Combined Effect of a Catalytic Reduction Devicewith Waste Frying Oil-Based Biodiesel on NO_x Emissions of Diesel Engines

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Abstract

Internal combustion engines with application in automobiles and other rele- vant industries constitute significant environmental pollution via the release of toxic exhaust gasses like carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and nitrogen oxide (NO_x). Engine researchers and man- ufacturers are challenged to develop external and internal measures to ensure environmentally friendly solutions to accommodate and conform to the growing list of emission standards. Therefore, this work presents an experimental investigation of the NO_x emission profile of a diesel engine that is fuelled and fitted with waste frying oil-based biodiesel and catalytic converter. Using a single-cylinder, four-stroke air-cooled CI engine at a constant speed of 1900 rpm and different loadings of 25%, 50%, 75%, and 100%; fitted with a catalyt- ic converter at the exhaust outlet of the engine and linked to a dynamometer and a gas analyser, an experiment was conducted at biodiesel/diesel volume blends of B0 (0/10), B5 (5/95), B20 (20/80), B30 (30/70), B70 (70/30), B100
(100/0); and 30% concentration (v/v), 0.5 litre/hr flow rate of aqueous urea from the catalytic converter. The results show an increasing NO_x emission asthe biodiesel component increased in the blend. The catalytic converter showeda downward NO_x reduction with a significant 68% reduction in efficiency athigh exhaust gas temperatures. It is concluded that the combined utilisation of waste frying oil-based biodiesel and the catalytic converter yields substan-tial NO_x emission reduction.

Keywords

Catalytic Converter, Waste Frying Oil, Biodiesel, NO_x Emission, DieselEngines

1. Introduction

The emissions from internal combustion engines (IC) include but are not limited to; NO_x, CO, hydrocarbons (HCs), and particulate matter. A singular IC engine such as an automotive engine will expel an insignificant amount of NO_x into the atmosphere. However, collectively in a group, internal combustion engines emit most of the total anthropogenic NO_x. For more than three decades, regulatory agencies have addressed NO_x emissions; however, there is an appetite for more stringent NO_x control measures beyond current requirements. The appetite for more stringent NO_x control is based on the role that NO_x emission plays in the development of ground-level ozone and photochemical smog (EPA, 2002 [1]); (Clean Air Technology Center, 1999 [2]). Biodiesel is a fuel type that continues to be evaluated as replacing diesel fuel in the automotive industry. Although it is sourced from many materials such as cooking oil and animal fat, it is cleaner, renewable. It can serve as a suitable replacement or an additive to diesel fuel. More so, it offers a high heat content, high density, and better lubricating prop- erties (Barabas and Todoru, 2012 [3]; Shahid and Jamal, 2011 [4]; Murugesan *et al.* 2009 [5]; Fasogbon and Asere, 2014 [6]). In addition, biodiesel is very differ- ent from conventional diesel due to its physicochemical properties. However, with biodiesel, there is reduced emission of carbon monoxide (CO), particulate matter (PM), and hydrocarbon (HC), it also causes higher NO_x emissions pri- marily because of the presence of oxygen in the oil (Murugesan *et al.*, 2009 [5]; Fasogbon, 2015 [7]).

A literature review has shown that NO_x emissions vary when diesel engines are fired with biodiesel produced from different organic sources. For example, Thangavelu and Thamilkolundhu, 2011 [8] evaluated the combustion and emis-sion characteristics of compression ignition (CI) engine fueled with Jatropha- diesel oil blends and observed the emissions include but are not limited to; NO_x emission and combustion characteristics of the blends to be comparatively higher than that of the baseline diesel. In addition, Vallinayagam *et al.*, 2013 [9] also investigated a Kirloskar stationary CI engine fueled using pine oil blends while loading the engine with an eddy current dynamometer at varying loads. The study observed a significant reduction in NO_x emission by 15.2% compared to pure diesel and concluded that pine oil biofuel positively impacts the atmos- phere.

Although research is still ongoing on improving the quality and yield of bio- diesel from waste frying oil (WFO), the idea of converting WFO to biodiesel ori- ginates from the perspective of a waste management approach (Banerjee *et al.*,2014 [10]). The significant characteristics of WFOs concern high levels of free fatty acids, density, and viscosity. However, in producing biodiesel from WFOs, several factors such as; the type of oil source, duration of use, and the nature of the fried food products largely influence the quality of the biodiesel for use as fuel (Al-Kofahi, 2017 [11]; Shaban, 2018 [12]). Interestingly, with waste frying oil (WFO) biodiesel, studies have shown variations in NO_x emission, for exam- ple, Al-Kofahi, 2017 [11]; Guo *et al.*, 2012 [13]; and Sanli, 2018 [14], reported an increase in NO_x emission when using pure WFO biodiesel as against using pure diesel while Koçak *et al.*, 2007 [15], and Utlu *et al.*, 2008 [16], reported a de- crease in NO_x emission and some others have reported no significant effect on the NO_x emission (Dennis, 2001 [17]). The variations in the NO_x emission as ob- served from using WFO biodiesels in the various studies were probably because of the increased sensitivity of NO_x emission due to engine combustion condi- tions and the differences in the chemical properties of the WFO as well as the in- fluence of the injection timing and the subsequent premixed and diffusion burn characteristics during combustion (Benjumea *et al.*, 2011 [14]; Guo *et al.*, 2012 [18]). However, with the SCR technology, NO_x emission from diesel engines po- wered with WFO biodiesel has significantly reduced.

The Selective Catalytic Reduction (SCR) method is an efficient approach to reducing NO_x emissions from biodiesel-fueled CI engines (Sala *et al.*, 2018 [19]; Yang *et al.*, 2015 [20]). Its principle is based on injecting a reducing agent (urea) into the exhaust gas flow stream of an internal combustion engine. The urea im- mediately converts to ammonia, and the ammonia reacts with the nitrogen oxide in the presence of a catalyst to produce nitrogen and water as the exhaust (EPA, 2002 [1]; Sinzenich, 2015 [21]). With diesel fuel, the SCR system is considered a more effective means of reducing NO_x emission (Sala *et al.*, 2018 [19]; Clean Air Technology Center, 1999 [2]). However, the SCR technology application is faced with some challenges. One of such challenges is the need to achieve a threshold temperature of about 200˚C before injecting the urea solution into the hot ex- haust gas, which in most cases is above the exhaust gas temperature (Kröcher, 2018 [22]). To address this challenge, Sala *et al.*, 2017 [23] in an experiment preheated and evaporated the urea solution before injecting it into the engine exhaust gas. In addition, while using biodiesel with SCR technology, because of the high concentration of impurities (potassium in the biodiesel), the catalyst [mostly V_2O_5-WO_3/TiO_2 (VWT) vanadium/titanium-based] has been observed to be deactivated due to the neutralization of the catalyst's acid sites by the high ba- sicity content of the potassium, thus decreasing the adsorption of NH_3 (Kröcher, 2018 [22]; Schill and Fehrmann, 2018 [24]). Several studies have considered us-ing SCR technology alongside biodiesel blends to further investigate and reduce the NO_x emission from diesel engines. For example, Sundarraj *et al.*, 2014 [25] achieved a maximum of 73.94% reduction in NO_x emission using a urea-SCR system (with a urea concentration of 32.5%, at a constant flow rate of 0.75 lit/hr.) fitted to a CI engine operating at different loading conditions and fuelled with diesel-jatropha blends (25% of Jatropha and 75% diesel blends).

More so, Praveen and Natarajan, 2014 [26] fueled a CI engine using a diesel- ethanol blend and observed a 70% reduction in NO_x emission while using a cat- alytic converter (TiO_2)-coated catalyst with 5% urea concentration, at a constant flow rate of 0.75 litre per hr. as against 66% reduction in NO_x emission obtained when the engine was fueled with pure diesel, and 76.9% reduction was also rec- orded in another study that combines both an SCR device and an exhaust gas re- circulation (EGR) approach (Praveen and Natarajan, 2014 [26]; Praveena *et al.*, 2022 [27]). Consequently, it can be concluded that biodiesel blends nonetheless, when coupled with an SCR technology, and without any engine calibration or modifications would produce a significant reduction in NO_x emission in the range of 58% to 75% (Shi *et al.*, 2008 [28]; Praveen and Natarajan, 2014 [26]; Sa-la *et al.*, 2018 [19]; Sundarraj *et al.*, 2014 [25]; Vallinayagam *et al.*, 2013 [9]; Yu-suf *et al.*, 2022 [29]). In sum, a relevant review pertaining to this research is pro-vided in [30].

This study primarily observes the NO_x emission from a diesel engine fueled using biodiesel blends obtained from waste frying oil (WFO) and investigates the influence of a small-scale selective catalytic converter on the NO_x emission. The objective of the study is limited to examining the level of nitrogen oxide re-duction with the catalytic converter when firing with a WFO biodiesel blend. It, however, does not cover the analysis of the biodiesel effect on the catalyst, and neither does it evaluate the engine performance while operating with the WFO biodiesel.

Materials and Methods

Biodiesel Production

This study produced biodiesel from waste vegetable cooking oil via a transesteri- fication process as followed in previous studies by Dennis, 2001 [17]; Guo *et al.*, 2012 [14]; Koçak *et al.*, 2007 [16]; and Tziourtzioumis *et al.*, 2017 [31]. The waste cooking oil sample was collected from roadside bean cake and fried yam sellers on the streets of Agbowo, Ibadan, Nigeria. Using a simple transesterification batch process, 10.5 millilitres of the waste cooking oil sample was measured, filtered to remove residues and unwanted particles, poured into a 250 milliliter conical flask, and heated to a preselected temperature of 50˚C. A solution of potassium me- thoxide was equally produced using 0.25 g of potassium hydroxide pellet and 63millilitres of methanol (catalyst concentration of 0.5% and an oil/Methanol mole ratio of 1:6). The potassium hydroxide pellet was stirred vigorously until it dis- solved completely in the methanol mixture. The potassium methoxide solutionwas then mixed with the warm waste cooking oil, stirred vigorously with a me-chanical stirrer while heating until 60˚C for about 50 minutes. The solution waskept to cool and settle for a day and later transferred to a gravity separating fun- nel until two distinct layers were visible. The glycerol and residual catalyst were removed, while the biodiesel was extracted, washed with warm deionized water, and heated to 30˚C to remove water. The WFO based produced biodiesel was characterised and the results presented in **Table 1** and the expected standard for biodiesel properties. Diesel engine test rig for biodiesel-diesel blends with speci- fications is detailed in **Table 2**. The biodiesel blends were; pure diesel [B0]-0% biodiesel and 100% diesel [B100]; [B5]-5% biodiesel and 95% diesel; [B20]-20% biodiesel and 80% diesel; [B30]-30% biodiesel and 70% diesel; [B70]-70% bio- diesel and 30% diesel [B100]-00% biodiesel and 0% diesel.

Table 2. Test engine specifications.

Make: Kama KM170F Air Cooled Diesel Engine Parameter	Notes/Values
Combustion system	Direct injection
No of cylinder	Single cylinder
Max output	2.8 kw - 3.1 kw
Con output	2.5 kw - 2.8 kw
Engine speed	3000 rpm - 3600 rpm
Bore × stroke	70 mm × 55 mm
Fuel used	Light diesel oil
Displacement	0.211
Fuel tank capacity	2.5 L
Starting system	Recoil or electric starter

The Selective Catalytic Converter and Reagent

The study developed a catalytic converter similar to those previously developed by Tan *et al.*, 2020 [32]; and Bhaskarrao and Shinde, 2015 [33]. The catalytic converter had a honeycomb structure with a cylindrical shell with length and diameter, approximately 92 mm and 69 mm, respectively. It had a converter vo- lume of 0.3393 litres (339.23 cc), designed for an exhaust gas volume flow rate of 0.006349 m^3/sec. It had a platinum catalyst and a wash-coat coated with an alloy of Al_2O_3. The reagent system, however, consists mainly of the following compo- nents: a storage tank, a dc pump, piping, a time relay-delay module to regulate the injection timing of the warm aqueous urea solution, an atomizer nozzle, anda 12-volt battery to power the dc pump and the relay-delay module. The study utilized a warm anhydrous aqueous urea of 30% concentration (volume/volume %)at 40˚C stored in a plastic container tightly covered to prevent contamination and for ease of handling and simplicity of design. Although the scope of this study does not cover the analysis on the effect of reagent concentration on the converter, however, the reagent set-up follows a similar approach and set-up puttogether in the study by Sundarraj *et al.*, 2014 [25]; Vallinayagam *et al.*, 2013 [9];and Kumar *et al.*, 2021 [34].

Experimentation

Praveena *et al.*, 2022 [27]; Kumar *et al.*, 2021 [34]; and Vallinayagam *et al.*, 2013[9] developed a similar experimental set-up to those used in this research, as shown in **Figure 1**. The experiment was conducted using a four-stroke, air-cooled C.I engine with the specification given in **Table 2**, fueled with biodiesel blends

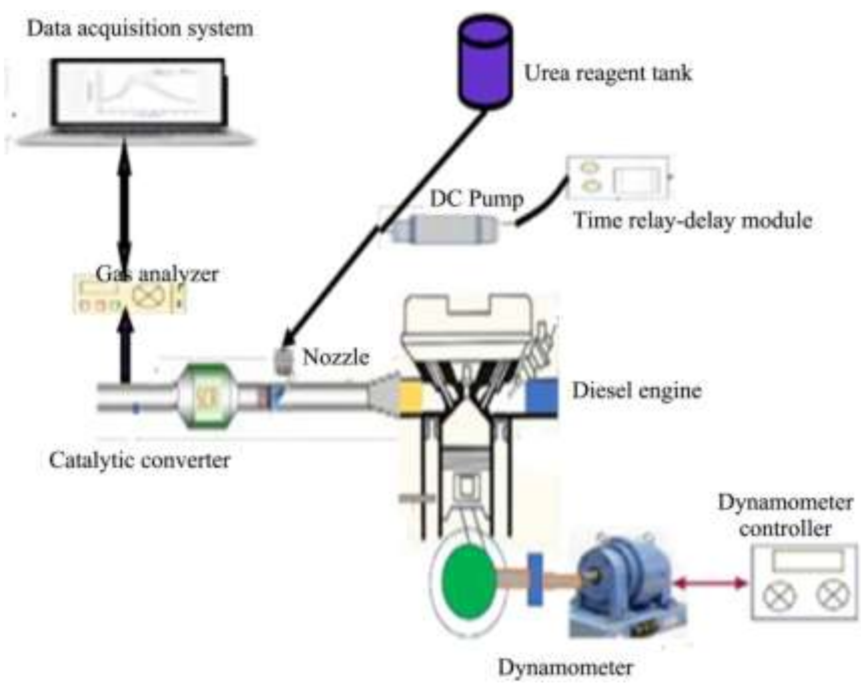

Figure 1. Experimental configuration.

[B0], [B5], [B20], [B30], [B70], and [B100], and operating at a constant engine speed of 1900 rpm. The engine was connected to a Megatech DG2 dynamometer for loading varying from 25%, 50%, 75%, and 100% full load, a PCA 3 Bacharach Gas analyzer also connected to a computer for data collection, and the catalytic converter connected at the exhaust gas outlet tail end of the diesel engine, as shown in **Figure 1**. The warm aqueous urea stored in a container was metered and injected (using a time relay-delay module and a dc pump connected to a 12-volt battery) into the exhaust gas flow stream through a fine atomizer nozzle fixed upstream of the exhaust gas flow. The experiment maintained the proce- dure over time while varying the engine load; the NO_x emission data were col-lected, and the graphs presented the results.

Results and Discussions

The exhaust gas temperature and NO_x emission against different load ranges are plotted for the base fuel diesel [B0], pure biodiesel [B100], and the various bio-diesel blends [B5], [B20], [B30], and [B70].

Exhaust Gas Temperature at Different Load Ranges

The necessary information on performance characteristics of relevant systems could be found in the work of Utlu *et al.*, 2008 [15]. Although performance cha- racteristics are not the focus of this work, the extraction of exhaust gas tempera- ture provides an understanding of NO_x emission. **Figure 2** depicts the exhaust gas temperature relative to the load percentage revealing an increasing trend.

NO_x Profile without the Use of the Catalytic Converter

Figure 3 shows a plot of NO_x emission against biodiesel-fossil diesel blends with- out catalytic converter as an add-on technology at different loadings. It was ob-served that an increasing percentage of biodiesel in biodiesel-fossil diesel blends leads to an increase in NO_x emission. And this observation is in tandem with Shahid *et al.*, 2011 [4] and Fasogbon, 2015 [7]. The study observed that the oxy- gen richness of biodiesel could have been responsible for the increasing content of NO_x; as the higher the exhaust gas temperature, the higher the NO_x emission. Thus, the oxygen content/richness of Waste Frying Oil-based biodiesel must have supported combustion; thereby leading to high NO_x emission emanating from high exhaust gas temperature.

NO_x Profile with the Use of the Catalytic Converter

Even though the increasing percentage of biodiesel in biodiesel-fossil diesel blends leads to an increase in NO_x emission, as in the case of **Figure 3**, the in- jection of a catalytic converter as an add-on technology/device significantly reduces NO_x emission, as shown in **Figure 4**. At higher engine loads which is equivalent to higher exhaust gas temperature and NO_x emission, there were higher reductions of NO_x; this is because, at the higher temperature, Ammonia

Figure 2. Plot of exhaust gas temperatures at various loads.

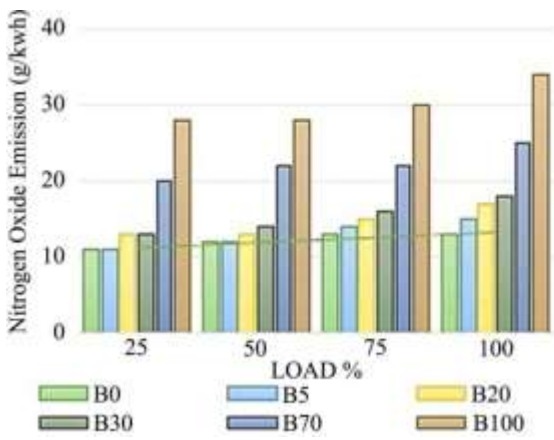

Figure 3. Plot of NO_x emissions for biodiesel blends without the use of the catalytic converter device.

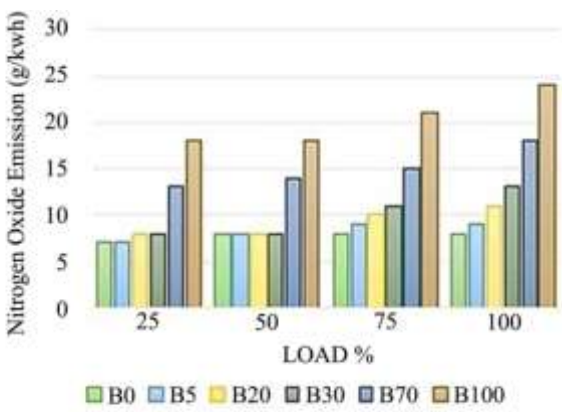

Figure 4. Plot of NO_x emissions for biodiesel blends with the use of the catalytic converter device.

(Urea reagents) do show better reaction with NO_x. This observation is in linewith the work of Sala *et al.*, 2017 [23].

Conclusion

This study ascertained the NO_x emission profile of a diesel engine powered with a Waste frying oil-based biodiesel at different blends and further evaluated a cat- alytic converter's NO_x emission reduction efficiency. With the conclusion that a combined effect of waste frying oil-based biodiesel and catalytic converter as add-on technology will yield a significant NO_x emission reduction.

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