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Use of cashew nut shell liquid as biofuel blended in diesel: Optimisation of blends using additive acetone–butanol–ethanol (ABE (361))

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ABSTRACT

In this study, the feasibility of increasing the proportion of cashew nut shell liquid (CNSL)-based biofuels in diesel was assessed. Biofuel–diesel blends with different percentages of CNSL were prepared, and their physical properties, including the density, viscosity, and heating value, were determined. B10 (CNSL/diesel = 10:90 v/v) satisfied the diesel specifications without preheating, whereas B20 (20:80 v/v) and B30 (30:70 v/v) met the specifications only after preheating to 60 and 80 °C, respectively. To avoid preheating B20 and B30, an acetone/butanol/ethanol (ABE) mixture (30:60:10 v/v) was added to the fuel blends to improve their flow characteristics. The blends with CNSL/ABE (361)/diesel ratios of 20:10:70 and 30:30:40 (v/v) exhibited properties comparable to those of diesel and remained stable for one month of storage. These fuel blends allow up to 30 vol% CNSL and 30 vol% ABE (361) to be incorporated into diesel and can be used as alternative fuels in diesel engines.

1. Introduction

The world is heavily dependent on petroleum-based fuels, such as diesel, kerosene, petrol, and heavy fuel oil, to satisfy the energy demands of agriculture, transportation, and industry. Diesel engines are preferred in many applications, such as standby and emergency applications in hospitals, airports, hotels, and industries, because diesel exhibits high energy density at a low price (Zaabi et al., 2022). However, the use of diesel contributes to environmental pollution via the emission of higher levels of nitrogen oxides and particulate matter than that of petrol (Kumar et al., 2020). The increase in energy consumption has intensified the volatility of crude oil prices, resulting in concerns regarding the depletion of oil reserves and growing climate change (Adhikesavan et al., 2022). Hence, researchers have begun investigating alternative fuels derived from sustainable renewable resources with low environmental impact.

Biofuels can be easily accessed by rural population and improve energy independence in countries without fossil fuel resources (Aslan et al., 2021). In sub-Saharan Africa, many countries rely primarily on imported petroleum products; however, these countries can utilise their own biomass resources to produce African biofuels, such as cashew nut waste. Africa is the second largest producer of cashew nuts after India, with a production level of approximately 432,026 tonnes in 2017–2018 (Mgaya et al., 2019). Further, in 2000–2019, cashew nuts (with shells) were grown and harvested from 1157,001–4704,272 ha of land in sub-Saharan Africa (Biscoff and Enweremadu, 2023). Following the removal of kernels, large quantities of cashew nutshells were produced (approximately 30,104,678 tonnes). Cashew nutshells contain a dark viscous brown liquid known as cashew nut shell liquid (CNSL). The nutshells contain 25 %–35 % CNSL, which could have potentially generated approximately 6020,935 tonnes of CNSL for the period of 2000–2019 in sub-Saharan Africa. However, the potential of CNSL has not been acknowledged, owing to inadequate knowledge and inefficient technologies. CNSL is a prospective alternative fuel with the potential to benefit both the cashew nut processing and energy industries (Kandaswamy et al., 2023).

The chemical structure of CNSL is similar to that of diesel (C11–C20 range) because of its cardanol composition. With a calorific value higher than that of diesel, CNSL is a potential alternative fuel for diesel engines (Deepanraj et al., 2022). However, its viscosity and density are higher than those of diesel (Senthilkumar et al., 2023). The main issues posed by high viscosity include pumping, atomisation, combustion

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inefficiency, and accumulation of gum deposits (Krishna, 2022). Moreover, a higher viscosity implies a lower fuel flow rate and engine output (Fombu et al., 2023).

Over the past five years, researchers have extensively investigated methods for reducing the viscosity of CNSL for use as a biofuel. Among the various strategies studied, such as transesterification to produce CNSL biodiesel and use of green-diesel-based CNSL from distilled and thermally cracked CNSL, the blending of the CNSL biofuel with diesel is effective (Krishna, 2022). This process does not require chemical treatment, and its cost is limited to the CNSL class.

Senthilkumar et al. (2023) reported that blending CNSL with diesel in different proportions resulted in products with diverse characteristics. To achieve an optimal combustion performance, biofuels must exhibit viscosity comparable to that of diesel (Tosun and Aydin, 2022). Srinivasan et al. (2023) investigated the performance and combustion characteristics of a diesel engine using a thermally cracked CNSL (TC–CNSL) blended with diesel. CNSL was thermally cracked at 350–400 °C using a liquefied petroleum gas burner as the heating source. The properties of TC–CNSL were improved, with a significant decrease in viscosity and density and a slight increase in the calorific value, which were similar to those of diesel. However, the combustion of TC–CNSL in internal combustion engines resulted in low performance and high emissions. The authors stated that a blend of 20 % TC–CNSL is a globally accepted high-performance biofuel for compression ignition engines. Thermal cracking and distillation require high temperatures, which constrain the efficiency of these processes.

A comprehensive review conducted by Adekanbi and Olugasa (2022) concluded that fuel blend B20 (80 % diesel and 20 % CNSL biodiesel) is a promising alternative fuel for diesel engines. Coulibaly et al. (2022) explored the feasibility of using high content of CNSL in stationary diesel engines. To obtain purified CNSL, they mixed CNSL with ethanol, followed by evaporation. Despite the improvements in viscosity and the calorific value, purified CNSL did not exhibit the potential for application as a biofuel. Next, they blended purified CNSL with diesel at different ratios and found that fuel blends with up to 60 % CNSL worked efficiently in a stationary diesel engine. However, this method required considerable amounts of ethanol, and the authors stated that the purification technique requires further improvements. Krishna (2022) investigated the performance characteristics of a diesel engine fuelled by CNSL biodiesel–diesel blends. They prepared the CNSL biodiesel from CNSL via a transesterification reaction using methanol as the reagent in the presence of an acid (catalyst). The CNSL biodiesel was mixed with various proportions of CNSL (5 %–30 %) and diesel, and the authors investigated the performance of diesel engines using CNSL biodiesel blends. A blend of 25 % CNSL biodiesel was concluded to be the most efficient. However, the transesterification reaction requires considerable amounts of alcohol (methanol), and the use of CNSL necessitates pretreatment with sulfuric acid as a catalyst. Moreover, this reaction produces considerable amounts of glycerol as a byproduct, and excess ethanol which needs to be evaporated using a rotary evaporator.

Govindan et al. (2019) investigated the performance and emission characteristics of diesel engines powered by preheated CNSL–diesel blends at various temperatures (60, 70, and 80 °C) with ethanol fumigation. The results indicated that B20 preheated to 80 °C improved engine efficiency and emission levels. However, a preheating system is required to maintain fuel blend properties similar to those of diesel to maintain engine performance.

Many researchers have used additives, such as butanol, acetone, and ethanol, to improve the properties of the CNSL biofuel to improve its performance in diesel engines. Kasiraman et al. (2016) explored the use of the high-density and high-viscosity CNSL fuel blended with butanol at various volumes and analysed its combustion, performance, and emission behaviour. This investigation showed that 30 % butanol in a blend with CNSL afforded the optimum engine performance. Moreover, butanol can be obtained from carbohydrates via an acetone–butanol–ethanol (ABE) fermentation process with a typical ratio of 30 % acetone, 60 % butanol, and 30 % ethanol (361) (Veza et al., 2021). Shantharaman et al. (2021) added acetone (4 %, 8 %, and 12 %) as an additive to CNSL–diesel blends (B20) to increase the content of CNSL and analysed their performance as a fuel in diesel engines. The results revealed that 12 % acetone with a B20 blend serves as a better alternative fuel for diesel engines. Thanigaivelan et al. (2022) tested a diesel engine with TC–CNSL blended with diesel. Ethanol and hydrogen were added to a B20 blend (20 % TC–CNSL, 80 % diesel) at various flow rates. They concluded that a 10 %-ethanol-blended B20 blend with a hydrogen flow rate of 8 L/min exhibited the highest brake thermal efficiency and reduced CO and HC emissions. To the best of our knowledge, no previous studies have used a blend of acetone, butanol, and ethanol as an additive to improve the properties of pristine CNSL and its blends.

Previous studies have demonstrated various techniques for improving the properties of pristine CNSL. However, these techniques are still in the experimental phase and do not facilitate the production of large quantities of CNSL biofuels. Even when the CNSL biofuel is produced, it must be blended up to 20 % with diesel or other additives to achieve a performance close to that of diesel. The use of the low-content CNSL biofuel in blends does not enable the appropriate exploitation of the potential of cashew-nut processing units.

This study sought to address these issues. The novelty of this study lies in the improvement of the fuel properties of CNSL without the use of chemical agents or heating systems. ABE (361) was used as a renewable additive to enhance the properties of CNSL, mainly by reducing its viscosity and density. Moreover, this study evaluated the effect of ABE (361) in CNSL–diesel blends, while satisfying the standard specifications of conventional fuels. The properties of CNSL–diesel, CNSL–ABE, and CNSL–diesel–ABE blends were analysed, and the effects of temperature on the fuel blends were examined. Furthermore, stability studies of the appropriate fuel blends and their key fuel properties were performed.

2. Materials and methods

2.1. Materials

CNSL samples were procured from Anacardium Transformation (ANATRANS), a company specialising in cashew nut processing in the Bobo–Dioulasso region of Burkina Faso. As illustrated in Fig. 1, the pressing of cashew nut shells (CNSs) yields natural cashew nut shell liquid (CNSLP), which is then heated to approximately 160 °C in a batch reactor for approximately 4 h and stored in barrels for 2 weeks to obtain technical cashew nut shell liquid (CNSLT).

The ABE mixture was prepared using acetone (analytical grade), 1-butanol (99.5 %), and ethanol (99.97 %) in a 3:6:1 volumetric ratio, which is the typical composition of butyl-acetone products of carbohydrates fermentation. The resulting blend is referred to as ABE (361). The three reagents were mixed for 15 min at 800 rpm using a magnetic stirrer.

CNSLT, ABE (361), and commercial diesel (Total Petroleum Service, Ouagadougou) were used to prepare the fuel blends.

2.2. Sample characterisation

2.2.1. CNSL composition

The cardanol, cardol, and anacardic acid contents of the CNSL samples were determined by high-performance liquid chromatography (HPLC) using a Dionex Ultimate 3000 HPLC system equipped with a diode detector. A SUPELCOSIL LC-18 HPLC column (20 × 4.6 mm, 5 μm particle size) was used to separate the components, and an acetonitrile/water/acetic acid solution (80:20:1 v/v) was injected at an elution rate of 1.80 mL/min. The eluent was monitored at $\lambda = 280$ nm. All samples (25 mg in 5 mL acetonitrile) were injected in 20 μL aliquots (Rodrigues et al., 2011).

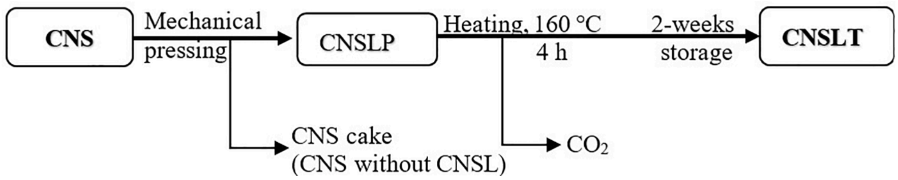

Fig. 1. Extraction process of pressed cashew nut shell liquid (CNSLP) and technical cashew nut shell liquid (CNSLT) from cashew nut shells (CNSs).

2.2.2. Elemental analysis

Elemental analyses of the CNSL and commercial diesel samples were performed using a Vario Macro Cube elemental analyser. The process involved burning the sample, after which the resulting gases (e.g., carbon dioxide, water vapour, and nitrogen oxide) were detected using a thermal conductivity detector that emitted an electrical signal proportional to the content of the respective gas. The oxygen content was then estimated from the difference between the original weight and the analysed content of hydrogen, carbon, and hydrogen (oxygen content = 100 % - (% H+% C+% N)).

2.3. Fuel blend formulation

2.3.1. Testing of physicochemical properties

The properties of biofuels, such as the density, viscosity, heating value, moisture content, and acid number, must meet certain specifications for their use in diesel engines. Biofuels with a high acid number may corrode engine parts, and those with a low heating value have insufficient output power. The physicochemical properties of the CNSL samples were evaluated using the standard testing methods listed in Table 1. The acid numbers of samples were evaluated by acid-base titration according to ASTM D664.

2.3.2. Preparation of fuel blends and specifications

Based on the acid number, moisture content, and heating value results, CNSLT was selected as the optimal biofuel for obtaining suitable blends for diesel engines. The fuel blends were prepared in conical tubes (50 mL) with vigorous stirring for 10 min at room temperature. Three independent batches of each blend were prepared and tested. Twenty blends were prepared: CNSLT–diesel blends containing 10, 20, 30, 40, and 50 vol% CNSLT (designated as B10, B20, B30, B40, and B50, respectively); CNSLT–ABE (361) blends containing 70, 80, and 90 vol% CNSLT (designated as C70ABE30, C80ABE20, and C90ABE10, respectively); and CNSLT–diesel–ABE blends containing x vol% CNSLT and y vol% ABE (361) (designated as BxABEy, where x = 20, 30, 40, and 50 vol% and y = 10, 20, and 30 vol%). For example, B20ABE10 comprises 20 vol% CNSLT, 10 vol% ABE, and 70 vol% diesel, and B30ABE30 comprises 30 vol% CNSLT, 30 vol% ABE, and 40 vol% diesel.

The fuel blends were centrifuged at 6000 rpm for 5 min to be separated from the unfiltered CNSL impurities. The density, viscosity, and heating value of the blends were measured as described in Section 2.3.1. Heating values of blends were calculated based on the component ratios (Aguado-Deblas et al., 2022). For the CNSLT–diesel–ABE blends, the results are only given for those that met the diesel requirements. Fuel blends must exhibit consistent properties to be suitable for engine testing and evaluation. To select the blends that best satisfied the diesel specifications, the physical properties, such as density, viscosity, and heating value, were evaluated and compared to the requirements for diesel fuel, straight vegetable oil (SVO), and heavy fuel oil (HFO), as listed in Table 2. Because preheating can reduce the viscosity, the fuel blends that exceeded the viscosity requirement at 40 °C were retested after preheating to 60 and 80 °C.

Table 1
Equipment and standards used to assess the physicochemical properties of fuel.

Property	Equipment	Standard	Accuracy
Density at 20 °C	Pycnometer (Blaubrand)	NF ISO 4787	±0.01 kg/m^3
Viscosity at 40 °C	Viscosimeter (Pro. Brookfield DV-II)	ASTM D445	±0.01 mm^2/s
Heating value	Calorimeter (Parr 6200)	ASTM D240	±0.001 MJ/kg
Moisture content	Karl Fischer Titrator (Mettler Toledo)	ASTM E203	±0.01 wt.%

2.3.3. Storage and accelerated aging of fuel blends

Prolonged storage can result in the degradation of the properties of biofuels, including the density and viscosity. Therefore, storage stability and accelerated aging tests were conducted on the fuel blends that had similar key properties to those of diesel. The storage stabilities were examined using a method adapted from Bora et al. (2016). Briefly, the blends were visually inspected after storage for 1–4 weeks in a desiccator at room temperature. The fuel blends that separated were assumed to be unstable, whereas those that maintained a stable single phase were considered suitable for use in diesel engines.

Accelerated aging tests were conducted using the method described by Lehto et al. (2013). The fuel blends were maintained at an elevated temperature (80 °C) for 24 h, and their stability was assessed based on changes in viscosity (measurement at 40 °C).

Finally, the properties of the stable fuels were analysed and compared with diesel requirements, including density, viscosity, heating value, acid number, moisture content, and cetane number. The cetane number was evaluated based on calculations of the cetane index using the equations proposed by Jiménez Espadafor et al. (2009) and Aguado-Deblas et al. (2022). Because diesel engines fuelled with vegetable oils offer acceptable engine performance and emissions (Department of Energy, and Office of Energy Efficiency and Renewable Energy (USA) 2020), the requirements were established in this study based on the diesel and SVO specifications proposed by Blin et al. (2013).

3. Results and discussion

The physicochemical properties of the CNSL samples were analysed before the preparation of the fuel blends. Twenty fuel blends were prepared from CNSLT, diesel, and ABE (361), of which three (B10, B20ABE10, and B30ABE30) were selected for stability testing because their physical properties were similar to those of diesel fuel.

3.1. CNSLP and CNSLT composition

The anacardic acid, cardanol, and cardol contents of CNSLP and CNSLT are listed in Table 3.

CNSLP contained 26.7 % cardanols, 20.8 % cardols, 43.8 % anacardic acids, and 8.7 % other components, similarly to previous reports (Oliveira et al., 2011; Srinivasan et al., 2023). By comparison, CNSLT contained less anacardic acids (17.6 %) and more other components (25.9 %). CNSLP is thermally treated at 160 °C to form CNSLT, which causes the decarboxylation of the anacardic acids. This led to the slight increase in cardanol content (Chatterjee et al., 2017). Similarly, the increase in other components is attributed to the formation of polymeric material during thermal treatment. Notably, HPLC only enables the analysis of low-molecular-weight components (Rodrigues et al., 2011).

Table 2
Physicochemical properties and their limits for biofuels in accordance with standard specifications for conventional fuels.

Property	Viscosity 40 °C (mm^2/s)	Density 20 °C (kg/m^3)	Heating value (MJ/kg)	Acid number (mg KOH/g)	Moisture Content (% wt.)
Diesel specifications[1]	1.6–5.9	820–890	40[b]	≤ 1	≤0.05
Straight vegetable oil specifications[1]	50	900–960	≥ 36	≤ 3.00	≤ 0.075
Heavy fuel oil specifications[2]	≤ 420[a]	960–990	≥ 40.6	4.31	≤ 0.50

[1] (Blin et al., 2013).
[2] (Blin et al., 2013; Lehto et al., 2014; Park et al., 2020).
[a] Value measured at 50 °C.
[b] Estimated minimum value (Hashim et al., 2017).

Table 3
Chemical composition of CNSLP[a] and CNSLT[b] using HPLC[c].

Constituent	Content (wt.%)			
	CNSLP	CNSLT	Oliveira et al. (Oliveira et al., 2011)	Srinivasan et al. (Srinivasan et al., 2023)
Cardols	20.8	28.8	7.0	33.7
Anacardic acids	43.8	17.6	47.0	51.8
Cardanols	26.7	27.7	42.0	8.1
Other	8.7	25.9	8.0	6.0

[a] CNSLP: Natural cashew nut shell liquid extracted from cashew nut shells (CNSs) via mechanical pressing
[b] CNSLT: Technical cashew nut shell liquid obtained by heating CNSLP at 160 °C for 4 h
[c] HPLC: High performance liquid chromatography.

The elemental compositions of the CNSL samples and commercial diesel in terms of the relative percentages of carbon, hydrogen, oxygen, and nitrogen are listed in Table 4.

The CNSLT indicated a high carbon content, whereas the CNSLP showed a high oxygen content. The carbon and hydrogen contents in CNSLT increased after the thermal treatment, which is attributable to decarboxylation reactions. The C:H:O ratio in vegetable oil is typically 78:12:10 (Deepanraj et al., 2022), whereas that in technical CNSLT is approximately 81:10:9. Therefore, the high carbon content of the CNSLT may explain its higher heating value than that of vegetable oil.

3.2. *Physicochemical properties of CNSL samples, diesel fuel, and ABE (361)*

The properties of CNSLP, CNSLT, and ABE (361), such as density, viscosity, heating value, moisture content, and acid number, are summarised in Table 5.

A difference of approximately 0.5 % was observed between the densities of the CNSLT (985 kg/m^3) and CNSLP (991 kg/m^3), which was approximately 17 % higher than that of diesel. The low density of the CNSLT is attributable to the molar mass of their components. It contains slightly more cardanols than the CNSLP with a low molar mass and less anacardic acid with a medium molar mass (Table 3).

The viscosities of the CNSLP (184.70 mm^2/s) and CNSLT (738.25 mm^2/s) differed significantly, which were 66 and 267 times higher than those of diesel, respectively. Polymerised materials have higher viscosities than monomers with lower molar masses, which explains the observed differences. The viscosity of the CNSLT was slightly higher than that reported in the literature (Rodrigues et al., 2011). The use of CNSLT in diesel engines is limited because of issues related to the engine's fuel injection system (pump and injector) arising from its high viscosity.

Table 4
Elemental composition of CNSLP, CNSLT, and commercial diesel.

Composition	Content (%)			
	Carbon	Hydrogen	Oxygen	Nitrogen
CNSLP	76.51	8.55	14.60	0.34
CNSLT	80.85	9.83	8.90	0.42
Commercial diesel	86.13	13.39	0.38	0.07

The heating values of the CNSLP (36.17 MJ/kg) and CNSLT (40.34 MJ/kg) differed by approximately 10 %. The heating value of the CNSLT was approximately 11 % lower than that of diesel. The presence of oxygen atoms in the CNSL samples contributed to the lower heating value compared with that of diesel. The CNSLT indicated a significantly higher heating value than CNSLP because of thermal treatment, which increased the carbon content and reduced the oxygen and moisture contents.

The acid numbers of the CNSLT (20.30 mg KOH/g) and CNSLP (113.24 mg KOH/g) differed significantly owing to the high anacardic acid content in the CNSLP. The high anacardic acid content in the CNSLP rendered it more acidic than the CNSLT. The acid number of the CNSLT was approximately seven times higher than that of diesel, thus rendering it unsuitable for use in diesel engines as it can result in the high corrosion of engine components.

In the following section, the use of CNSLT is discussed as their properties (acid number, moisture content, and heating value) are the most appropriate for the current study. However, the values of its flow properties exceed the diesel specifications; therefore, it must be blended with diesel to improve its physical properties and satisfy the diesel requirements.

3.3. *Study of CNSLT–diesel blends*

3.3.1. *Properties of CNSLT–diesel blends*

The physical properties of the CNSLT–diesel blends are listed in Table 6.

The viscosities and densities of the fuel blends increased as the diesel ratio decreased, in particular, B10, which was the only blend that satisfied the diesel requirements, indicated the most significant decrease in viscosity. A similar study by Chatterjee et al. (2017) showed that the B10 blend indicated a viscosity of 2.71 cSt, which exhibited diesel specifications.

The density of fuel blends used in diesel engines should be between 820 and 889 kg/m^3, and all fuel blends with up to 40 % CNSLT should satisfy this requirement. The B10 blend indicated a higher heating value compared with other blends owing to its higher diesel ratio. Therefore, the amount of CNSLT affected the heating values of the fuel blends. The CNSLT–diesel blends indicated heating values that were 2 %–6 % lower than that of diesel but higher than the diesel requirements.

The physical properties of the B10 blend satisfied the diesel specifications, thus implying that it is likely to perform similarly to diesel fuel in diesel engines. By contrast, the viscosities of the B20, B30, B40, and B50 blends exceeded the required range, which implies that they must be preheated because their viscosity decreases as temperature increases. Therefore, the effect of the preheating temperature on these blends was investigated.

3.3.2. *Effect of temperature on CNSLT–diesel blends*

The viscosities of the CNSLT–diesel blends as a function of the

Table 5
Fuel properties of each pre-blended component.

Components	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)	Acid number (mg KOH/g)	Moisture Content (% wt.)
CNSLT	738.25	985.48	40.34	20.30	0.87
CNSLP	184.70	991.04	36.17	113.24	1.12
Commercial diesel	2.76	822.37	45.45	0.50	0.02
ABE (361)	1.79	800.00	33.56	n/a	n/a
Diesel specifications	1.6–5.9	820–890	≥ 40	≤ 1	≤0.05

n/a: Not available.

Table 6
Properties of CNSLT–diesel blends.

Fuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
B10 (10 % CNSLT, 90 % diesel)	4.56	842.17	44.94
B20 (20 % CNSLT, 80 % diesel)	7.50	856.87	44.42
B30 (30 % CNSLT, 70 % diesel)	13.88	871.58	43.91
B40 (40 % CNSLT, 60 % diesel)	23.60	885.53	43.40
B50 (50 % CNSLT, 50 % diesel)	44.03	897.01	42.90
Diesel specifications	1.6–5.9	820–890	≥ 40

Table 7
Properties of CNSLT–ABE blends.

Biofuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
C90ABE10 (90 % CNSLT, 10 % ABE)	270.96	976.03	39.67
C80ABE20 (80 % CNSLT, 20 % ABE)	99.28	955.92	38.99
C70ABE30 (70 % CNSLT, 30 % ABE)	53.70	940.55	38.31
Diesel specifications	1.6–5.9	820–890	≥ 40
Straight vegetable oil specifications	50	900–960	≥ 36
Heavy fuel oil specifications	≤ 420	960–990	≥ 40.6

preheating temperature are shown in Fig. 2.

The viscosities of the fuel blends decreased significantly as the preheating temperature increased. To achieve a viscosity of less than 5.9 mm^2/s, the B30 blend had to be preheated at 80 °C. However, B20 required preheating at 60 °C to achieve the same viscosity; its use obviates the necessity for the heating device, thereby facilitating fuel conditioning. Therefore, the B20 and B30 blends can be preheated to achieve flow characteristics similar to those required for diesel engines. A similar study showed that 20 % CNSL mixed with diesel and preheated to 80 °C can be used as fuel for diesel engines without any modifications (Govindan et al., 2019).

By contrast, the B40 and B50 blends exhibited viscosities in the range of 20–40 mm^2/s, which is the range required to achieve the appropriate atomisation at the burner nozzle of an oil-fired boiler (Park et al., 2020). Therefore, the B40 and B50 blends can be used as burner fuels instead of HFO.

3.4. Study of CNSLT–ABE blends

3.4.1. Properties of CNSLT–ABE blends

The physical properties of the CNSLT and its blends with different ABE ratios are listed in Table 7.

The viscosity of the CNSLT was reduced by adding ABE (361) at different ratios (10 %, 20 %, and 30 %). C70ABE30, C80ABE20, and C90ABE10 exhibited viscosity reductions of 92.27 %, 86.55 % and 63.30 %, respectively. Despite the greater reduction in the viscosity of C70ABE30, it was approximately 7 % higher than the SVO specification, although its density satisfied the SVO requirements. This blend indicated a heating value of approximately 6 %, which was slightly higher than the SVO specifications. The density and viscosity of the C80ABE20 blend satisfied the HFO requirements; however, it indicated a heating value of approximately 4 %, which was slightly lower than that of HFO. Meanwhile, the energy density of C80ABE20 (40.79 MJ/L) was slightly higher than that of HFO (39.50 MJ/L). Therefore, the addition of 20 % and 30 % ABE (361) to the CNSLT resulted in fuel blends comparable to those of HFO and SVO, respectively.

3.4.2. Effect of temperature on CNSLT–ABE blends

The viscosities of the CNSLT–ABE blends as functions of the preheating temperature are shown in Fig. 3.

As the preheating temperature and ABE ratio increased, the viscosity of the fuel blends decreased. A more significant decrease in viscosity was observed in the CNSLT with 30 % ABE (361); however, its viscosity remained significantly higher than that of diesel. The C70ABE30 blend preheated to 80 °C indicated a viscosity of 12.5 mm^2/s, which was lower than the maximum value of 17 mm^2/s recommended for stationary diesel engines (Blin et al., 2013). In fact, the density and heating value of this fuel blend satisfied the SVO requirements. Therefore, they can be used as an alternative to SVO in diesel engines. However, when preheated to 60 °C, the C70ABE30 and C80ABE20 blends exhibited

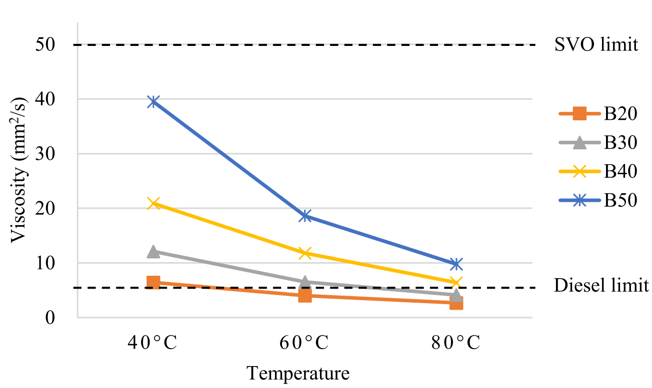

Fig. 2. Viscosity for CNSLT–diesel blends as function of temperature.

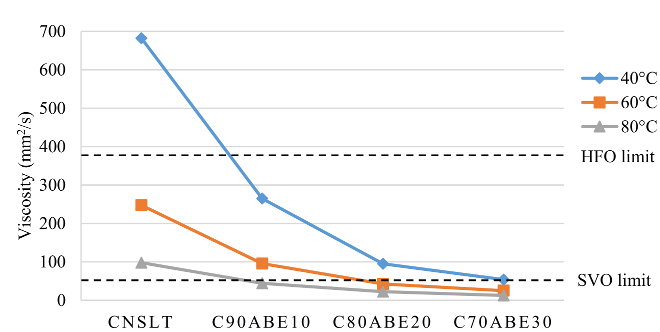

Fig. 3. Viscosity of CNSLT–ABE blends as a function of temperature.

viscosities between 20 and 40 mm^2/s, which were the values required to achieve adequate atomisation at the burner nozzle of an oil-fired boiler. Therefore, the C70ABE30 and C80ABE20 blends can be used as burner fuels instead of HFO.

3.5. Analysis of CNSLT–diesel–ABE blends

3.5.1. Properties of CNSLT–diesel–ABE blends

To satisfy diesel specifications, fuel blends must exhibit a viscosity of less than 5.9 mm^2/s. In this regard, B20ABE10, B20ABE20, B20ABE30, and B30ABE30 satisfied this requirement, as shown in Fig. 4.

The viscosity decreased as the ABE (361) ratio increased, and a significant decrease was observed for fuel blends with 30 % ABE (361). For all the fuel blends, the viscosity decreased linearly as the ABE ratio increased.

The physical properties of the CNSLT–diesel–ABE blend that satisfied the diesel requirements are listed in Table 8.

An increase in the ABE ratio decreased the density, viscosity, and heating value of the fuel blend. A difference of approximately 5 % was observed between the heating values of B20ABE10 and B20ABE30 blends with the same volume of CNSLT. Owing to its higher ABE ratio (30 %), B30ABE30 indicated the lowest heating value of 40.81 MJ/kg, which is higher than the diesel requirement. Thus, the B20ABE10 and B30ABE30 blends can be used instead of B20 and B30 blends, which require heating to 60 °C and 80 °C, respectively.

3.5.2. Effect of temperature on CNSLT–diesel–ABE blends

The effect of the heating temperature on the viscosity of CNSLT–diesel with ABE blends is shown in Fig. 5.

The viscosity decreased as the preheating temperature of the fuel blend increased. Blends B30ABE10 (CNSLT/ABE (361)/diesel=30:10:60 v/v) and B30ABE20 (30:20:50 v/v) preheated at 60 °C satisfied the diesel viscosity requirements. Meanwhile, blends B40ABE10 (40:10:50 v/v), B40ABE20 (40:20:40 v/v), and B40ABE30 (40:30:30 v/v) required heating at 80 °C to satisfy the diesel requirements. The B30ABE10 blend was more suitable than other fuel blends because of its high heating value and low preheating temperature (60 °C).

3.6. Stability of the most appropriate fuel blends

3.6.1. Selection of fuel blends

Based on the results, B10, B20ABE10, and B30ABE30 possess physicochemical properties that render them suitable substitutes for diesel fuel. However, these fuel blends must remain stable during their transport and prolonged storage.

3.6.2. Stability analysis of fuel blends

Storage stability and aging tests were conducted on fuel blends B10, B20ABE10, and B30ABE30. Their physical stability was assessed by visually observing the phase separation of the fuel blends at room temperature. The B10 blend exhibited no phase separation during the first month of storage. This is because of the presence of stabilisers in diesel, which prevented the formation of undesirable compounds such as gums or sediments, and the presence of cardanols as antioxidants (Paula et al., 2020). Furthermore, B20ABE10 and B30ABE30 exhibited no phase separation because of the high solubility of CNSLT in diesel and ABE (361). This can be explained by the miscibility of CNSLT with each ABE component (acetone, butanol, and ethanol).

As shown in Fig. 6, the viscosities of B10, B20ABE10, and B30ABE30 blends varied only slightly with storage time, and their densities were 841, 849, and 850 kg/m^3, respectively. The viscosities and densities of these blends were within acceptable limits for diesel engines during one month of storage.

The viscosities of B10, B20ABE10, and B30ABE30 blends exhibited an increase after the aging test at 80 °C for 24 h, and they were comparable to those stored at room temperature (Fig. 7). After the aging test, the viscosities of the blends were almost identical to the diesel requirements. As the result, these fuel blends can be stored for about one year without significant changes in their fuel properties.

3.6.3. Characteristics of the most suitable fuel blends for diesel applications

The physicochemical characteristics of the fuel blends were compared with the diesel specifications to ensure that they satisfied the

Table 8
Properties of CNSLT–diesel with ABE.

Fuel blends	Viscosity, 40 °C (mm^2/s)	Density, 20 °C (kg/m^3)	Heating value (MJ/kg)
B20ABE10 (20 % CNSLT, 10 % ABE, 70 % diesel)	5.06	849.04	43.34
B20ABE20 (20 % CNSLT, 20 % ABE, 60 % diesel)	4.22	842.89	42.25
B20ABE30 (20 % CNSLT, 30 % ABE, 50 % diesel)	3.65	834.39	41.17
B30ABE30 (30 % CNSLT, 30 % ABE, 40 % diesel)	5.83	849.02	40.81
Diesel specifications	1.6–5.9	820–890	≥ 40

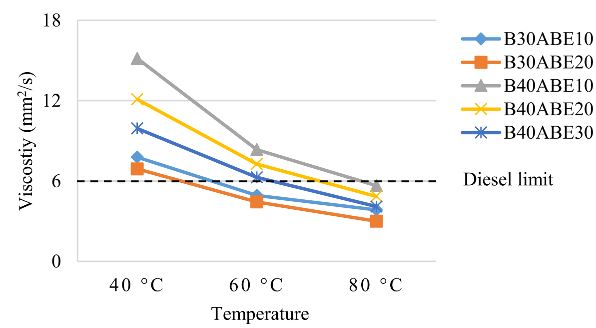

Fig. 5. Viscosity of CNSLT–diesel–ABE blends as function of preheating temperature.

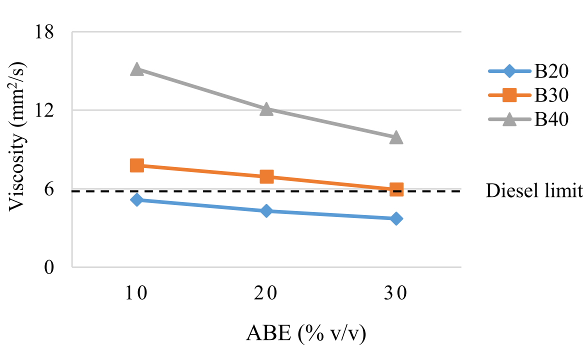

Fig. 4. Viscosity of CNSLT–diesel blends vs. ABE ratio.

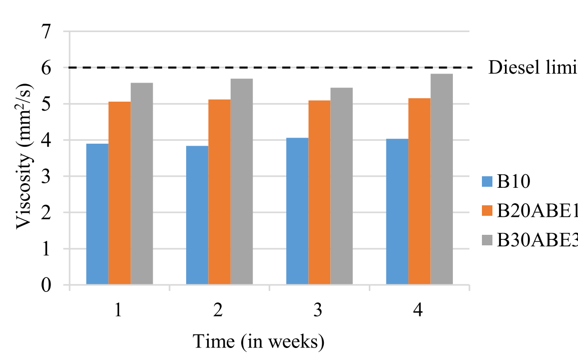

Fig. 6. Viscosity of fuel blends (stored at room temperature).

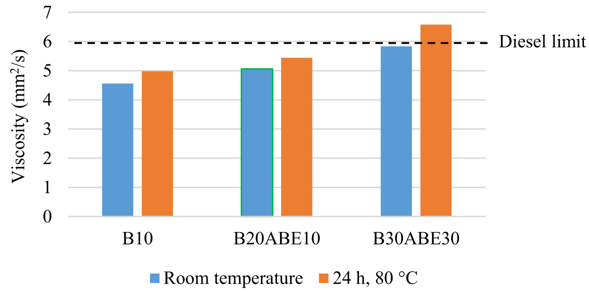

Fig. 7. Viscosity of fuel blends (stored at room temperature and after aging test).

diesel requirements, as summarised in Table 9.

The density, viscosity, and heating value of B10 were within the standard limits for diesel engines. However, the B20ABE10 and B30ABE30 blends exhibited acid numbers ranging from 4.92 to 6.60 mg KOH/g, which were higher than the diesel specifications. According to Blin et al. (2013), some engine manufacturers accept acid numbers of up to 15 mg KOH/g, which are higher than those of suitable fuel blends. The moisture content of the B20ABE10 and B30ABE30 blends varied from 0.24 % to 0.41 %, which was higher than the diesel specifications and slightly lower than that of HFO. Manufacturers of low-speed diesel engines recommend a cetane index (which indicates the ignition quality of the fuel) exceeding 30 (Jiménez Espadafor et al., 2009). This requirement was fulfilled by the B10, B20ABE10, and B30ABE30 blends. Although the heating values of the blends were lower than those of diesel, they were higher than those specified for diesel in this study.

4. Conclusions

This study aimed to improve the properties of CNSL blended with diesel to obtain a product with fuel characteristics comparable to those of diesel. Among the biofuel–diesel blends, only fuel B10 (CNSLT/diesel = 10:90 v/v) satisfied the diesel specifications. For other fuel blends, such as B20 (20:80 v/v) and B30 (30:70 v/v), preheating was required at 60–80 °C to optimise their fuel flow properties. Acetone/butanol/ethanol (ABE) mixture (30:60:10 v/v) applied to B20 and B30 produced appropriate fuel blends B20ABE10 (CNSLT/ABE/diesel=20:10:70 v/v) and B30ABE30 (30:30:40 v/v), which were stable over one month of storage and satisfied diesel specifications. They could operate efficiently in diesel engines without modification; however, the performance and emission characteristics of diesel engines must be investigated. These fuel blends could promote the use of ABE (361) and CNSL as partial substitutes for diesel by up to 60 %. Considering the high potential of CNSL in sub-Saharan Africa, the use of these formulated fuel blends could reduce the dependence on petroleum diesel imports as well as reduce greenhouse gas emissions. However, the cost of the required reagent (acetone, butanol, and ethanol) may limit this process. The use of cashew apples in the production of ABE (361) could add value to cashew by-products; however, further studies are required to confirm the feasibility of this strategy. Cashew trees are a unique source that can be used to generate food (cashew nuts) and biofuels (CNSL and ABE) from single crops. Our results revealed that the C70ABE20 (CNSLT/ABE (361) =70:30 v/v) and C80ABE20 (80:20 v/v) blends can be used as burner fuels instead of HFO. Moreover, C70ABE30 could be used instead of SVO as a fuel for diesel engines. An in-depth study of the physico-chemical properties of these blends as well as performance tests in a diesel engine or burner must be conducted to verify the applicability of these systems as alternative fuels.

CRediT authorship contribution statement

Sabba Gwoda: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Jérémy Valette:** Methodology, Validation, Resources. **Sayon Sadio dit Sidibé:** Conceptualization, Supervision, Project administration, Writing – review & editing. **Bruno Piriou:** Conceptualization, Supervision, Writing – review & editing. **Joël Blin:** Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. **Igor W.K. Ouédraogo:** Conceptualization, Supervision, Writing – review & editing.

Table 9
Properties of the most suitable fuel blends.

Properties	B10	B20ABE10	B30ABE30	Requirements
Viscosity at 40 °C (mm^2/s)	4.56	5.02	5.83	1.6–5.9
Density at 20 °C (kg/m^3)	842.17	850.00	849.02	820–890
Heating value (MJ/kg)	44.94	42.20	40.81	≥ 40
Acid number (mg KOH/g)	3.25	4.92	6.60	≤ 3
Moisture content (% wt.)	0.11	0.24	0.41	≤ 0.05
Cetane number	44.00	40.80	35.40	45–55

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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