOX (LEAN NOX)

Lean NOx" catalysts application is another effective approach to NOx reduction. These work on the same principle as SCR, but instead of using an ammonia solution, it employs hydrocarbons as the NOx reductant [67]. The NOx to N_2 conversion reaction using Lean NOx catalysts is shown in Eq (12).

$$HC + NO_X \rightarrow N_2 + CO_2 + H_2O \quad (12)$$

There are two types of De NOx catalysts: active and passive De NOx. The capability of passive operation is restricted depending on the precise condition of the mechanism and lower content of HC in the exhaust, although they are quick, effective, and low cost. Enrichment of flue gases with supplementary HC content, on the other hand, has been proposed as a solution to this issue [67,68]. Such a condition could be accomplished using one of the two techniques: injection of HC, usually diesel fuel. The problem of a passive DeNOx system can be solved by using catalysts with HC enrichment. Catalysts that transform a large fraction of NOx to N_2O, a potent greenhouse gas, are known as DeNOx or "Lean NOx" catalysts.

THE USE OF SELECTIVE NON-CATALYTIC REDUCTION (SNCR)

Another technique is SNCR, which provides a significant reduction in NOx discharge. In the absence of any catalyst, a reducing agent, like ammonia, is injected into the exhaust section at about of temperature 760-870 ^{O}C. It is possible to reduce NOx emissions to about 70% [36]. According to Krahl et al.[69], investigated the inclusion of amine products in both traditional diesel and biodiesel fuels up to high concentrations (2–4%). The exhaust NOx gases are broken down into atmospheric nitrogen and water by the included ammonia. Fig. 5. depicts the process of reducing NOx after treatment with an SNCR device. But because of amine solubility and excessive cost, NOx mitigation techniques like SNCR have some commercial limitations.

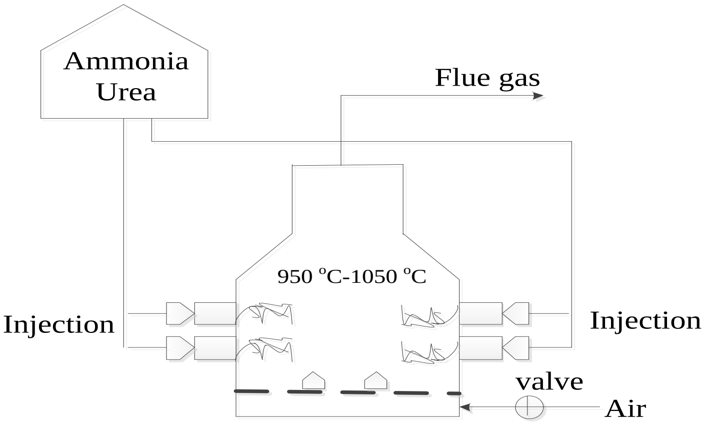

FIGURE 5. Schematic description of selective non-catalytic reduction (SNCR) process [36].

EXHAUST GAS RECIRCULATION (EGR) METHOD

EGR is a post method, commonly applied in reducing NOx emissions from diesel engines through regulating the amount of oxygen as well as combustion burning peak temperature [70,71]. The process of (EGR) reduces the temperature of the burning gas, done with free impact on dilution together with the inert gases, such as carbon dioxide and H_2O [72,73]. Some researchers [74–77] have studied the impact of (EGR) on biodiesel, fossil diesel, and gasoline-fueled engine, demonstrating the efficacy of the EGR process as an emission control technology. The impact of (EGR) on engine efficiency and emissions while using RME and ULSD blended fuels in a diesel engine was conducted [78]. The result discovered that using 20% (EGR) was more successful, achieving a reduction of about 10% and 30% for B50 and B100, respectively, at 4.5 bar IMEP, for 3°crank angle (CA) reduction in injection timing (IT). Nevertheless, around 6.1 bar, the IMEP NOx decline was around 20% for both B50 and B100, with no discernible impact on fuel consumption or engine efficiency. As compared to neat diesel combustion without (EGR), a drastic reduction in NOx to about 41.4–65.2 % was obtained around 12–20 % (EGR) rate with declining CO_2, HC and smoke. Table 5 shows the NOx emissions reduction results of various biodiesel blended fuels using the (EGR) process.

TABLE. 5 Summary of some (EGR) operations during fuel combustion

EGR condition	Engine utilized	Fuel type	Results	Explanation	Ref.
10% EGR rate	4C, WC, TC, IDI diesel	Biodiesel 20% JME	NOx decreased by 36%, Smoke reduced by 31%	Small impact on engine efficiency on EGR rate of 5–15%,	[70]
Maximum EGR rate 12 % at FL	2C,4S, WC, DI diesel engine	JOME	NOx decreased by 33% while brake specific fuel consumption (BSFC) increased by 11%	Decrease on the maximum cylinder temperature due to decrease in O_2 density	[79]
Cold start OEV (0,50,100).	1C, DI diesel engine	Diesel	NOx decreased by 60% at 100% OCV.	Stable combustion with Low-pressure fluctuation	[74]
20% EGR at 80% engine capacity	1C, vertical, 4S, HCCI diesel engine	Diesel	NOx reduction by 41.4%, smoke decreases by 8.3%, while CO_2 decreased by 29.1%	Lowering of the combustion peak	[80]

Emissions are greatly reduced with combustion efficiency improved through flameless combustion [81,82]. Compared to traditional combustion, flameless combustion has several advantages. Flameless burning is distinguished by transient temperature uniformity, but arises from the distributed reaction zone and is followed by a slight increase in temperature as a result of the mixture of combustion air or fuel with exhaust gases [81,82]. The most striking feature of flameless combustion has been its nature, which could be seen once there is a low concentration of oxygen in the air (less than 5 %)[83]. The appearance of such flame is determined not only by the diluents but transitional species, as well as by the chemical features of the fuel [5,36,41]. Fuel was fully consumed without a visible flame in a 1989 experiment when the heating rate was 1000 °C and the preheated burning air was about 650°C [5,83]. These results demonstrated that the combustion system is stable and smooth, with low NO emissions, low noise, and low CO content in the exhaust (<1 ppm) [5,84]. liquefied petroleum and Propane gas flames were green under low oxygen levels and high air preheat temperatures; however, methane flames were not green under any conditions [85]. Kumar Et al.[86] conducted a search on the influence of (EGR) on combustion performance used fuel of diesel blended with pentanol and compared to pure diesel. The study observed that smoke quality rises with increasing engine load and reaches a peak at high engine loads [86,58]. This is because, at high engine loads, more fuel is burned to achieve higher power output. When compared to diesel fuel, smoke levels are lower with all n-pentanol/diesel blends. Explaining the good performance of blended diesel, could be from the oxygen atoms cleaved with the hydroxyl group of n-pentanol reduce soot formation, inhibiting smoke pre-cursors, resulting in low smoke from pentanol blended diesel [87]. Fig. 6 (a) and (b) display the effects of different EGR percentages on smoke quality for all pentanol/diesel blends at medium and high loads, respectively. As compared to diesel fuel, smoke emissions for all pentanol/diesel blends remained low at any given EGR rate and both loads.

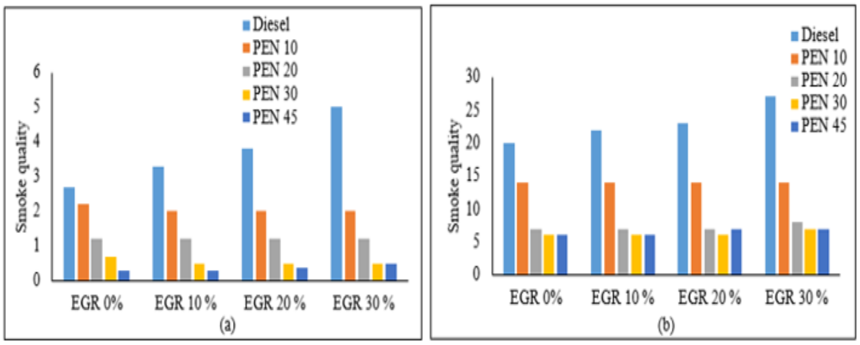

FIGURE 6. Effects of different EGR percentages on smoke quality from pentanol/diesel blends at medium (a) and high (b) loads, respectively [86].

The trade-off between NOx emissions and smoke opacity for 45% pentanol/diesel blends at high load conditions under various EGR rates is shown in Fig.7. Since the units of smoke and NOx emissions is different, the trade-off can be best expressed by normalizing the values to dimensionless numbers [86]. The trade-off relationship between smoke and NOx occurs between 20% and 30% EGR rates as clearly described (Fig. 7).

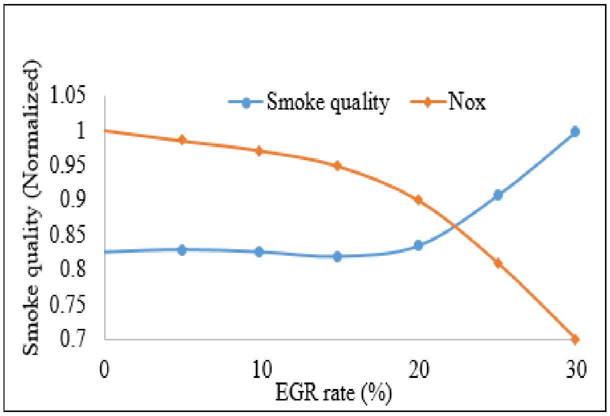

FIGURE 7. Behavior of smoke and NOx emissions under application of EGR at high load with 45PEN [86]

CONCLUSION

Biodiesel, which is made from renewable and mostly domestic sources, is a more sustainable option and hence will play a larger role in addressing energy consumption in the future as fossil fuel yielded high NOx emissions. Other techniques discussed can save as a promising way of minimizing emissions from fossil fuels. Biodiesel, which is made from renewable and mostly biomaterials, is a more sustainable option and hence will play a larger role in addressing energy consumption in the future. Notwithstanding, the following conclusions can be made from this article's review of relevant literature:

1 In general, thermal NOx dominates combustion processes; however, prompt NOx plays an important role in biodiesel combustion as well. Since biodiesel has a high cetane number, it has a shorter ignition delay and produces fewer NOx emissions. However, increased NOx emissions are caused by higher combustion temperatures achieved during the combustion phase as a result of advanced combustion timing and a longer residence duration. The oxygen concentration in biodiesel fuel causes more heat to be released during premixed phase combustion, which is the primary cause of increased NOx emissions. However, few researchers, have found that oxygenated fuels emit less NOx.

2 High adiabatic heating rate may be one of the causes of biodiesel NOx pollution, but it isn't the only one. With rising engine load, biodiesel produces higher NOx emissions and vice versa. The simultaneous addition of a small amount of H_2 into the combustor via the engine intake will minimize NOx and smoke emissions.

3 Owing to higher density, high bulk modulus of compressibility, and other factors, biodiesel injection timing is improved compared to neat diesel fuel, resulting in higher NOx emissions. NOx emissions can be decreased by 8.2–40% using the delayed injection timing approach compared to the initial injection timing, but in most situations, this technology increases CO and HC emissions, as well as BSFC emissions.

4 The application of additives to biodiesel substantially lowers NOx emissions by enhancing chemical composition such as viscosity, density, and so on. Nevertheless, this raises the cost of engine operation and reduces the engine's reliability. On diesel and biodiesel-fuelled vehicles, the water injection approach minimizes NOx levels by up to 50%. Notwithstanding, by lowering the premixed combustion temperature, it increased CO and BSFC marginally while decreasing BTE.

5 Another approach with great potential for lowering NOx emissions is EGR. At a 5–25 % EGR rate, biodiesel lowers NOx emissions by less than 25–75 %. It also reduces HC and CO emissions marginally while increasing BSFC and smoke emissions slightly.

Nomenclature

ABE	Acetone butanol and ethanol
BC	Black Carbon
B100	Neat (100%) biodiesel
BSFC	Brake specific fuel consumption
BSU	Bosch smoke unit
BTDC	Before top dead center
CO	Carbon monoxide
CO_2	Carbon dioxide
COME	Corn oil methyl ester
CME	Canola oil methyl ester
EC	Elemental Carbon
EGR	Exhaust gas recirculation
NAC	NOx adsorbent catalyst
OC	Organic Carbon
RME	Rapeseed methyl ester.
RsFO	Refined sunflower oil
SOI	Start of injection
SNCR	Selective non-catalytic reduction
VRpO	Vegetable rapeseed oil
VsFO	Vegetable sunflower oi
ULSD	Ultra-low sulphur diesel
WI	Water injection

REFERENCE

1. United Nations, “The adoption of the kyoto protocol of t he united nations framework convention on climate change,” (1998).
2. F. Cherubini, “The biorefinery concept: Using biomass instead of oil for producing energy and chemicals,” *Energy Convers. Manag.*, 51 (7) 1412–1421 (2010).
3. M. Balat, M. Balat, E. Kirtay, and H. Balat, “Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: Pyrolysis systems,” *Energy Convers. Manag.*, 50 (12) 3147–3157, (2009).
4. S. Rezania, M. Ponraj, M. F. M. Din, A. R. Songip, F. M. Sairan, and S. Chelliapan, “The diverse applications of water hyacinth with main focus on sustainable energy and production for new era: An overview,” *Renew. Sustain. Energy Rev.*, 41 943–954 (2015).
5. A. A. Abuelnuor, M. A. Wahid, H. A. Mohammed, and A. Saat, “Flameless combustion role in the mitigation of NOx emission : a review,” *Int. J. ENERGY Res.*, 38 (X) 827–846 (2014).
6. S. E. Hosseini, M. A. Wahid, and A. A. A. Abuelnuor, “Biogas Flameless Combustion : A Review,” *Appl. Mech. Mater.*, 388 273–279 (2013).doi: 10.4028/www.scientific.net/AMM.388.273.
7. V. S. Sikarwar, M. Zhao, P. S. Fennell, N. Shah, and E. J. Anthony, “Progress in biofuel production from gasification,” *Prog. Energy Combust. Sci.*, 61 189–248 (2017).
8. Raphael Slade et al., “Energy from biomass: the size of the global resource,” (11) 1- 20 (2011).
9. S. V. Vassilev, D. Baxter, and C. G. Vassileva, “An overview of the behaviour of biomass during combustion: Part I. Phase-mineral transformations of organic and inorganic matter,” *Fuel*, 112 391–449 (2013).
10. S. V. Vassilev, D. Baxter, L. K. Andersen, and C. G. Vassileva, “An overview of the composition and application of biomass ash.: Part 2. Potential utilisation, technological and ecological advantages and challenges,” *Fuel*, 105 19–39, (2013).
11. N. L. Panwar, S. C. Kaushik, and S. Kothari, “Role of renewable energy sources in environmental protection: A review,” *Renew. Sustain. Energy Rev.*, 15 (3) 1513–1524 (2011).
12. S. E. Hosseini and M. A. Wahid, “Development of biogas combustion in combined heat and power generation,” *Renew. Sustain. Energy Rev.*, 40 868–875 (2014).

13. S. E. Hosseini and M. A. Wahid, “Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia,” *Renew. Sustain. Energy Rev.*, 19 454–462 (2013).
14. S. E. Hosseini and M. A. Wahid, “Necessity of biodiesel utilization as a source of renewable energy in Malaysia,” *Renew. Sustain. Energy Rev.*, 16 (8) 5732–5740 (2012).
15. S. E. Hosseini, M. A. Wahid, and N. Aghili, “The scenario of greenhouse gases reduction in Malaysia,” *Renew. Sustain. Energy Rev.*, 28 (12) 400–409 (2013).
16. I. I. Enagi and Z. A. Zainal, “Liquid biofuels utilization for gas turbines : A review,” Sustain. Energy Rev, 90 (4) 43–55 (2018).
17. C.-Y. Chan, G. Engling, X. Sang, and T. Zhang, “Biofuel Combustion Emissions - Chemical and Physical Smoke Properties,” in *Environmental Impact of Biofuels*, 1–24 (2011).
18. I. Veza, M. F. M. Said, and Z. A. Latiff, “Progress of acetone-butanol-ethanol (ABE) as biofuel in gasoline and diesel engine: A review,” *Fuel Process. Technol.*, 196 (5) 106179 (2019).
19. S. van Wyk, A. G. J. van der Ham, and S. R. A. Kersten, “Pervaporative separation and intensification of downstream recovery of acetone-butanol-ethanol (ABE),” *Chem. Eng. Process. - Process Intensif.*, 130 (11) 148–159 (2018).
20. S. Niglio, A. Marzocchella, and L. Rehmann, “Clostridial conversion of corn syrup to Acetone-Butanol-Ethanol (ABE) via batch and fed-batch fermentation,” *Heliyon*, 5 (3) e01401 (2019).
21. A. C. Opia, M. K. B. A. Hamid, S. Syahrullail, A. B. A. Rahim, and C. A. N. Johnson, “Biomass as a potential source of sustainable fuel, chemical and tribological materials – Overview,” *Mater. Today Proc.* (x) 1–7 (2020).
22. B. Joffres, D. Laurenti, N. Charon, A. Daudin, A. Quignard, and C. Geantet, “Thermochemical Conversion of Lignin for Fuels and Chemicals: A Review,” *Oil Gas Sci. Technol.*, 68 (4) 753–763, (2013).
23. N. E. A. El-Naggar, S. Deraz, and A. Khalil, “Bioethanol production from lignocellulosic feedstocks based on enzymatic hydrolysis: Current status and recent developments,” *Biotechnology*, 13 (1) 1–21 (2014).
24. R. S. Varma, “Biomass-Derived Renewable Carbonaceous Materials for Sustainable Chemical and Environmental Applications,” *ACS Sustain. Chem. Eng.* 7 (7) 6458–6470 (2019).
25. J. S. José, Y. Arroyo, and M. A. Sanz-Tejedor, “Descriptive statistical analysis of vegetable oil combustion in a commercial burner to establish optimal operating conditions,” *Energies*, 12 (12) 1–11 (2019).
26. O. Doğan, “The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions,” *Fuel* 90 (7) 2467–2472 (2011).
27. L. A. Graham, S. L. Belisle, and C. L. Baas, “Emissions from light duty gasoline vehicles operating on low blend ethanol gasoline and E85,” *Atmos. Environ.*, 42 (19) 4498–4516 (2008).
28. L. Sileghem *et al.*, “Laminar burning velocity of gasoline and the gasoline surrogate components iso-octane, n-heptane and toluene,” *Fuel*, 112 355–365 (2013).
29. P. S. Veloo, Y. L. Wang, F. N. Egolfopoulos, and C. K. Westbrook, “A comparative experimental and computational study of methanol, ethanol, and n-butanol flames,” *Combust. Flame*, 157 (10) 1989–2004 (2010).
30. H. Peng *et al.*, “Analytical Assessment of C2–C8 Alcohols as Spark- Ignition Engine Fuels,” in *Proceedings of the FISITA World Automotive Congress*, 191(3) 333–342 (2013).
31. C. T. Chong and S. Hochgreb, “Measurements of laminar flame speeds of acetone/methane/air mixtures,” *Combust. Flame*, 158 (3) 490–500 (2011).
32. S. Zhang *et al.*, “Experimental and kinetic studies on laminar flame characteristics of acetone-butanol-ethanol (ABE) and toluene reference fuel (TRF) blends at atmospheric pressure,” *Fuel*, 232 (6) 755–768 (2018).
33. S. M. Correa, “A Review of NOx Formation Under Gas-Turbine Combustion Conditions,” *Combust. Sci. Technol.*, 87 (10) 329–362 (2012).
34. F. L. Oliveira, P. T. Lacava, R. W. Ferreira and F. A. Torres, “Experimental Analysis of Flameless Combustion for Reduction of Pollutants,” in *9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics 16* (x) 375–381 (2012).
35. A. A. Nizami and N. P. Cernansky, “Kinetics of Pollutant Formation and Destruction in Combustion,” *Symp. Combust.*, 17 (1) 475–483(1979).
36. S. Fernando, C. Hall, and S. Jha, “NOx Reduction from Biodiesel Fuels,” *Energy & Fuels*, 20 (1) 376–382 (2006).

37. S. Cao *et al.*, "Numerical and experimental studies of NO formation mechanisms under methane MILD combustion without heated air," *energy fuel*, 1–30 (2015).
38. J. Sarkar and S. Bhattacharyya, "Application of graphene and graphene-based materials in clean energy-related devices Minghui," *Arch. Thermodyn.*, 33 (4) 23–40 (2012).
39. G. G. Szegö, "Experimental and Numerical Investigation of a Parallel Jet MILD Combustion Burner System in a Laboratory-scale Furnace," *PhD Thesis*, (7) 168 (2010).
40. H. Teng and T. S. Huang, "Control of NOχ emissions through combustion modifications for reheating furnaces in steel plants," *Fuel*, 75 (2) 149–156 (1996).
41. M. A. Galbiati, A. Cavigiolo, A. Effuggi, D. Gelosa, and R. Rota, "Mild combustion for fuel-NOx reduction," *Combust. Sci. Technol.*, 176 (7) 1035–1054 (2004).
42. A. Keskin, M. Gürü, and D. Altiparmak, "Influence of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission," *Bioresour. Technol.*, 99 (14) 6434–6438 (2008).
43. S. M. Palash, M. A. Kalam, H. H. Masjuki, B. M. Masum, I. M. R. Fattah, and M. Mo, "Impacts of biodiesel combustion on NOx emissions and their reduction approaches," *Renew. Sustain. Energy Rev.*, 23 (x) 473–490 (2013).
44. D. H. Qi, H. Chen, L. M. Geng, and Y. Z. Bian, "Effect of diethyl ether and ethanol additives on the combustion and emission characteristics of biodiesel-diesel blended fuel engine," *Renew. Energy*, 36 (4) 1252–1258 (2011).
45. H. Aydin and C. Ilkiliç, "Effect of ethanol blending with biodiesel on engine performance and exhaust emissions in a CI engine," *Appl. Therm. Eng.*, 30 (10) 1199–1204 (2010).
46. H. H. Masjuki et al., "Experimental evaluation of an unmodified diesel engine using biodiesel with fuel additive," Proceeding - 1st Int. Forum Strateg. Technol. "e-Vehicle Technol. IFOST, 96–99 (2006).
47) A. Keskin, M. Gürü, and D. Altiparmak, "Biodiesel production from tall oil with synthesized Mn and Ni based additives: Effects of the additives on fuel consumption and emissions," *Fuel*, 86 (7–8) 1139–1143 (2007).
48. D. T. Hountalas, G. C. Mavropoulos, T. C. Zannis, and S. D. Mamalis, "Use of water emulsion and intake water injection as NOx reduction techniques for heavy duty diesel engines," *SAE Tech. Paper.*, (724) 17 (2006).
49. X. Tauzia, A. Maiboom, and S. R. Shah, "Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine," *Energy*, 35 (9) 3628–3639 (2010).
50. B. Tesfa, R. Mishra, F. Gu, and A. D. Ball, "Water injection effects on the performance and emission characteristics of a CI engine operating with biodiesel," *Renew. Energy*, 37 (1) 333–344 (2012).
51. K. A. Subramanian, "A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions," *Energy Convers. Manag.*, 52 (2) 849–857 (2011)..
52. R. Adnan, H. H. Masjuki, and T. M. I. Mahlia, "Performance and emission analysis of hydrogen fueled compression ignition engine with variable water injection timing," *Energy*, 43 (1) 416–426 (2012).doi:http://dx..
53. C. J. Mueller, A. L. Boehman, and G. C. Martin, "Investigation of the origin of increased NOx emissions in a heavy-duty compression-ignition engine fueled with soy biodiesel," *ACS Natl. Meet. B. Abstr.*, 4970 (x) (2009).
54. J. G. Suryawanshi and N. V. Deshpande, "Effect of injection timing retard on emissions and performance of a pongamia oil methyl ester fuelled CI engine," *SAE Tech. Pap.*, 7 (724) 1–15, (2005).
55. A. Monyem, "The effect of timing and oxidations on emissions from biodiesel - A. Monyem," *American Society of Agricultural Engineers*, 44 (1) 35–42 (2001).
56. M. S. Graboski and R. L. McCormick, "Combustion of fat and vegetable oil derived fuels in diesel engines," *Prog. Energy Combus*, 24, (97) 125–164 (1998).
57. C. Y. Choi and R. D. Reitz, "Experimental study on the effects of oxygenated fuel blends and multiple injection strategies on DI diesel engine emissions," *Fuel*, 78 (11) 1303–1317 (1999).
58. C. Sayin, M. Gumus, and M. Canakci, "Effect of fuel injection timing on the emissions of a direct-injection (DI) diesel engine fueled with canola oil methyl ester-diesel fuel blends," *Energy and Fuels*, 24 (4) 2675–2682 (2010).

59. Z. Wang, K. K. Srinivasan, S. R. Krishnan, and S. Som, “A computational investigation of diesel and biodiesel combustion and NOx formation in a light-duty compression ignition engine,” *Spring Tech. Meet. Cent. States Sect. Combust. Inst.*, (4) 1–11 (2012).
60. P. Ye and A. L. Boehman, “An investigation of the impact of injection strategy and biodiesel on engine NOx and particulate matter emissions with a common-rail turbocharged di diesel engine,” *Fuel*, 97, (x) 476–488 (2012).
61. E. Buyukkaya and M. Cerit, “Experimental study of NOx emissions and injection timing of a low heat rejection diesel engine,” *Int. J. Therm. Sci.*, 47 (8) 1096–1106 (2008).
62. A. Parlak, H. Yaşar, C. Haşimoğlu, and A. Kolip, “The effects of injection timing on NOx emissions of a low heat rejection indirect diesel injection engine,” *Appl. Therm. Eng.*, 25 (17–18) 3042–3052 (2005).
63. B. Kegl, “Effects of biodiesel on emissions of a bus diesel engine,” *Bioresour. Technol.*, 99 (4) 863–873 (2008).
64. S. K. Hoekman and C. Robbins, “Review of the effects of biodiesel on NOx emissions,” *Fuel Process. Technol.*, 96 237–249 (2012).
65. W. T. Hung, H. Y. Tong, and C. S. Cheung, “Development of a Heavy-Duty Diesel Modal Emissions and Fuel Consumption Model,” *J. Air Waste Manag. Assoc.*, 55 (10) 1431–1440 (2005).
66. M. Tatur, H. Nanjundaswamy, D. Tomazic, M. Thornton, and R. L. McCormick, “Biodiesel effects on U.S. light-duty tier 2 engine and emission control systems - Part 2,” *SAE Tech. Pap.*, 2 (1) 88–103 (2009).
67. T. V. Johnson, “Review of diesel emissions and control,” *SAE Tech. Pap.*, 3 (1) 16–29 (2010).
68. T. Selleri, A. D. Melas, A. Joshi, D. Manara, A. Perujo, and R. Suarez-Bertoa, “An overview of lean exhaust denox aftertreatment technologies and Nox emission regulations in the european union,” *Catalysts*, 11 (3) 1-36 (2021).
69. J. Krahl, S. Tanugula, and H. Hopf, “Diesel fuel additives to reduce NOx emissions from diesel engines operated on diesel and biodiesel fuels by SNCR,” *SAE Tech. Pap.*, 8 1–8 (2010).
70. M. Gomaa, A. J. Alimin, and K. A. Kamarudin, “The effect of EGR rates on NO_X and smoke emissions of an IDI diesel engine fuelled with Jatropha biodiesel blends,” *Int. J. Energy Environ.*, 2 (3) 477–490 (2011).
71. D. Agarwal, S. K. Singh, and A. K. Agarwal, “Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine,” *Appl. Energy*, 88 (8) 2900–2907 (2011).
72. B. Shin, Y. Cho, D. Han, S. Song, and K. M. Chun, “Hydrogen effects on NOx emissions and brake thermal efficiency in a diesel engine under low-temperature and heavy-EGR conditions,” *Int. J. Hydrogen Energy*, 36 (10) 6281–6291 (2011).
73. S. . Turns, *Turns SR. An Introduction to Combustion Concepts and Applications.* 2013.
74. H. Peng, Y. Cui, L. Shi, and K. Deng, “Effects of exhaust gas recirculation (EGR) on combustion and emissions during cold start of direct injection (DI) diesel engine,” *Energy*, 33 (3) 471–479 (2008).
75. N. K. Miller Jothi, G. Nagarajan, and S. Renganarayanan, “LPG fueled diesel engine using diethyl ether with exhaust gas recirculation,” *Int. J. Therm. Sci.*, 47 (4) 450–457 (2008)..
76. A. Tsolakis, A. Megaritis, and D. Yap, “Application of exhaust gas fuel reforming in diesel and homogeneous charge compression ignition (HCCI) engines fuelled with biofuels,” *Energy*, 33 (3) 462–470 (2008).
77. V. Pradeep and R. P. Sharma, “Use of HOT EGR for NOx control in a compression ignition engine fuelled with bio-diesel from Jatropha oil,” *Renew. Energy*, 32 (7) 1136–1154 (2007).
78. A. Tsolakis, A. Megaritis, M. L. Wyszynski, and K. Theinnoi, “Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation),” *Energy*, 32 (11) 2072–2080 (2007).
79. H. E. Saleh, “Effect of exhaust gas recirculation on diesel engine nitrogen oxide reduction operating with jojoba methyl ester,” *Renew. Energy*, 34 (10) 2178–2186 (2009).
80. P. K. Bose and D. Maji, “An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation,” *Int. J. Hydrogen Energy*, 34 (11) 4847–4854 (2009).
81. V. Fortunato, G. Mosca, D. Lupant, and A. Parente, “Validation of a reduced NO formation mechanism on a flameless furnace fed with H_2-enriched low calorific value fuels,” *Appl. Therm. Eng.*, 144 (7) 877–889 (2018).

82. G. G. Szegö, B. B. Dally, and G. J. Nathan, "Scaling of NOx emissions from a laboratory-scale mild combustion furnace," *Combust. Flame*, 154 (1–2) 281–295 (2008).
83. A. A. Abuelnuor, M. A. Wahid, A. Saat, and M. Osman, "Characterization of a Low NOx Flameless Combustion Burner Using Natural Gas," J. Teknol. (Sciences Eng., 66 (2) 121–125 (2014).
84. J. A. Wuenning and J. G. Wuenning, "Flameless Oxidation to Reduce Thermal {NO}-formation," *Prog. Energy Combust. Sci.*, 23 81–94 (1997).
85. A. K. Gupta, "Thermal characteristics of gaseous fuel flames using high temperature air," *J. Eng. Gas Turbines Power*, 126 (1) 9–19 (2004).
86. B. Rajesh Kumar and S. Saravanan, "Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed di diesel engine fueled with pentanol/diesel blends," *Fuel*, 160 217–226 (2015).
87. L. Siwale *et al.*, "Combustion and emission characteristics of n-butanol / diesel fuel blend in a turbo-charged compression ignition engine," *Fuel*, 107 409–418 (2013).