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Research Article

Performance and Emission Characteristics of Compression Ignition Engine Running on a Blend of Cashew Nut Shell Liquid and Biodiesel Produced from Orange Peel

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ABSTRACT

This study evaluates the performance and emission characteristics of an orange peel biodiesel blended with cashew nut shell liquid. It investigates the efficacy of cashew nut shell liquid in reducing nitrogen oxide (NO_X) emissions resulting from the combustion of the biodiesel, while optimizing its performance.

The biodiesel was prepared via transesterification. It was obtained by reacting orange peel oil produced through Soxhlet extraction with methanol in the presence of NaOH. The biodiesel was blended with cashew nut shell liquid in the ratio 70%:30% (B70).

Experimental results demonstrate that blending cashew nut shell liquid with orange peel biodiesel causes a slight decrease in NO_X emission. B70 generates 150 ppm of NO_X, while B100 and diesel produce 159 ppm and 193 ppm, respectively. The hydrocarbon emission of B70 was 8% lower than that of B100 and 22.3% lower than that of diesel. As regards CO and CO_2 emission, B70 performs better than B100 and diesel. The performance parameters were computed at brake powers of 2.5 kW, 5.0 kW, 7.5 kW, and 10 kW. In comparison to diesel and B100, B70 has higher brake thermal efficiency at all loads. The brake specific fuel consumption (BSFC) of B70 is higher than that of diesel, but less than that of B100 at 2.5 kW and 5.0 kW. At 7.5 kW and 10 kW, the BSFC of B70 is higher than that of B100 and diesel. Conclusively, B70 gives optimal performance and less emission. Hence, cashew nut shell liquid is a good additive.

Keywords: orange peel, cashew nut shell liquid, biodiesel, CI engine

INTRODUCTION

With the current depletion rate of fossil fuel reserves, growing energy demands and the side effects of the combustion of conventional fuels on the environment, it is expedient to source for other alternative fuels that have the capability to meet these global concerns. Fossil fuel, which currently accounts for 80% of the world's energy mix, is the largest source of greenhouse gas emissions (Adepoju et al., 2021; Ortiz et al., 2020). The presence of a higher amount of carbon molecules in fossil fuels results in the production of harmful gases during the combustion of these fuels. Diesel ranks high when compared to other fuel in terms of energy density (Edwin Geo et al., 2021). Apart from oxides of carbon, other pollutants like NO_X, unburned HC, smoke as well as particulate matter are also products of the exhaust emission of fossil fuel combustion and they are notorious for causing environmental issues like acid rain coupled with health challenges like cancer and other respiratory illness (Edwin Geo et al., 2021). Attaining a state of a secure and sustainable future, increased energy security conjoined with reduced environmental degradation is dependent on the rate at which fuels or energy resources that have the ability to combat air contamination, reduce global warming and also reduce fossil fuel dependency are being deployed (Adepoju et al., 2021; Chaichan, 2017).

Diesel engines possess good properties which include high thermal efficiency, less CO_2 emission, durability, longer engine life, low setup cost, high stability and ability to work effectively under a variety of operating conditions (Hoseini et al., 2017). This makes it a top choice in the transportation sector, agricultural industries and other high energy-consuming firms. Despite the numerous advantages offered by diesel engines, using conventional diesel for its operation makes it unfit and unsafe for the environment. The transportation sector, which is the largest fuel consumer, is associated with traffic congestion, which leads to idling in engines (Ashok et al., 2020; Rashid et al., 2012). During idling, vehicles operate under low load and low speed for prolonged duration and this is responsible for a quarter of fuel consumption and other serious consequences like emissions and engine wear (Ashok et al., 2020). Diesel also contributes a large share to the world's carbon footprint (Ashok et al., 2020; Fasogbon et al., 2021). For example, the global emission produced by the transport sector in 2014 was around 7.0GtCO_2 equivalent and diesel accounts for 70% of the fuel consumed in this industry (Oladunni et al., 2022). Since movement is a major necessity, clean fuel remains the best solution to this challenge.

Biodiesel, which is a typical example of biofuel, has proven to be a suitable replacement for the usage of conventional diesel in compression ignition engines. Its unique properties such as non-toxicity, high flash point, the absence of aromatic compounds, biodegradability, inherent lubricity, negligible sulphur and carbon-neutral characteristics make it preferable to conventional diesel (Rathinam et al., 2018). It also possesses low calorific value compared to diesel (Ganesan and Masimalai, 2019). Although carbon-negative fuel as an alternative fuel is better than all form of fuels due to its ability to absorb carbon from the environment, it is yet to be available for commercial purposes in most countries. Any fuel in which the amount of carbon absorbed by the biomass used for its production during the photosynthesis stage of the bio-based feedstock exceeds the emission associated with the use of the fuel is referred to as carbon negative (Matthews, 2008). Other examples of biofuel include biogas as well as bio-alcohols like ethanol, methanol and butanol (Ashok et al., 2018). In compression ignition engine, the major properties used in determining the superiority of fuels are cetane index, boiling point, low poly aromatic content, low density, and viscosity (Ashok et al., 2018).

Biodiesel is composed of a mixture of monoalkyl esters of long-chain fatty acids (C_{12}-C_{22}) like fatty acid methyl esters (FAME) and fatty acid ethyl esters (FAEE) (Ghasemi and Moosavi-Nasab, 2020; Hussein et al., 2021). It is often produced from renewable biological sources like vegetable oil and animal fat through trans-esterification reactions with short-chained alcohols in the presence of a suitable base catalyst (Fasogbon et al., 2019; Hussein et al., 2021). Biodiesel is usually grouped into three categories based on the feedstock used. It is categorized into first-generation biodiesel, second-generation biodiesel and third-generation biodiesel. Biodiesels, whose feedstock is gotten from edible food crops like vegetable oil falls under the first-generation section while the second-generation category hosts biodiesel produced from non-edible feedstock such as waste biomass (Anwar et al., 2019; Ashok et al., 2018; Vignesh et al., 2021). The major feedstocks used in the production of third-generation biodiesel are microorganisms which include microalgae, algae, fungi, latexes, bacteria and terpenes (Anwar et al., 2019). Due to the disparate climatic conditions and agricultural practices in different countries, the selection of feedstock for biodiesel production is region-specific (Alagumalai et al., 2021). This still does not alter the fact that feedstocks obtained from wastes are preferred by several industry players. More so, cheap feedstocks should be used in biodiesel production as about 75% of the over biodiesel generation costs result from the choice of the feedstock (Ghasemi and Moosavi-Nasab, 2020). The competition between fuel and availability of food for consumption conjoined with arable land, easy accessibility and low-cost, place second-generation biodiesel over their first-generation counterpart (Alagumalai et al., 2021; Etim et al., 2020).

A typical example of organic waste that could be employed in the production of second-generation biodiesel is the orange peel. During the production of orange juice, only about 50% of the orange is transformed into juice. The remaining 50% consists of the pulp, peel and seeds (Ortiz et al., 2020). About 95% of the waste generated during orange juice production or direct consumption is orange peel and the mismanagement of this waste can lead to air, water and soil contamination (Ortiz et al., 2020). The Food and Agricultural Organization of the United Nation indicated that orange is the most produced organic product, with Brazil as the main producer (Ashok et al., 2020). Brazil produces about 19.2 million metric tonnes of the total 105 million metric tons of orange produced globally per annum (Rashid et al., 2012). The orange industry delivers an estimate of 25 to 30 mt of wastes annually while a significant fraction of the overall municipal solid wastes generated globally emanates from food waste (Ashok et al., 2020; Dhiman and Mukharjee, 2020). Generally, food wastes account for almost one-third of the entire food produced worldwide for human consumption (Dhiman and Mukharjee, 2020). The peels of fruits have the potency to produce environmentally friendly fuels (Ashok et al., 2018; Vignesh et al., 2021). Specifically, using oil produced from orange peel has the ability to improve brake thermal efficiency (BTE) and reduce brake specific fuel consumption (BSFC) in compression ignition engines (Ashok et al., 2018; Vignesh et al., 2021). The major challenge that accompanies the usage of pure biodiesel in compression ignition engine (CI engine) is its low thermal efficiency and the rate of NO_X emission generated during combustion (Siva et al., 2019). The reason behind its increased NO_X emission is due to the improvement in oxidation stability (Ganesan and Masimalai, 2019). The oxidation of biodiesel is always as a result of the high degree of unsaturation of the fatty acid molecules, which forms several products like aldehydes, polymers, alcohol, peroxides and acids, when attacked by oxygen from the air (Bastos and Tubino, 2017). This further causes an increase in the acid number of the fuel and also affects the viscosity of the fuel (Bastos and Tubino, 2017). However, it has been proven that adding additives with anti-oxidative properties has the ability to reduce this emission (Ganesan and Masimalai, 2019).

Carota et al. (2020) also investigated the feasibility of using orange peel extract as the basis of a liquid medium for microbial lipid production. This considerably increased the yield of the biodiesel produced through this technique. Kumar and Kumar (2019) also optimized the conversion of orange peel into orange peel oil (OPO) and OPO methyl ester through response surface methodology. This increased the yield of the methyl ester by more than 2%, but had little or no effect on the reaction time.

The fuel properties of the biodiesel produced through the use of the oil extracted from the seeds of *citrus reticulata*, a special specie of orange commonly known as mandarin orange, was investigated by Rashid et al. (2012). The fuel was prepared via a sodium methoxide-catalyzed transesterification reaction of the oil and methanol. Its performance was compared with both ASTM D6751 and EN 14214 Biodiesel standards. The major problem with this fuel was the low value of the induction time and high cold flow (Rashid et al., 2012).

The engine operating parameters conjoined with the vibroacoustic and combustion characteristics of a commercial diesel vehicle, which is operating under idling condition and also fuelled with a blend of OPO and diesel, was investigated by Ashok et al. (2020). The results obtained indicated that OPO 20 fuel blend performs better than OPO 10 fuel blend when compared to pure diesel. OPO 20 exhibited similar vibration characteristics and noise level when compared to pure diesel. There was an 8% improvement in the heat release rate. Heavy vibrations were also recorded at the engine mount. The combustion characteristics fell within a considerable limit.

The major problem that is common to these studies is the high emission of NO_x. Research has shown that this decreases on the addition of additives. In a bid to improve on the work done on orange peel biodiesel, Mahesh Kumar et al. (2019) prepared a nano-emulsion of orange peel biodiesel and assessed its performance in a single-cylinder engine. Using the solvent extraction method, the orange oil was extracted and then converted to methyl ester. The nanofluid was prepared in two different concentrations by doping 50ppm and 100ppm of titaniumdioxide nanoparticle (Mahesh Kumar et al., 2019). After using it as fuel in a mono cylinder engine, it was observed that all emissions reduced, which is not obtainable with pure orange peel biodiesel. The NO_X emission, which is a major problem when using pure orange peel biodiesel in compression ignition engine, was reduced by 9.7%. However, the cylinder peak pressure and the heat release rate increased for the nano emission fuel.

From the work of Mahesh Kumar et al. (2019) and Rathinam et al. (2018), it can be deduced that the amount of NO_X emission produced from the use of orange peel biodiesels in diesel engines can be as high as 1,400 ppm and as average as 750 ppm or less. The amount of the biodiesel burnt during combustion and the oxygen content of a fuel determines the quantity of NO_X emission released by the diesel engine used Rathinam et al. (2018). The value of the BTE and BSFC obtained while running diesel engines with biodiesel is also dependent on inherent properties of the fuel. This is in conjunction with the nature of the engine used coupled with experimental conditions involved. The BSFC obtained in the work of Mahesh Kumar et al. (2019) for pure orange peel biodiesel and diesel varies with load condition. At maximum brake power, the BSFC of the biodiesel is 0.256 kg/kWh, while that of diesel is 0.237 kg/kWh.

Meeting global climate goals coupled with ensuring total commitment to the Paris Agreement hugely depends on the deployment of fuels that are totally clean and free from all forms of greenhouse gas emissions. Although pure biodiesel effectively combats major unsafe gas emissions, biodiesel produced from orange peel waste increases the emission of oxides of nitrogen (Rathinam et al., 2018), which is also a greenhouse gas. This still subjects our climate to danger. However, additives with good antioxidative abilities are capable of putting an end to this anomaly (Rangel et al., 2020). Cashew nut shell liquid is a non-food byproduct obtained from the shell of cashew, *anacardium occidentale*, and it is always found at the pith of the sponge (Bastos and Tubino, 2017; Rangel et al., 2020). Cashew nut shell liquid possesses antioxidative properties and it is preferable to other synthetic antioxidants because it is sustainable and affordable (Bastos and Tubino, 2017; Rangel et al., 2020). This study seeks to investigate the potency of cashew nut shell liquid to solve the problems resulting from the use of pure orange peel based biodiesel in compression ignition engines.

Cashew nut shell liquid has been used for biodiesel production in past research, both as main feedstock and in blend with other additives. For example, Devarajan et al. (2017) investigated the potential of cashew nut shell biodiesel blended with pentanol in compression ignition engines. In this work, the emission characteristics coupled with the performance of this fuel in a constant speed compression ignition engine were examined. The study involved three test fuels which are neat cashew nut shell biodiesel (C100), a blend of 10% volume of pentanol and 90% of cashew nut shell biodiesel (C90P10) as well as a blend of 20% pentanol and 80% cashew nut shell biodiesel (C80P20). The pentanol used is 98.4% pure and it acts as an oxygenative additive. The result reveals that there is significant reduction in the CO, HC, NO_X, and smoke emission when the constant speed compression ignition engine is running on the blend that contains 10% or 20% pentanol. The BSFC reduced slightly while the BTE increased marginally.

Kumar et al. (2018) reviewed the state of research of the use of cashew nut shell liquid as biodiesel. The review provides detailed information on cashew crop cultivation; oil extraction methods and fuel modification techniques conjoined with the combustion behavior and emission characteristics of cashew nut shell liquid in a compression ignition engine. It was observed that neat cashew nut shell liquid performs poorly in a compression ignition engine when compared to diesel. Preheating, blending, using fuel additives and also enriching air oxygen intake can be used in improving the fuel. The study indicated that a maximum of 40% substitution of cashew nut shell liquid is possible without deteriorating the performance of the engine.

Radhakrishnan et al. (2018) investigated the effect of alumina nanoparticles on the emission profile and performance characteristics of cashew nut shell biodiesel. The biodiesel blend was produced by the trans-esterification of cashew nut shell liquid with the addition of the alumina nanoparticles. The result showed that the blend exhibited low NO_X and smoke emission when compared to the neat cashew nut shell biodiesel. The alumina nanoparticles caused an increase in the evaporation tendency which in turn leads to complete combustion and reduction in the emission of CO and HC. There is also a 1.1% reduction in the BTE of the biodiesel blend as well as a 3.8% increase in the BSFC at full load. **Table 1** contains the quantitative review of past research works.

MATERIALS AND METHODS

Orange peel was collected from local orange sellers in Ibadan, Nigeria. It was dried in the sun for approximately 10 days. It was then ground into particles. Using soxhlet extraction technique, OPO was extracted from the grinded

Table 1. Quantitative review of some related past research works

Authors	Test fuel	Aim	Effect on performance	Effect on emission
Sekar et al. (2021)	Orange peel biodiesel & diesel blended in different ratio	To study the performance & emission characteristics of an orange peel biodiesel run in engines with different bowl geometry. The two distinct bowl shapes used are the hemispherical combustion shape & the toroidal combustion shape.	Under the hemispherical shape condition, the observed BTE ranges from 27% to 30.2% & the toroidal combustion shape condition gives a BTE ranging from 28.3% to 31.5%. The BSFC recorded when the orange peel biodiesel blends were run under hemispherical combustion shaped piston ranges between 0.265 to 0.315 kg/kWh & the one with toroidal shaped piston ranges from 0.255 to 0.298 kg/kWh.	Using the orange peel biodiesel blend under the hemispherical shape condition produces 0.20% to 0.22% CO, 45 ppm to 47 ppm HC, 842 ppm to 875 ppm NO_X & 83% to 89% smoke emission. The toroidal shape piston generates between 0.19% to 0.21% CO, 36% to 42% HC, 925 to 956 ppm NO_X & 58% to 71% smoke emission.
Ganesan and Masimalai (2019)	Blend of orange peel biodiesel & L-ascorbic acid	To investigate the performance & emission profile of a diesel engine powered by a blend of orange peel biodiesel & L-ascorbic acid.	For the orange peel biodiesel blends, the BTE recorded ranges from 26.8% to 27.9%, while diesel gives a BTE of 30.5%. The BSEC recorded for the orange peel biodiesel fuel blends ranges from 15.2 kJ/kWh to 16.2 kJ/kWh, while diesel produces a BSEC of 13.3 kJ/kWh.	The range of NO_X & HC emission for the orange peel biodiesel blends is 507 ppm to 670 ppm & 53 ppm to 58 ppm respectively. The orange peel biodiesel blends also generate 0.057% to 0.061% CO & 44% to 52%.
Deep et al. (2013)	Blend of orange peel oil methyl ester & diesel	To investigate the emission & performance parameters of orange peel oil methyl ester in a single cylinder diesel engine	For the fuel blend that contains 10% orange peel oil methyl ester, a BSEC of 16.58 MJ/kWh was recorded & the BTE observed is 13.3% higher than that of diesel. The fuel blend with 20% biodiesel yields 13.91 MJ/kWh BSEC & a BTE that is 23% higher than that of diesel.	The engine emits reduced CO, NO_X, smoke & HC emission. The fuel blend with 20% orange peel oil methyl ester produces HC emission that is 14% lower than that of diesel.
Karthickeyan et al. (2020)	Blend of orange peel oil methyl ester & diesel	To examine the performance, combustion & emission characteristics of orange peel biodiesel under two different compression ratios	A BTE of 30.44% & 29.29% was observed for the orange peel oil methyl ester blend at compression ratio of 18 & 17 respectively. At compression ratio 18, the BSEC varies from 38.02 MJ/kWh to 11.98 MJ/kWh for the orange methyl ester blend & ranges between 38.85 MJ/kWh to 12.39 MJ/kWh at compression ratio 17.	At a compression ratio of 18, the engine produces 0.04 to 0.21% CO, 23 ppm to 33 ppm HC, 177 to 1481 ppm NO_X. Using 17 as the compression ratio, the engine generates 0.11% to 0.44% CO, 40 ppm to 66 ppm HC, 42 ppm to 920 ppm NO_X.
Thiyagarajan et al. (2021)	Low carbon fuels-blend of karanja oil methyl ester plus orange oil & other biodiesel fuel blends	To reduce CO_2 emissions by comparing the performance & emission of different vegetative oils.	The orange & karanja oil blend produces a BTE & energy consumption level of 32.36% & 11.16MJ/kWh, respectively.	There is a 27.4% reduction in CO_2 emissions, production of 10.35 g/kWh NO_X, 0.25 g/kWh HC, 2.5 g/kWh CO & 47% smoke. The orange & karanja oil fuel blend produces the least CO_2, CO & HC among other low carbon vegetable test fuels.

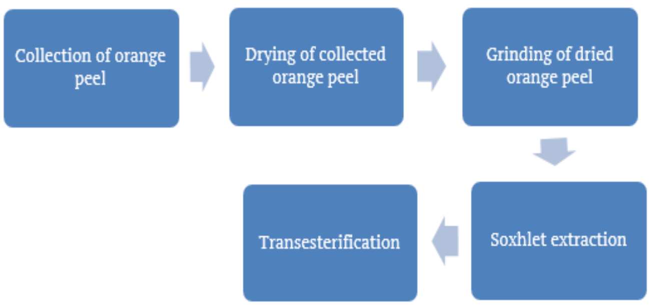

Figure 1. Schematic diagram of orange peel biodiesel production

Figure 2. The orange peel biodiesel on a magnetic stirrer

orange peel. An approximate mass of 10 kg of orange peel yielded 550 mL of oil. The solvent used for this extraction was n-hexane and 7.5 liters was used for this work. After obtaining the OPO, transesterification process was carried out to produce the orange peel based biodiesel. Five gram of NaOH crystals was dissolved in 181mL of methanol in order to form a methoxide. The methoxide was mixed with the 550 mL OPO, which had been heated to about 60^{O}C (**Figure 1**).

Using a magnetic stirrer (**Figure 2**), the solution was stirred for 45 minutes under 60^{O}C in order to ensure uniform reactivity and also accelerate the process. The mixture was left for 24 hours. This prompted the formation of two distinct layers of glycerol and ester. The glycerol was separated from the ester, which is the main biodiesel. For the sake of blending the biodiesel with cashew nut shell liquid, it was divided into two. A portion was isolated as pure orange peel biodiesel, while the second was blended with 30% cashew nut shell liquid. This

Table 2. The physico-chemical properties of orange peel biodiesel and its blends

	B100	B70	Diesel	Method	Test instrument
PH	13.72	7.38	6.0	ASTM E70	PH meter
Fire point (°C)	55	98.5	71	ASTM D1310	Tag open-cup apparatus
Flash point (°C)	53.5	95	67	ASTM D3828	Seta flash flashpoint tester
Density (g/cm^3)	0.8762	0.9332	0.83	ASTM D891	Pycnometer
Kinematic viscosity (Centistokes)	2.7	10.2	3.2	ASTM D445	Ostwald viscometer
Dynamic viscosity (Centipulse)	2.3414	9.5184	2.656	--------	---------
Pour point (°C)	-9.44	-14.44	-5	ASTM D97	Cloud & pour point cryostat
Cloud point (°C)	-16.39	-12.22	-2	ASTM D2500	Cloud & pour point cryostat
Cetane number	54.4	48.34	45	ASTM D976	--------
Calorific value (MJ/kg)	38.8	39.64	43.2	ASTM D420	Digital bomb calorimeter

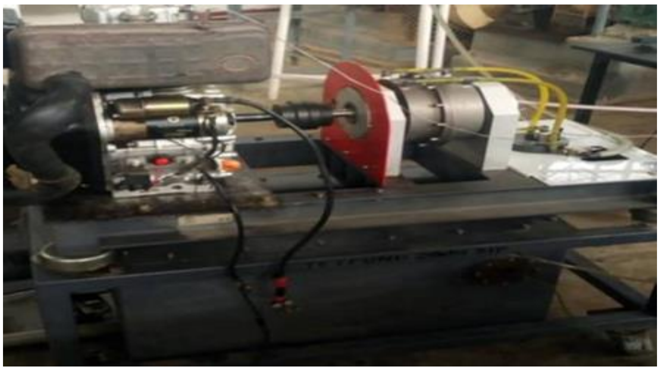

Figure 3. The engine-dynamometer setup

Table 3. Engine specification

Engine test set makeup	TecQuipment TQ
Test set model	TD 300
Name & model of engine	OEM HR198FA
Engine type	Compression ignition engine
Cylinder	Single
Nature of cooling	Air cooled
Stroke	4
Engine capacity (cc)	663
Rated speed (rpm)	3000
Maximum speed (rpm)	3600
Rated power (kW)	9
Maximum power (kW)	9.9
Starting system	Recoil or electric starter

same blend ratio had been used in past works to obtain optimal engine performance and low emission. Devarajan et al. (2017), Fadairo and Ip (2021), and Rameshbabu et al. (2020) reported in their work that fuel blend that contains 70% biodiesel and 30% additive yields low emission as well as optimal BTE and BSFC. The cashew nut shell liquid used for this study was obtained from Abod Cashew Factory, Ogun State, Nigeria.

The properties of the test fuels obtained were then evaluated and recorded in **Table 2**. For the calorific value and cetane index, the standard followed in the work of Bangjang et al. (2014), Kumar and Kumar (2019) and Siva et al. (2019) was used in this study.

Engine Setup

The engine used for the experiment is a naturally aspirated, air-cooled, four stroke, and direct injection single cylinder compression ignition engine (**Figure 3**). Its specification is highlighted in **Table 3**. The engine test bed consists of a data acquisition unit, fuel supply system, and a dynamometer. The engine test was carried out using B100, B70, and diesel. Several parameters, which can be largely categorized into performance and emission parameters, are used as criteria in comparing the efficacy of the test fuels in a compression ignition engine. These include the BTE, BSFC, and the components of the emission. The analyzer used in generating the emission profile of the test fuel was NHA–506 nanhua automotive exhaust gas analyzer.

Table 4 contains the range and percentage uncertainties of the emission analyzer. The approach used in the work of Agbulut et al. (2019) and Pilusa et al. (2012) was followed to calculate the emission in terms of g/kWh. It involves the conversion of the value of the emissions from concentrations (ppm/ % vol) to g/kWh by using the equations below.

Table 4. Range/percentage uncertainties of emission analyzer

Parameter	Range	Percentage uncertainties
HC	0-9999 ppm	±12 ppm
NO_X	0-5000 ppm	±1 ppm
CO	0-10 vol %	±0.06 vol %
CO_2	0-18 vol %	±0.1 vol %

Table 5. Percentage uncertainties of performance parameters

Parameter	Percentage uncertainties
Brake power	±1.06 %
BTE	±0.1%
BSFC	±0.01 %

$$HC\ (g/kWh)=2.002\times10^{-3}\times HC\ (ppm)$$

$$NO_X\ (g/kWh)=6.636\times10^{-3}\times NO_X\ (ppm)$$

$$CO_2\ (g/kWh)=3.591\times10^{-3}\times CO\ (ppm)$$

$$CO_2\ (g/kWh)=63.470\times CO_2\ (vol\ \%)$$

Experimental Uncertainties

Uncertainty and errors from experiments are largely caused by factors like observation, calibration, environment conditions and instrument selection. For this work, **Table 4** and **Table 5** cover the experimental uncertainty of the emission and performance parameters of the study conducted. The data in **Table 4** were sourced from the manual of the emission analyzer used.

The approach used in calculating the uncertainty of the performance parameters in **Table 5** was adopted from the work of Kanth and Debbarma (2021). Given that $X_1, X_2, ..., X_N$ are the results of N number of measurements of quantity X, the uncertainty δ_X is expressed as:

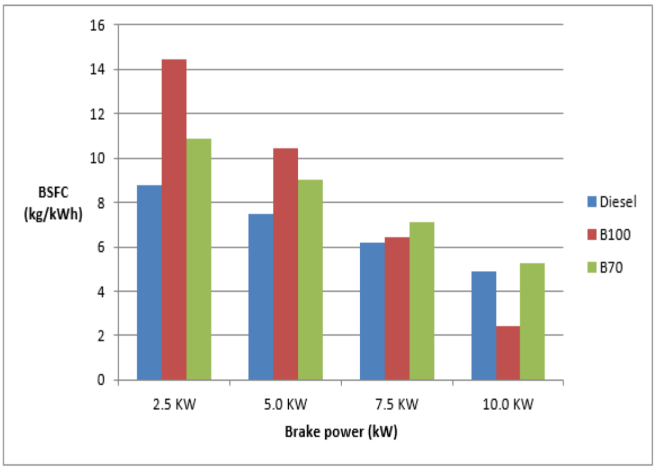

Figure 4. Comparison of BSFC for test fuels under different brake powers

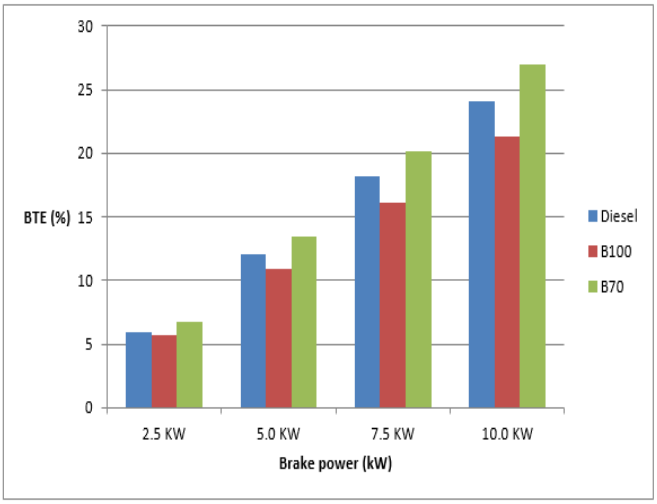

Figure 5. Comparison of BTE for test fuels under different brake power

$$\delta_X = \frac{\sigma X}{\sqrt{N}},$$

where δ_X is standard deviation of the mean and σ_X is standard deviation.

RESULTS AND DISCUSSION

Performance Parameter

Brake specific fuel consumption

The BSFC is simply the amount of fuel needed by the test engine to generate one kilowatt of power output at the crankshaft. For all the fuels, the BSFC decreases with increase in brake power.

Figure 4 compares the BSFC of the fuels examined at different brake powers. From the chart, it is observed that the BSFC decreases with increase in brake power. It was discovered that diesel performs better than B100 and B70. This is due to its higher calorific value. Diesel has a calorific value higher than that of B100 and B70. At 4.5 kW loading condition, the value of the fuel consumption rate in kgs^{-1} for diesel, B100 and B70 is 0.00136 kgs^{-1}, 0.00146 kgs^{-1}, and 0.0148 kgs^{-1}, respectively. This result is consistent with work of Joy et al. (2019). The biodiesel fuels used in their work exhibited higher BSFC when compared with diesel and this is due to the high viscosity of the biodiesel fuel.

Brake thermal efficiency

For the three test fuels, the BTE increases with brake power. This variation aligns with the trend in other related research works.

Figure 5 compares the BTE of the three test fuels under different brake power. It shows that B70 performs better than diesel and B100 at all brake power. This indicates that cashew nut shell liquid is an additive that helps to improve the BTE of a fuel. The BTE of a fuel is not only dependent on its calorific value, other properties play a role in improving the combustion of a fuel, which later results in obtaining high BTE. These fuel properties include lubricity, cetane number and kinematic viscosity. For example, the ignition quality of a fuel in an engine is dependent on its cetane number and this gives an indication of the delay period during combustion. As recorded in **Table 2**, diesel has a cetane number of 45, which is comparatively low to that of B70. Hence, B70 has a better ignition quality than diesel and this may have contributed to improving the BTE of B70. The viscosity of a fuel has an effect on its atomization and vaporization and poor lubricity reduces the performance of fuels in internal combustion engines. Although diesel has a higher viscosity than B100 and this should make the BTE of diesel better than that of B100, the calorific value of B100 is lower than that of diesel and this may have played a role in the reduced BTE of B100. Hence, a single fuel property may not be able to accurately give the prediction of the BTE of a fuel when used in an engine. Furthermore, there is an inverse relationship between BTE and the product of calorific value and fuel consumption rate of a fuel. The product of the calorific value and fuel consumption rate of diesel is slightly higher than that of B70 and this means that it is safe to affirm that the BTE of B70 can be better than that of diesel. Similar trends have been reported in past research works. In a study conducted by Celebi and Aydin (2018), a ternary blend of safflower biodiesel, diesel, and butanol with a calorific value lower than that of diesel has higher BTE.

In this work, the calorific value of diesel was 43,500 kJ/kg and that of the ternary blend was 37,733 kJ/kg. This scenario was also reported in the work of Lin and Lin (2006). In this study, the first biodiesel sample used was obtained by reacting soybean oil with methanol to produce soybean methyl ester, while the second sample was obtained by enriching the first biodiesel sample with hydrogen peroxide. The experimental results obtained in this study demonstrated that the BTE of the two biodiesel samples is higher than that of diesel. The calorific value of the diesel used in this study is 11,035.7 cal/g, while the two biodiesel samples used have a calorific value of 9,715.2 cal/g and 9,687.3 cal/g. At higher load conditions, the BTE of an ultra-low sulphur diesel with a calorific value of 44.8 MJ/kg was less than the BTE of a biodiesel with a lower calorific value as reported in the work of An et al. (2012). The calorific value of the biodiesel is 39.1 MJ/kg. The BTE observed when using the test fuel used in the study conducted by Imtenan et al. (2014) is also greater than that of diesel, while the calorific value of diesel is higher than all the test fuels.

Table 6. Emission parameters in terms of brake specific values (g/kWh)

	HC (g/kWh)	NO_X (g/kWh)	CO (g/kWh)	CO_2 (g/kWh)
Diesel	0.35	1.28	126.76	299.58
B100	0.30	1.06	111.32	252.61
B70	0.27	1.02	111.68	242.46

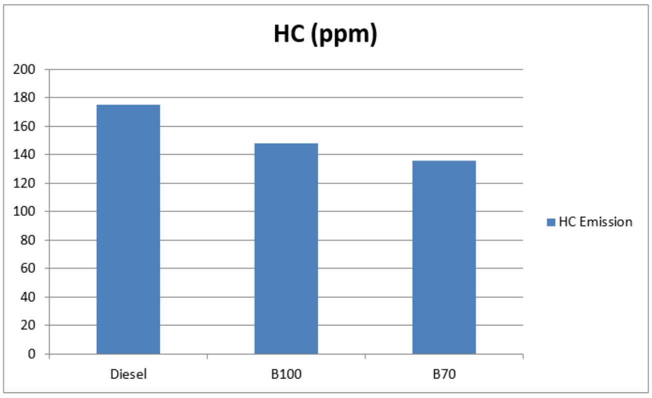

Figure 6. Hydrocarbon emission of the test fuels in ppm

Emission Parameters

The emission properties of the test fuels were obtained when the engine was running under load 4.5 kW and at 1,500 rpm. The emission particles and gases analysed were hydrocarbon emission, nitrogen oxide (NO_x) as well as oxides of carbon. **Table 6** contains the value of the emission parameters in terms of g/kWh.

Hydrocarbon emission

The HC emission profile is presented in **Figure 6**. It was observed that B100 and B70 emitted fewer HC when compared to the conventional diesel. The diesel produced 175 ppm, while B100 and B70 generated 148 ppm and 136 ppm respectively. Hence, the addition of cashew nut shell liquid decreased the level of the production of HC. Formation of HC during combustion is caused by partial combustion of fuel in the combustion chamber and it hugely depends on the operating condition of the engine, the physicochemical properties of the fuel used as well as spray formation. The constituents of HC emissions are majorly incompletely oxidized hydrocarbons, products of the pyrolysis of fuel compounds and some other fuel molecules. The result reported in the work of Devaraj et al. (2020) is consistent with this work. The fuel blends used in this study contains cashew nut shell liquid and these fuels produce less HC emission when compared with diesel. In the work of Karikalan et al. (2021), it was also reported that presence of cashew nut shell liquid in a test fuel leads to a decrease in the level of HC emission.

Nitrogen oxide emission

The rate of NO_X generation was obtained for B100, B70 and normal diesel. **Figure 7** shows the results and the differences of burning these test fuels. B100 and B70 have better performance than diesel in terms of the emission of NO_X. Diesel produces 193 ppm, while B100 and B70 generate 159 ppm and 153 ppm. These values show that there is a slight difference between the NO_X emission value in ppm for B100

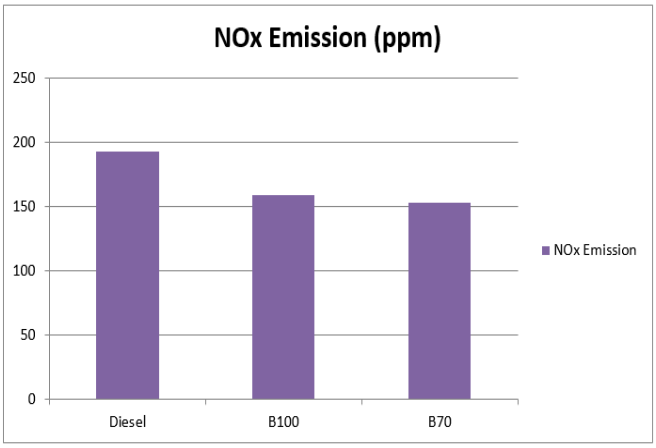

Figure 7. NO_X emission of the test fuels in ppm

and B70. Although the difference is small, it still depicts the fact that the cashew nut shell liquid has the potential of decreasing the production of NO_X in ppm. The fuel with the lowest ppm performs better and this is B70. In the presence of high combustion temperature generated by burning fuel sprays subjected to various local conditions, the combination of nitrogen and oxygen molecule produces NO_X. Hence, conditions like the oxygen content inside the combustion chamber and the combustion temperature are core factors that determine the formation of NO_X. Ignition delay also affects the rate of formation of NO_X. Periasamy et al. (2021) also reported a case similar to the result obtained in this work. In their research, it was recorded that orange peel biodiesel produces less NO_X emission than diesel.

Carbon emission

The study compared and analyzed both the production of CO and CO_2 for the test fuels. B100 emits 3.10% of CO, while diesel and B70 emit 3.53% and 3.11%. The difference between the CO emission of B100 and B70 is 0.01%. This difference appears statistically insignificant, but it could be scientifically consequential.

Diesel gives the least performance in terms of the emission of CO. For CO_2 emission, B100 and B70 produce 3.98% and 3.82% emission. Diesel emitted 4.72% CO_2. This translates to the fact that both B100 and B70 are better than the conventional diesel. Since B70 emits the least CO_2, it is safe to conclude that cashew nut shell liquid is a potent additive that reduces the emission level of CO_2. The representation of the carbon emission is shown in **Figure 8**.

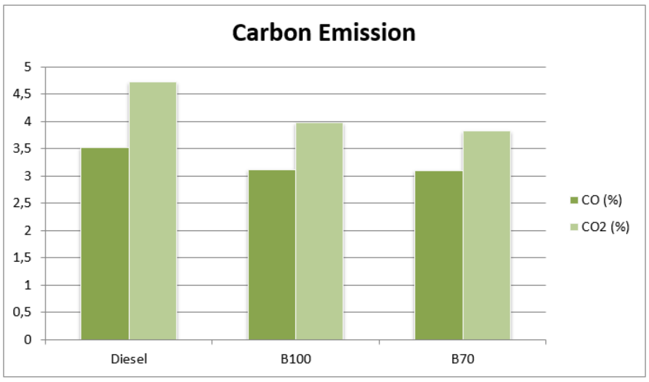

Figure 8. The level of CO & CO_2 emission of the test fuels in %

It has been reported in past research that pure orange peel biodiesel tends to produce high amount of CO_2 emission and reduced CO emission when used in a diesel engine without blending with any additives, which is largely due to the inherent properties of the fuel (Mahesh Kumar et al., 2019; Periasamy et al., 2021; Rathinam et al., 2018). This behavior also aligns with the result obtained in this study.

Result Summary

The performance parameter indicates that the addition of cashew nut shell liquid improved the BTE of B70. The BSFC of diesel was better than that of B100 and B70. Diesel also had the least rate of fuel consumption in kgs^{-1}. In terms of emission, B70 performs better than the other test fuels. It emits the least CO, CO_2, HC, and NO_X.

CONCLUSIONS

Production of biodiesel from wastes is a research pathway currently being explored by different studies for the total valorization of wastes. Orange peel and CNSL are produced in bulk as secondary products of orange juice producing companies and cashew nut factories respectively. Using these wastes as feedstocks and additives to produce environmentally friendly fuel that performs optimally in diesel engines is an option that can be harnessed to derive value from both orange peel and CNSL. This research shows that CNSL is a good additive that improves the performance of orange peel biodiesel. The performance and emission parameters of the blend of the cashew nut shell liquid and orange peel biodiesel are excellent. B70, with a calorific value of 39.64 MJ/kg, performs better than other test fuels in terms of BTE at all brake powers. The only performance parameter in which pure diesel performs best is the BSFC. Using pure diesel, the engine consumes 0.0136 kgs^{-1} at 4.5 kW loading condition. For other parameters, the blended fuel performs best. In terms of emission, the blend of orange peel biodiesel and cashew nut shell liquid performs best. Diesel generates 175 ppm HC, 193 ppm NO_X, 4.72% CO_2 and 3.53% CO. B70 emits 136 ppm HC, 153 ppm NO_X 3.82% CO_2 and 3.11% CO, while B100 emits 148 ppm HC, 159 ppm NO_X, 3.98% CO_2 and 3.10% CO. Although there is only a slight improvement in the emission profile of the orange peel biodiesel when blended with cashew nut shell liquid, the fact that there is some bit of improvement is enough a justification. The little improvement still shows that cashew nut shell liquid is a good additive for orange peel biodiesel.

Since the feedstock for B100 and B70 are waste, the fuel is still the best choice when compared to other conventional fuels. Cashew nut factories, local orange sellers and companies that generate orange peel in bulk can get value out of it and even use it to produce the fuel used in their firms. Future research can focus on improving B70 and also look for a way to optimize its BSFC. Techniques like preheating of fuel, improving fuel injection pressure, reduction of ignition delay and optimizing fuel injection timing could also be employed to improve the performance of B70. With this anecdote, it is safe to conclude that fuel is good for compression ignition engines.

ABBREVIATIONS AND SYMBOLS

ASTM	American Society for Testing and Materials
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
B100	Pure Orange Peel Biodiesel
B70	Blend of 70% Orange Peel Biodiesel and 30% Cashew Nut Shell Liquid
CO	Carbon monoxide
CO_2	Carbon(IV)Oxide
HC	Hydrocarbon
NO_X	Nitrogen Oxide

LIST OF UNITS

	Unit
Brake Power	kW
Brake Specific Energy Consumption	kJ/kWh
Brake Specific Fuel Consumption	kg/kWh
Brake Thermal Efficiency	%
Calorific Value	MJ/kg
Cloud Point	°C
CO Emission	%
CO_2 Emission	%
Density	g/cm3
Dynamic Viscosity	Centipulse
Fire Point	°C
Flash Point	°C
Fuel Consumption Rate	kgs^{-1}
Hydrocarbon Emission	ppm
NO_X Emission	ppm
Pour point	°C
Speed	rpm

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