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Energy, Emissions and Exergy Analyses of Ethanol-Biodiesel-Coconut Oil Ternary Fuel Blends and Comparative Assessment of Their Performance in Compression Ignition Engines

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Abstract: *The demands on future energy conversion technologies are becoming increasingly stringent. Biofuels, which are considered to have a critical role in meeting growing energy needs, must find increasing avenues for compliance. Accordingly, ternary fuel blends have received significant attention because their physiochemical properties can be very similar to diesel, while overcoming some challenges associated with traditional biofuel use. Consequently, this work assesses the use of alcohol-biodiesel-vegetable oil blends in Compression Ignition (CI) engines. Three ethanol-biodiesel-vegetable oil blends were developed using 10%, 20% and 30% alcohol and their performances were compared to diesel and neat coconut oil. These blends were tested in a single cylinder diesel engine and their performances assessed using energy, emissions and exergy analyses. The results indicated that the blends had better brake thermal efficiency (BTE) values than diesel at high to medium loads, with the E30 blend having the highest BTE value of 31% at full load conditions as compared to 28.9% for diesel. The blends were also found to be comparable to diesel based on a First Law energy analysis. Additionally, it was found that the blends had better nitric oxides (NO) emission levels than diesel; at full load conditions, the E30 blend had the lowest value of 281 ppm as compared to diesel having a value of 299 ppm. However, they were found to have comparable levels for the other emissions characteristics that were examined. Further, the Second Law analyses indicated that the blends made better use of their fuel energy potential and thus, can be considered as a more suitable fuel for CI engine combustion. Collectively, the results suggest that the ternary blends are a viable candidate for future energy conversion via CI engines.*

Keywords: *Ternary blends; ethanol; coconut oil; CI engines; exergy analysis; alternative fuels*

1. Introduction

The role of energy in the advance of human civilisation is perhaps more critical than it has ever been. As the global population increases towards a projected 9 billion by 2050 and the economic prosperity of some nations continues to rise, the demand for increased energy utilisation is inevitable. At the same time, the increasingly evident impacts of changes in the global climate are presenting new challenges to many societies. In keeping with this, increased access to renewable and sustainable sources of energy with minimal emissions over their life cycles, are critical to meeting the growing global demand in a manner that minimises the rise in global surface temperatures. Concurrently, energy conservation and efficient energy utilisation are critical to keeping the growth of demand within manageable limits. Thus, technologies such as cogeneration, enhanced recovery and other methods that increase system efficiency are critical to ensuring that the maximum amount of available energy is extracted from a particular energy source.

Notwithstanding, the requirements for grid stability and dispatchability place further demands on energy conversion technologies. This must all be achieved in a manner that takes into consideration the existing energy architecture, identifying a transition pathway that is ultimately financially feasible. Consequently, the demands being placed on energy sources and their associated technologies, are perhaps more rigorous, multifaceted and stringent than ever before.

Biofuels have been identified by many as a potential energy source capable of contributing meaningfully to meeting the future of global energy demand. They are renewable with almost net zero emissions if implemented correctly. They can utilise existing energy architecture with little to no modification, making them more financially accessible and thus, easy transition pathways for many nations. Further, given their compatibility with existing energy conversion equipment such as IC engines and gas turbines, they easily meet the requirements for grid stability and for dispatchability. Thus, they make an excellent choice for base load power generation and can also complement non-dispatchable sources like wind and solar. Accordingly, the identification of suitable biofuel sources that perform sufficiently well with existing technologies and that have sufficiently available quantities, continues to be an area of much research.

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As first-generation biofuels, vegetable oils have long been considered as a substitute for diesel in power generation, particularly in internal combustion engines. Their relatively high calorific values, good lubricity and higher oxygen content than diesel, are favourable physiochemical properties for compression ignition (CI) engine performance. Accordingly, many investigators have examined the use of various vegetable oils in CI engines, and under varying conditions (Tippayawong and Wongsiriamnuay, 2002; Agarwal and Rajamanoharan, 2008; Haldar et al., 2008; Hellier et al., 2015; Haozhong et al., 2016). However, their use has been plagued by several issues such as gum formation, choking of injector nozzles, carbon deposit build-up, crankcase oil dilution and ring sticking to name a few (Ramadhas et al., 2004; Salmani et al., 2015). The literature provides many reviews which summarise their use in CI engines and details the key issues for consideration (Ramadhas et al., 2004; Corsini et al., 2015). Much of these issues continues to persist when neat vegetable oil biofuels are considered. In like manner, alcohols such as methanol and ethanol have also been considered as potential liquid biofuels. Their fast-burning rates, low viscosities and highly oxygenated nature, improve spray characteristics and usually facilitate good combustion in CI engines.

Further, their low cetane numbers and high latent heats of vaporisation cause a longer ignition delay and produce higher heat release rates and lower in-cylinder pressures, when compared with that of diesel (Zaharin et al., 2017). As such, many researchers have investigated their use via differing methods and yielding differing results (Mitchell et al., 1991; Seko and Kuroda, 1998, 2001). However, the general issues of low lubricity, low cetane number and lower calorific content, present significant challenges that must be overcome (Stone, 1999; Rossomando et al., 2017). Consequently, neat alcohol use in CI engines is usually discouraged.

Fuel blending is a common approach to addressing the challenges of neat vegetable oil and/or neat alcohol use in CI engines. It potentially leads to a fuel with enhanced physiochemical properties and can be more economical than other methods such as transesterification (Murray et al., 2019). Moreover, it potentially increases the quantities of suitable fuel available by incorporating fuel components that may be infeasible as standalone fuels. In keeping with this, much research has targeted the use of binary blends in CI engines. Blends of diesel and various vegetable oils have been thoroughly investigated and reported on.

In general, these blends have been found to exhibit better emissions than neat diesel but yield lower power outputs and lower efficiencies (Corsini et al., 2016; Haozhong et al., 2016; Che Mat et al., 2018). Similarly, binary blends of diesel and alcohols have also been investigated. These have generally led to higher efficiencies and better emissions than neat diesel. However, lower power outputs, higher fuel consumption and phase separation issues have challenged their suitability (Huang et al., 2004; Bayraktar, 2007; Yao et al., 2007; Sahin et al., 2015). In like manner, researchers have investigated the use of blends of diesel and biodiesel. These blends have been shown to have similar physiochemical properties to neat diesel (Kumar et al., 2016).

Like the blends of diesel and alcohols, these blends have led to better emissions and higher efficiencies; however, they have also led to lower BTEs and power outputs (Heidary et al., 2013; Habibullah et al., 2014; Siavash et al., 2015; Kumar et al., 2016; Ashok et al., 2018). Moreover, biodiesel addition in these binary blends has also been shown to decrease the rate of wear in engine components, due to its higher lubricity (Singh et al., 2018a 2018b). In the recorded instances of improved performance, the result has been attributed in large part to the highly oxygenated nature of the alcohol or biodiesel. The higher lubricity and lower viscosity of biodiesel have also been found to contribute positively to these effects (Senthil Kumar et al., 2003; Mistri et al., 2016; Agarwal et al., 2018; Patel et al., 2018). Lastly, several researchers have also examined the use of vegetable oil and alcohol blends. In almost all instances, alcohol addition has led to increases in brake thermal efficiency, specific fuel consumption and better emissions than both diesel and the neat vegetable oil (Senthil Kumar et al., 2003; Che Mat et al., 2018). However, power output was generally found to be lower than diesel and higher in specific fuel consumption.

Notwithstanding, researchers have reported some limitations with binary blends. Key among these are lower cetane numbers, higher viscosity and limited miscibility among the fuel components (Ali et al., 2016; Rossomando et al., 2017; Redel-Macias et al., 2017). More specifically, Shahir et al. have reviewed the work done on the use of diesel-biodiesel-ethanol blends (Shahir et al., 2015). They reported that a diesel–biodiesel– ethanol/bioethanol blend has improved physicochemical properties as compared to a diesel–biodiesel or diesel–ethanol/bioethanol blend separately. Redel-Macias et al. (2017) have also reported improvements in physiochemical properties for ethanol-castor oil-diesel blends, as compared to ethanol-diesel blends. Similarly, Hassan et al. have reported improvements in engine behaviour for diesel-biodiesel-butanol blends, as compared to a diesel-biodiesel blend (Hassan et al., 2018). These reports indicate that ternary blends have the capacity to yield better physiochemical properties and consequently, engine performance than binary blends. Accordingly, the research into ternary fuel blends is a current area of great focus (Atmanlı et al., 2014; Yang et al., 2016; Mofijur et al., 2016; Saleh and Selim, 2017; Prakash et al., 2018).

A review of the literature has revealed that the greater proportion of the investigation into the use of biofuels and their blends focus on an energy or first law analysis and not on an exergy analysis. As such, insight into the use of the biofuel is limited to open-system applicability and a more detailed understanding of the efficacy of energy conversion and utilisation is not presented. In the instances where exergy analyses were conducted, the results sometime vary but often indicate favourable potential. Kul and Kahraman (2016) conducted energy and exergy analyses of biodiesel-diesel blends in CI engines. They found that the exergy associated with mechanical power output decreased while exergy destruction increased, as the percentage of biodiesel in the blend increased. However, though slightly lesser, the exergy associated with the exhaust gases was comparable to that of neat diesel. Other researchers have found similar results for the fuel blends examined (Panigrahi et al., 2016; Nazzal and Al Doury, 2019). Conversely, some researchers have reported on fuel blends with higher exergy efficiencies and even lower exergy destruction values than diesel, indicating a better utilisation of the inherent fuel energy (Reddy et al., 2018). Collectively, the literature suggests that the exact result of such analyses is highly dependent on the nature of the biofuel being examined.

To date, the approach to the development of ternary blends, usually involves the use of diesel as a blend component in order to achieve stability or attain specific fuel properties that are within an acceptable range. However, the work presented by the aforementioned researchers suggests that the development of ternary biofuel blends with vegetable oils and alcohols as key components are in fact possible. It suggests that such blends are likely to yield comparable physiochemical properties to diesel, overcome the issues associated with neat vegetable oil or alcohol use and potentially yield better engine performance. In light of this, this work develops an ethanol-biodiesel-vegetable oil ternary blend and examines its performance in a CI engine.

Varying blend constitutions are investigated and compared to neat diesel operation, in order to better understand the behaviour of this class of ternary blend. The work reports on the results of energy analyses, emissions analyses and exergy analyses for the various blends, thereby facilitating a more holistic assessment of the suitability of the blends for modern energy conversion arrangements. In doing so, this work seeks to provide insight into the suitability of these ternary blends and the wider technique of fuel blending, as a means of providing viable biofuel sources for future energy utilisation.

2. Materials and Methods

2.1 Blend Development

This work assessed the performance of three alcohol-biodiesel-vegetable oil blends. Coconut oil was used as the vegetable oil component in all blends tested during experimentation. The selection of coconut oil was primarily due to its availability. However, though coconut oil has a slightly higher cetane number than most other edible and inedible vegetable oil sources, its viscosity, density, flash point and heating value are all very similar (Baharak et al., 2016).

In the absence of any other distinguishing fuel properties and taking into account differences in calorific content, it is expected that the use of coconut oil will yield results that are indicative of other vegetable oils. Coconut oil was also trans-esterified with methanol to produce biodiesel and was used as a component in the blend. The coconut oil biodiesel (CME) was used both as a fuel component and a surfactant, facilitating mixing of the alcohol and vegetable oil components. Lastly, the alcohol used in experimentation was ethanol. Its selection was based on its known properties and reported combustion performance. Ethanol was obtained as a laboratory grade chemical, at a purity of 99.9%.

For the purposes of these tests, the ethanol was not obtained from bio-renewable sources due to limited availability. For each fuel test, 1.5 L of the respective blend was prepared and used over the entirety of the test. In all cases, the blends were produced by mechanical mixing of the blend components for a period of 3-4 minutes.

A total of five fuels were tested in this work. This comprised of three fuel blends, neat coconut oil and neat diesel. The blends that were tested were as follows: an E10 blend, an E20 blend and an E30 blend. By increasing the ethanol content gradually, the work sought to examine the impact of increasing ethanol proportion upon blend performance. The composition of each blend is given in Table 1. In general, 5% more biodiesel by volume than the alcohol percentage was used in the development of the blends. These relative proportions were found to produce more stable fuel blends based on previous work done (Murray and Wyse-Mason, 2018).

Table 1. Composition of the Various Fuel Blends

Fuel blend	% Ethanol by volume	% Biodiesel by volume	% Coconut oil by volume
E10 blend	10	15	75
E20 blend	20	25	55
E30 blend	30	35	35

2.2 Engine Testing Procedure

In this work, the experimentation was conducted using a single cylinder, four-stroke, CI engine unit. The unit was developed for testing and its specifications are given in Table 2. All engine settings inclusive of throttle, fuel injection timing and fuel injection pressure, were kept constant during experimentation. The unit also contained a dynamometer, which was coupled to the engine and this allowed the engine load to be controlled. In addition, the unit was equipped with instrumentation which allowed for the measurement of air consumption, cooling water flow rate, temperatures and dynamometer force.

Exhaust gas temperatures were obtained by installing a thermocouple at the exhaust of the engine and engine speed measurements were taken from the engine shaft via a tachometer. Exhaust gas analyses were also conducted during experimentation. These comprised of two differing measurements. The first involved the measurement of engine emissions using an Enerac 700AV exhaust gas analyser. The second measurement concerned the assessment of smoke concentration. Smoke concentration measurements were made using an Applus Autologic smoke meter, model 310-0432. Exhaust gas temperatures and all emission samples were taken end-of-pipe, before being safely vented to the atmosphere. Exhaust gas measurement units both utilised the probe approach and offered real time data monitoring and recording.

Table 2. Engine Specifications

Parameter	Value
Manufacturer	Plint Engineers (UK)
Bore/mm	87.3
Stroke/mm	110
Swept volume/cm^3	659
Compression ratio	16.5:1
Fuel injection pressure/ MPa	20 – 22.1
Fuel injection timing / degrees	24° before TDC
Rated speed /rpm	1800
Capacity /kW	7

The engine unit was retrofitted with a second fuel tank and all fuel blends were placed in this tank (see Figure 1). Conversely, the built-in fuel tank that was supplied by the unit's manufacturers was considered the primary tank and this was only used to store neat diesel. The process of experimentation began by filling the primary tank with neat diesel and then the secondary tank with the fuel blend to be examined. The unit was then started using neat diesel and allowed to run for ten minutes. The purpose of this initial period was to allow the engine to arrive at normal operating conditions and this was evidenced by the stability in the measured parameters.

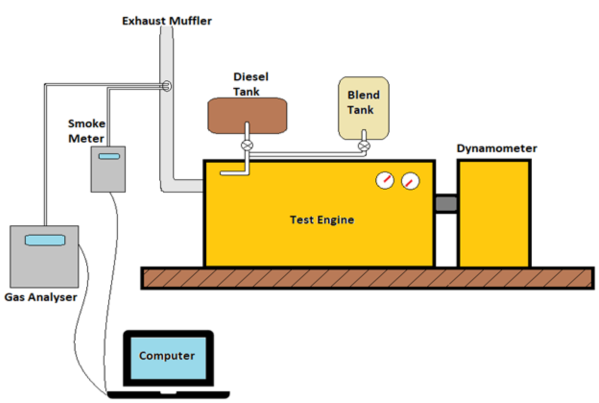

Figure 1. Schematic Diagram of Experimental Setup

Subsequently, the primary fuel tank was switched off and the secondary tank was switched on, allowing the engine to run using the fuel blend under consideration. The engine was then allowed to run for five minutes to arrive at fully developed conditions, using the fuel blend being tested. The various measurements were then recorded for six loading conditions, with the engine being allowed to achieve fully developed operational conditions each time the load was changed. All five fuels were tested using this procedure and the procedure was repeated for each fuel. The recorded engine parameters were subsequently used in the energy, emissions and exergy analyses.

2.3 Estimated Fuel Blend Properties

Given the prominent nature of the blend components and the standard mixing method used, homogenous blend theory was considered a suitable approach for estimating the blend properties in the absence of empirical equipment. This approach has been used by other researchers in similar circumstances and was proven to be very reliable (Atmanli et al., 2015; Rossomando et al., 2017). In keeping with this, the fuel properties of density, viscosity, cetane index and lower heating value (LHV) were estimated using Equations 1 through 4, respectively.

In Equations (1) to (4), *b* represents the calculated parameter for the blend; *x* represents the percentage volume of a blend component and *i* corresponds to a blend component.

$$\rho_b = \sum_{i=1}^{3}(x_i \rho_i) \quad (1)$$

$$\nu_b = \sum_{i=1}^{3}(x_i \nu_i) \quad (2)$$

$$CI_b = \sum_{i=1}^{3}(x_i CI_i) \quad (3)$$

$$LHV_b = \sum_{i=1}^{3}(x_i LHV_i) \quad (4)$$

$$\beta = 1 - \frac{a\varphi^b}{(t_{id})^c} \quad (5)$$

The properties for each blend component are presented in Table 3. Equation (5) was used to estimate the premixed burn fraction (β) for each blend, using the equivalence ratio (φ) and the ignition delay (t_{id}). The constants *a*, *b* and *c* were empirically determined and were specific to the engine studied, while φ and t_{id} were calculated based on other equations presented in Stone (1999). The estimated fuel properties are presented in Table 4.

Table 3. Fuel Properties for the Three Fuel Components of the Ternary Blends and Diesel

Fuel property	Ethanol	Biodiesel	Coconut oil	Diesel
Density (ρ) @ 15˚C (kg/m^3)	785	874.6	930	862.5
Viscosity (ν) @ 40°C (cst)	1.07	2.74	26.19	9.56
Cetane Index (CIn)	7	41	39	47
Lower Heating Value (LHV) (kJ/kg)	26,800	35,200	35,317	42,600

Table 4. Estimated Fuel Properties of the Ternary Blends

Fuel blend	Density (ρ) (kg/m^3)	Viscosity (ν) (cst)	Cetane Index (CIn)	Lower Heating Value (LHV) (kJ/kg)	Estimated Premixed Phase Burn Fraction (%)
E10	909.5	20.2	36.1	34562	9.63
E20	890.8	15.3	33.1	33780	11.7
E30	871.3	10.5	30.1	32961	13.9

2.4 Energy Analyses and Performance Assessments

The energy or First Law analyses were conducted to gain quantitative insight into the use and distribution of the energy delivered to the engine unit by the fuel. For the purposes of these analyses, the engine unit is considered as a control volume with the following assumptions:

- Standard conditions were evaluated at 1 atmosphere (P_0) and 25°C (T_0).
- The engine unit operates at steady-state conditions.
- The combustion processes of all fuels tested can be modelled as complete combustion.
- Air is a gaseous mixture that consists of approximately 21% oxygen and 79% nitrogen.
- All gases in the system can be modelled as ideal gases.
- All liquids in the system can be modelled as incompressible liquids.

As a consequence, the energy interactions of the system were modelled and evaluated using Equation (6).

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e\right) \quad (6)$$

Further to this, the engine unit's performance was assessed using the performance indicators of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). Using the parameter data recorded during testing, these performance indicators were calculated using the following equations:

$$Brake\ power\ (BP) = BT * \omega \quad (7)$$

where *BT* is the brake torque measured from the dynamometer and ω is the engine operational speed.

$$BTE = {BP}/{(\dot{v} * \rho * LHV)} \quad (8)$$

where $\dot{v}$ is the fuel volume flow rate, ρ the fuel density and *LHV* the fuel's lower heating value.

$$BSFC = {\dot{m}}/{BP} \quad (9)$$

where $\dot{m}$ is the mass flow rate of the fuel.

2.5 Exergy Analyses

The exergy analyses were conducted to provide insight into the quality of energy utilisation and the efficacy of the combustion processes for the various fuels tested. The primary assumptions presented in the energy analyses of the previous sub-section, were also considered to be applicable for these analyses. In keeping with this, the exergy interactions for the system were modelled using Equation (10).

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i\, ex_{f,i} - \sum_e \dot{m}_e\, ex_{f,e} - \dot{Ex}_d \quad (10)$$

The first summation term of Equation (10) represented the exergy associated with heat transfers. This was attributed to the heat losses to the cooling water. The second term was associated with the brake power output of the engine. Further, the last term of Equation (10) represented the exergy destruction rate.

The terms associated with the second and third summation signs of Equation (10) represented the flow exergy of the inlet and outlet streams respectively. The flow exergy ex_f is more completely represented by Equation (11). Further, the chemical exergy component ex^{ch} of Equation (11) was determined using Equation (12) if the stream consisted of a fuel, or via Equation (14) if it consisted of a gas or gaseous mixture. In instances where the stream consisted of a fuel, Equation (12) was evaluated using Equation (13), where h, c, o and α represented the mass fractions of hydrogen, carbon, oxygen and sulphur in the fuel, respectively (Kul and Kahraman, 2016; Nazzal and Al Doury, 2019). For Equation (14), the chemical exergy was evaluated on a molar basis where y_k represented the mole fraction of the kth component in the mixture at standard conditions, while y_k^e represented it in the environment (Moran and Shapiro, 2000).

$$ex_f = (h - h_0) - T_0(s - s_0) + \frac{v^2}{2} + gz + ex^{ch} \quad (11)$$

$$ex_{fuel}^{ch} = LHV\varphi \quad (12)$$

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \quad (13)$$

$$\overline{ex}_k^{ch} = \bar{R}T_0 \sum_k y_k \ln\left(\frac{y_k}{y_k^e}\right) \quad (14)$$

3. Results and Discussion

3.1 Engine Performance Assessment and Energy Analyses

Figures 2 presents the brake thermal efficiency (BTE) results for the five fuels tested. As shown, the highest BTE value recorded at full load was for the E30 blend. This was an average value of 0.312 and had a variation of 2.5% between values. Conversely, the lowest BTE value at full load was recorded for neat coconut oil. It had an average value of 0.272 and a variation of 6.3% between values. In general, the average values recorded for all fuels at the various load conditions, showed variations of less than 5% between the two trials. Coconut oil was the only exception to this, with a maximum variation of approximately 10% at the 20% load condition. Thus, the results generally demonstrated good consistency.

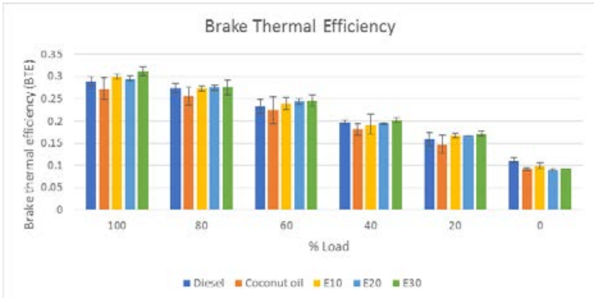

Figure 2. Brake Thermal Efficiency Values for the Five Fuels tested

Of the various trends noted from Figure 2, perhaps the most interesting is the higher BTE values associated with the fuel blends. All three fuel blends yielded higher BTE values than diesel at the 100%, 80%, 60% and 20% load conditions, while the E30 blend also had a higher BTE value at 40% load. This is a welcomed result, as most of the ternary blends reported in literature generally yielded lower BTE values than neat diesel. More importantly however, this result indicates that more of the fuel energy of the ternary blends is being converted or used for brake power. Thus, the blends can be considered to be more efficient than diesel in achieving the goal of generating brake power. This result is likely a consequence of differences in the combustion processes due to the presence of the alcohol in the ternary blends and will be further explored in the subsequent sections.

The second notable trend concerns the variation in BTE values among the three blends. In general, it was found that BTE increased with alcohol addition across all load conditions. Thus, the E30 blend generally had the highest BTE values, while the lowest of the three was recorded for the E10 blend. Once more, this result points to the significance and role of ethanol in the ternary blend's combustion process. Conversely, the low BTE values for neat coconut oil can be attributed to the issues previously discussed in the literature review, such as higher viscosity and poorer atomisation.

Figure 3 shows a reversed trend to that seen in Figure 2. Here, the lowest specific fuel consumption (SFC) value recorded at full load conditions was for neat diesel. It was an average of 0.293 kg/kWh, with a 2.5% variation between recorded values. In keeping with this, the highest SFC value at full load was recorded for neat coconut oil. This was an average value of 0.375 kg/kWh, with a variation of 6% between recorded values. These results are a consequence of the lower LHVs of neat coconut oil and of the ternary blends as estimated in Table 4. The lower values mean that larger masses of fuel must be consumed in order to produce similar power outputs to neat diesel.

Though all ternary blends have higher BSFC values than diesel, their values are all lower than neat coconut oil, except at the no load condition. This occurs despite the fact that the LHVs of all ternary blends are lower than that of neat coconut oil. This result is a consequence of the higher BTE values of the ternary blends. More specifically, the higher BTE values mean that more of the fuel energy is used and consequently, this decreases the mass of the ternary blend required to achieve the same brake power. With the exception of the no load condition, it would be noted that the BSFC values of the three blends show very little difference. However, both calorific value and density decrease with ethanol addition. Consequently, the general similarity in BSFC values can be attributable to the increasing BTE with ethanol addition.

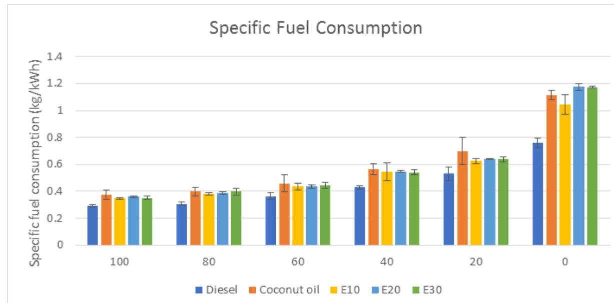

Figure 3. Specific Fuel Consumption Values for the Five Fuels Tested

From an operational standpoint, it is crucial to note that the higher BSFC values for the blends are also somewhat counterbalanced by their increased density. This effect however, decreases with increasing ethanol content. Together, the counterbalancing effects of increased BTE and increased density, mean that though BSFC increases for the blends the actual volume of fuel consumed may not vary significantly from that of diesel for blends of lower alcohol content. However, blends of higher alcohol content are likely to see some increases in volume consumption. Volume consumption can potentially be equivalent to diesel depending on blend constitution. Accordingly, a balance must be found. Given that liquid fuels are often traded on the basis of volume, this is a factor that must be carefully considered.

Figure 4 shows the First Law energy distribution for the five fuels at the full load condition. Given the differences in energy content among the various fuels, the evaluation is conducted on a percentage basis to facilitate better comparisons and a more insightful assessment.

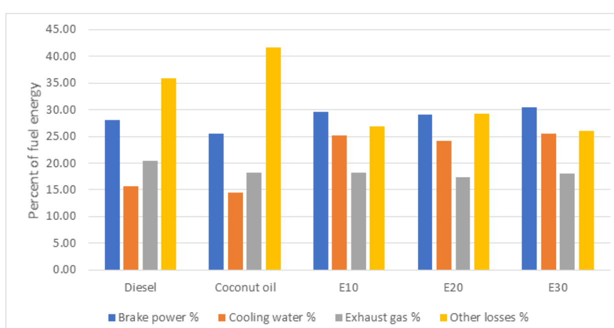

Figure 4. First Law Energy Distribution for All Fuels at Full Load Condition

The first noticeable result is that the E30 blend shows the highest percentage of fuel energy being used for break power generation. This is consistent with the BTE results discussed previously. Another trend of significance concerns the percentage of energy retained by the exhaust gases. It would be noted that the highest level of energy retention in the exhaust gases, is reported for neat diesel operation. This was also found to be true for all load conditions. Thus, with respect to the use of exhaust gases for further energy applications, diesel fuel operation is most suitable. The lowest percentage energy retention in the exhaust gases was recorded for the E20 blend. Further, all blends were also found to have lower percentages of energy in the exhaust gases than neat coconut oil. Nevertheless, these differences are generally between 2-3% and suggest that the exhaust from the ternary blends can likely be put to use for scavenging or cogeneration processes in a similar manner to diesel but are likely to be less efficient.

A consideration of the cooling water and other losses energy distributions, points to key differences between the combustion processes of the ternary blends and that of diesel or neat coconut oil. Firstly, the highest level of other losses is recorded for neat diesel at approximately 41.7%. This is only slightly lower for diesel. However, it is significantly lower for all ternary blends. Conversely, the lowest level of energy losses via the cooling water is reported for neat coconut oil, while the highest levels are reported for the blends. Moreover, the distribution of energy between the cooling water and other losses, is generally equal for all blends but not for neat diesel or coconut oil operation. However, though the results point to some underlying differences in the energy utilisation processes, an exact reason based solely on a First Law analysis is unclear.

3.2 Characteristics of the Emissions

Four exhaust gases and smoke concentration were assessed for all of the fuels examined. For each parameter, the data obtained from the analysers was further statistically assessed to determine its statistical significance. This assessment involved conducting pairwise comparisons of each fuel against the other, using a 95% confidence interval. The assessments were done using the Microsoft Excel, Analysis ToolPak solver add-in. The analyses of the Carbon Monoxide and Dioxide (CO and CO_2) and Unburned Hydrocarbons (UHC) emissions generally yielded the same results, i.e., the emissions of all blends were found to be statistically comparable to that of diesel.

The nitric oxides (NO) emissions results for all fuels are presented in Figure 5. As shown, NO emissions decrease with load for all fuels. This is a consequence of the chemical reaction kinetics associated with NO formation. NO and nitrogen oxides (NOx) formation are known to be influenced by flame temperature and flame speed; formation increases with increasing flame temperature and decreasing flame speed. In keeping with this, NO formation has been known to increase with decreasing engine speed. Thus, as engine speed increases with decreasing load, there is a decrease in NO emissions.

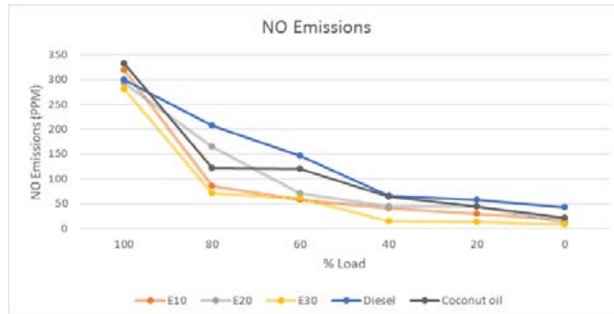

Figure 5. NO Emission Results for the Fuels Tested

Perhaps of greater interest is the comparative emission levels of the five fuels. Figure 5 shows that the highest levels of NO emissions are recorded for diesel and neat coconut oil. This is confirmed by the statistical analyses, which found all of the fuel blends with the exception of the E10 blend, to be significantly lower than diesel. The E10 blend was found to have comparable performance to diesel. In general, the decrease in the NO emissions associated with the blends is likely a direct consequence of the alcohol's high heat of vaporisation and is well documented in the literature. The higher heat of vaporisation of ethanol leads to lower in-cylinder temperatures than diesel during combustion. This in turn negatively affects the thermal mechanism of nitric oxide formation as described by the extended Zeldovich mechanism, resulting in lower NO emissions. This represents a clear advantage in the use of the ternary blends as compared to the use of diesel.

Figure 6 shows the smoke concentration measurements for all of the fuels tested. It shows a general trend for all fuels where smoke concentration decreases around mid-load but rises again to its initial levels at the lower loads. The lowest smoke concentration levels were recorded for the E30 blend and for diesel. The statistical analyses confirm that diesel was found to be less than the E10 and E20 blends, while the E30 blend was found to have a comparative performance.

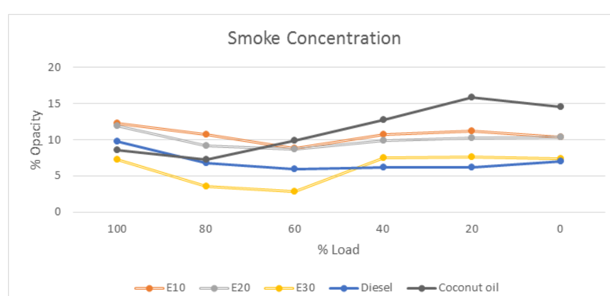

Figure 6. Smoke Concentration Measurements for the Fuels Tested

These results are a consequence of the alcohol concentration and its impact on the fuel blend's viscosity. Smoke concentration is known to be influenced by fuel viscosity. Fuels that are more viscous generally lead to poorer atomisation during injection; this in-turn leads to higher numbers of larger particles present in the exhaust. Accordingly, as alcohol concentration increases viscosity decreases and consequently, there is a decrease in smoke concentration. Alcohol addition is known to have this impact and other researchers have recorded similar decreases for the ternary blends examined. In like manner, the higher smoke concentrations recorded for neat coconut oil can be attributed to its higher viscosity.

3.3 Exergy Analyses

The results of the exergy analyses give insight into the quality of energy utilisation for each fuel. Critical to these analyses is an understanding that the total exergy of the input streams represents the maximum amount of work that can be obtained from the engine using a particular fuel. Here, the total exergy of the input streams is the sum of the fuel exergy and the exergy of the input air. However, the contribution of the input air to the total exergy is always less than 2% of the total. Thus, the total exergy is predominantly determined by the fuel stream. As the value of the total exergy varies for each fuel, a consequence of their varying LHVs, the analyses considered the percentage of the total exergy associated with different aspects of the engine's operation. Figure 7 shows the results of the exergy analyses for diesel fuel across all load conditions. The primary purpose of the exergy analyses in this work, was to facilitate a comparison of energy utilisation in each fuel. However, it is important to examine some key trends in exergy distribution with load variation for an individual fuel, as these trends help to further inform the comparison.

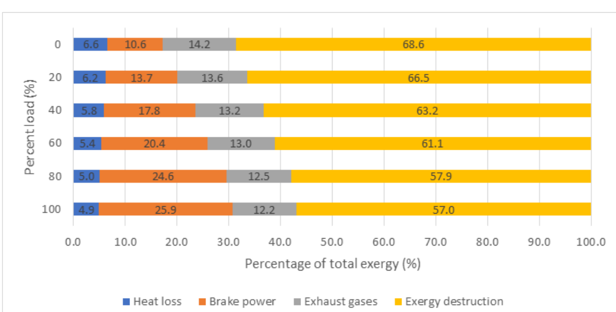

Figure 7. Exergy Distribution for Diesel Fuel at All Engine Load Conditions

The first of these trends concerns the brake power exergy. As can be seen from the figure, brake power exergy was found to decrease with decreasing load. This implies that a decreasing amount of the total fuel exergy is converted to brake power, as the load decreases. This was found to be the case for all fuels examined and is the reason for decreasing BTE with decreasing load. This trend has also been found by other researchers and is a standard feature of normal engine operation. Conversely, there is an increase in exergy destruction as the load decreases. This too is also a standard feature of engine operation and was observed for all fuels tested. However, the distribution of heat loss and exhaust gas exergies vary between the fuels, both in terms of quantities and rates of change. This will be discussed in the subsequent section.

Figure 8 shows the distribution of fuel exergy with respect to key engine operations, for all fuels at the full load condition. In considering these results, it must be recalled that engine combustion is an energy conversion process and providing that combustion is sufficiently complete, the final state is the same for all fuels. Therefore, the exergy analyses provide insight into how the energy of each distinct fuel is used as it moves towards a common final state. Accordingly, the percentage brake power exergy is of immediate interest.

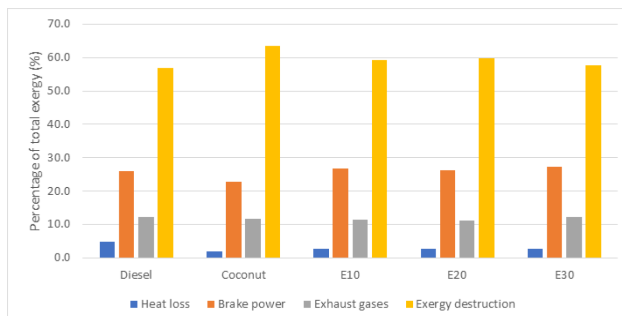

Figure 8. Exergy Distribution for the Various Fuels Tested at Full Load Conditions

It can be seen from the figure that the value for each of the ternary blends is higher than diesel. Further, this was also found to be generally true at the 80% and 60% load conditions. Conversely, at the lower load conditions diesel was generally found to have slightly higher values. The implication of this result is rather significant. It implies that the maximum work potential per unit mass of fuel is lower for the ternary blends than it is for diesel. However, despite being lower, the ternary blends are able to convert more of this potential to actual power output. Consequently, with respect to obtaining brake power, the ternary blends make better use of their lower energy contents than diesel does of its higher energy content. Accordingly, the ternary blends can be considered as a higher quality fuel, or as a fuel that is more suitable for generating power via CI engine combustion processes.

Further to the aforementioned result, it was found that the percentage exergy converted to brake power generally increased with increasing ethanol content across all loading conditions. This is the reason for increasing BTE with increasing alcohol content and can generally be attributed to the alcohol's role in the combustion process. The lower cetane numbers of alcohols cause longer ignition delay periods at the start of combustion. As a consequence, there is a larger premixed phase in the cylinder when combustion begins. This is in keeping with the results of Table 4, which show an increase in premixed fraction for increasing ethanol content. Compounded with their fast-burning speeds, there are faster heat release rates and ultimately higher conversion of the fuel energy to brake power as a result of their addition. Accordingly, this result is more pronounced at higher engine loads where greater fuel volumes are injected into the cylinder. However, at lower engine loads the impact of this phenomenon decreases.

The results for the percentage exergy destruction show that the highest values are recorded for coconut oil. This was further observed to be true for all engine loads. Consequently, the lowest BTE values were also obtained for neat coconut oil as discussed previously and suggest that neat coconut oil is not the most suitable fuel for CI engine operation. Beyond this, it would be noted that the lowest exergy destruction percentages were recorded for diesel and this was also found to be true at all loads.

The percentage exergy destruction for the ternary blends, though lower is comparable to that of diesel at full load. In particular, the E30 blend is higher by only 0.7%. This indicates that although more of the energy potential of the ternary blends is converted into brake power than for diesel, more of this potential is also destroyed. Further, it was found that the percentage of exergy destruction for the blends increased more quickly with increasing load than in the case of diesel operation. This can also be attributed to the impact of the alcohol and its effect of increasing ignition delay. It has been reported by other researchers (Nazzal and Al Doury, 2019) that increasing ignition delay increases the rate of exergy destruction. This would therefore account for the aforementioned result and partially for the increase in exergy destruction with decreasing load, as ignition delay also increases with decreasing load. Consequently, the impact of alcohol addition on the ternary blends simultaneously increases energy conversion to brake power, while increasing exergy destruction.

As shown in Figure 8, the highest recorded exhaust exergy percentage is for diesel. It would be noted however that the exergy allocated to the exhaust gases for all ternary blends is generally similar. As load decreases however, it was found that the exergy allocated to the exhaust gases increases slightly in diesel but not significantly for the ternary blends. Taking into consideration the results of the energy analyses, the quality of the energy in the exhaust gases is comparable for both diesel and the ternary blends. Considering the quantitative differences, both can be used for further applications where possible. However, this is likely to be more efficient for diesel operation.

Regarding the distribution of exergy to the cooling water, results show that a greater percentage of the fuel exergy is transferred away via heat losses, for diesel than for the ternary blends. This result holds true for all load conditions. This is a consequence of the lower in-cylinder temperatures associated with alcohol-based combustion. Lower temperatures result in lower heat transfer rates to the cooling water and the environment.

Given the increased exergy destruction percentages for the ternary blends when compared to diesel, the differences in brake power exergy are generally accounted for by variation in either exhaust gas exergy or heat loss exergy distribution. At the higher load conditions, the ternary blends appear to better utilise the fuel exergy that would be otherwise lost to the exhaust gases or the cooling water, by converting it to brake power. As a consequence, the energy lost to the cooling water in the ternary blends is of a lower quality to that of diesel, though it may be quantitatively larger. This explains the better energy utilisation processes of the blends and their greater suitability for CI engine combustion.

5. Conclusion

This work examined an alcohol-vegetable oil ternary blend and compared its performance to that of diesel in a CI engine. It assessed three configurations of the ethanol-biodiesel-coconut oil blend by conducting energy, emissions and exergy analyses. The results support the findings that blending can improve the physiochemical properties and consequently engine performance of neat vegetable oil. The results indicate that the ternary biofuel blend potentially not only matches the performance of diesel in a CI engine but in some ways surpasses it.

The following points regarding the performance of the ternary biofuel blend were noted, below:

- In the fuel blends between 1-2% more of the inherent energy content is used in the generation of useful power output at full load conditions, when compared to diesel. Approximately 6.5-10% more of the inherent fuel content of diesel is unrecoverable due to losses, as compared to the fuel blends. Based on a First Law analysis, the blends can be considered to be a more efficient fuel than diesel at higher loads, as more of the fuel energy is directed towards achieving the goal of generating brake power.
- The blends have higher BSFCs than diesel. However, this is offset by their higher BTEs and higher densities. At full load conditions, the blends were found to lead to an increase in BTE of at least 0.6%, with the E30 blend has a higher BTE by more than 2%. Thus, the collective effect is to make them comparable to diesel in general operation.
- The blends have better NO emission levels than diesel at all load conditions, with the E30 blend having a lower emission level by approximately 20 ppm at full load. The emission levels of diesel and the fuel blends are comparable with respect to other exhaust gases.
- Based on a Second Law analysis, the blends were found to better utilise their inherent work potential than diesel, at higher to medium load conditions, as

best seen in the E30 blend. Approximately 1.5% more of its work potential is converted into useful output, as compared to neat diesel at full load conditions. They can be considered as a better quality or more suitable fuel for CI engine operation.

To conclude, the ethanol-biodiesel-coconut oil blend can potentially serve as a replacement for diesel in a CI engine and can meaningfully contribute to the future of energy conversion.

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