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Synthesis and utilization of catalytically cracked cashew nut shell liquid in a diesel engine**S. Vedharaj^a, R. Vallinayagam^a, W.M. Yang^{b*}, C.G.Saravanan^c, W.L. Roberts^a**

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ABSTRACT

In this study, CNSL (Cashew nut shell liquid), an economically viable feedstock among the other contemporary resources, has been considered as an appropriate source of alternate fuel. Herein, CNSL was extracted from cashew nut outer shell, a waste product, through a unique approach of steam treatment process followed by mechanical crushing technique. In contrast to the past studies that have attempted to use unprocessed CNSL directly as substitute for diesel, this study has resorted to use processed CNSL by cracking it using zeolite catalyst. Thus, both the extraction of CNSL from cashew nut outer shell and processing of it through catalytic cracking process to help synthesize CC-CNSL (catalytically cracked CNSL) are different, which underscores the significance of the current work. In wake of adopting such distinct methodologies with fuel characterization, the properties of CC-CNSL such as viscosity and calorific value were figured out to be improved. Subsequently, CC-CNSL20 (20% CC-CNSL and 80% diesel) was tested at different fuel injection pressure such as 200 bar, 235 bar, 270 bar and 300 bar so as to optimize its use in a single cylinder diesel engine. From the engine experimental study, CC-CNSL20 was found to evince better engine performance than diesel and the composite emissions of CO (carbon monoxide), HC (hydrocarbon), NO_x (oxides of nitrogen) and smoke, computed based on ISO 8178 D2 standard test cycle, were found to be better than diesel and incompliance with the legislative norms for genset.

Keywords: CNSL (cashew nut shell liquid), catalytic cracking, fuel injection pressure, CC-CNSL, combustion, emission

1. Introduction

Over the years, though the emissions of deleterious toxic gases are abated when utilizing biodiesel, the cost of it is reported to be higher than conventional petroleum based fuels [1]. Basically, the exorbitant price of vegetable oil from which biodiesel is produced contributes to around 80% of total biodiesel production cost, increasing the total cost of biodiesel [2]. Therefore, despite the advantage of renewability and biodegradability, commercialization of biodiesel seems far-fetched in certain countries. In such a scenario, researchers have redefined the selection of feedstock for biodiesel production and have resolved to choose inedible oils, as they are cheaper when compared to edible vegetable oils and would not have a negative influence on food chain [3, 4]. By the time the production and characterization of biodiesel from inedible oils were prospering, an eminent threat to the availability of land to grow this inedible biomass propped up [5, 6]. Therefore, besides exploring an inedible feedstock, focus on utilizing waste products, which are economically viable, as suitable raw material for producing biodiesel has been targeted recently [7]. In all likelihood, biodiesel produced from these inedible as well as waste products would replace a fraction of petroleum based fuels in the near future and generate green energy to help prevent adverse effect on atmosphere.

From the research studies, which tend to report the use of waste products as alternate fuel in a diesel engine, it is construed that waste vegetable and frying oil, animal fats, plastic oil, engine lubricating oil, kapok oil and CNSL (cashew nut shell liquid) were being used as probable substitutes for diesel in a diesel engine [8-13]. Distinctly, CNSL, a waste product from cashew industry, has caught the attention of many researchers because of its much cheaper price [14, 15]. Notably, CNSL may be extracted from cashew nut outer shells by different processes viz

roasting, hot bath, cold extraction and solvent extraction techniques [16]. In hot bath process, CNSL is extracted by immersing cashew nut outer shells in a hot bath at 185 – 190°C and the produced CNSL is characteristically different from the one produced by cold extraction process [17]. On the other hand, general roasting of cashew nut outer shell in a controlled environment produces a dark brown liquid, which is a sort of different grade of CNSL [18]. Technically, during the extraction of CNSL, the anacardic acid present in it is converted into cardanol, through decarboxylation process. In addition to cardanol, CNSL obtained by these extraction techniques also consists of cardol and other polymeric material [19]. Some studies have reported distillation or pyrolysis of CNSL as additional processing strategies to increase the yield of cardanol and remove other polymeric and contaminated material [20, 21]. Of course, the phenolic material, cardanol, forms the major constituent of CNSL and materializes as pertinent fuel candidate for diesel engine application.

It is worthwhile to recount that CNSL processed by different methods does manifest different physical and thermal properties, considering each method are unique in their own right. In this regard, Velmurugan et al [19] subjected CNSL to pyrolysis process and reported that the calorific value of it is improved. Despite this, operation of CNSL in a diesel engine has been reported to evince poor engine performance and emission on account of its higher viscosity. To avert this limitation, attempts on diluting CNSL with less viscous fuels such as ethanol and camphor oil were up taken [15, 22]. As an outcome of dilution, the viscosity was reduced to some extent and the engine characteristics were reported to be improved and brought closer to diesel. In a measure to further reduce the viscosity, Vedharaj et al [13] subjected CNSL to double stage trans-esterification process, wherein an acid and alkali catalyst were used along with methanol. In event of this, viscosity was reduced to certain extent and the operation of trans-

esterified CNSL – diesel blend showed improved performance and emission in a coated diesel engine. Though dilution and trans-esterification appears to have reduced the viscosity, calorific value was found to be dropped. Thus, the above reported processing methods of CNSL has either improved the calorific value or viscosity of the fuel and, therefore, it is imperative to develop an appropriate processing method for CNSL so as to improve its fuel properties on the whole.

Given much improved processing methods of CNSL were not considered before, in this study, we resort to chemically treat CNSL and make its properties more appropriate for diesel engine application. In our previous work, we conventionally trans-esterified CNSL in two stages to produce CNSL biodiesel and experimentally investigated the synthesized biodiesel in a diesel engine [13]. Subsequently, in the current study, as an improvement in fuel characterization, CNSL was cracked using zeolite catalyst to help synthesize CC-CNSL (catalytically cracked CNSL). Catalytic cracking of CNSL has never been done before and therefore, it would be interesting to consider it, given the process itself improves the fuel properties than the traditional trans-esterification process. Distinctly, we have employed a unique strategy of steam treatment process followed by mechanical crushing technique to extract CNSL from cashew nut outer shells. As such, this work is unique in respect of both the extraction of CNSL from cashew nut outer shells and processing of it through catalytic cracking process. In the quantitative analysis, the synthesized CC-CNSL was estimated for its properties as per ASTM standard method and compared with CNSL biodiesel as well as diesel. Subsequently, 20% CC-CNSL was blended with diesel and operated in a diesel engine at various fuel injection pressures of 200 bar, 235 bar, 270 bar and 300 bar so as to optimize its use in a diesel engine. Herein, as a different attempt, the engine was operated in five mode ISO 8178 D2 test cycle and the estimated composite emissions were compared with legislative emission norms.

2. Materials and methods

2.1 Extraction of CNSL from cashew nut outer shells

The cashew nut outer shell is about 0.3 cm thick, having a soft feathery outer skin and a thin hard inner skin. Between these skins is the honeycomb structure containing the phenolic material known as CNSL. In this study, a unique approach to synthesize CNSL from cashew nut outer shells has been employed, as shown in figure 1. Large quantities of cashew shells are placed in a huge steel container and from the bottom; steam is fed into the container to initiate steam treatment process. The impingement of hot steam is deemed to soak the shells in a hot environment for some time and help recover some amount of oil. Subsequently, the hot shells are crushed in a mechanical expeller and by which, maximum quantity of CNSL has been extracted. Notably, this process was selected over other contemporary techniques like roasting and hot bath process, as it renders the benefit of bulk extraction of oil in a single trail, which is likely to reduce the production cost. Previously, either thermal or mechanical extraction methods were embraced to extract CNSL from cashew nut outer shells: however, herein, both the thermal and mechanical extraction strategies are coupled together, enabling better recovery of CNSL from cashew shells. Notably, the yield of CNSL by the above reported method was found to be 20% for given quantity of cashew nut outer shells. After the extraction of CNSL, the physical and thermal properties of it were determined by ASTM standard methods and are shown in table 1. Evidently, the viscosity of the extracted CNSL was observed to be lower in contrast to the one extracted by other processes, reported in [15, 19]. Thus, the employed method of steam treatment process followed by mechanical crushing has not only improved the recovery of CNSL from cashew, but also has enhanced the fuel properties.

2.2 Catalytic cracking of CNSL

Though the viscosity of CNSL was noted to be improved in this study, still it is perceived to impede its direct use in a diesel engine. Therefore, subsequent processing of it is required so as to make it amenable for diesel engine application. Past attempts on trans-esterifying CNSL enabled only reduction in fuel viscosity to certain extent, without any improvement in calorific value [23]. Therefore, more advanced processing method of catalytic cracking was considered in the current study to break the higher hydrocarbons into lower ones and improve the fuel properties of CNSL on the whole.

In catalytic cracking process, zeolite was chosen as a suitable catalyst and as opposed to thermal cracking process; use of catalyst aids in promoting the cracking process and reduces the requirement for higher temperature. Notably, zeolite catalyst was zeroed in over the other catalyst owing to its better material properties such as high porosity, increased ionic conductivity and better heterogeneity, which are expected to promote the cracking rate of CNSL. The experimental arrangement for the intended cracking process, entailing a preheater, reactor and condenser, has been depicted in figure 2. Initially, the temperature of the preheater was raised up to 200°C through an electric heater and CNSL being heated is stirred well for uniform temperature throughout the mixture. Subsequently, preheated CNSL is fed into the main reactor wherein: it was heated up to 400°C and care is taken to prevent the heat loss from the reactor by duly insulating the reactor zone using glass wool. Progressively, zeolite catalyst was added to the heated CNSL and the mixture is stirred well in order to trigger catalytic cracking process. As a result, CNSL vapors are formed that were sent to the condenser placed next to the reactor. The formed CNSL vapors are condensed in the condenser that use water as coolant and finally, CC-

CNSL (catalytically cracked CNSL) was collected in a storage tank. For instance, for cracking one liter of CNSL, 200 g of catalyst was used at the reported temperature and the yield was found to be fairly good at 90%.

2.3 Properties and composition of CC-CNSL

In conception, catalytic cracking reaction is deemed to incite molecular changes within CNSL and in order to ascertain this, the composition of CC-CNSL has to be examined. As such, the composition of CC-CNSL was figured out by performing a compositional analysis in GC-MS (gas chromatography mass spectrometer) at an operating temperature of 200°C, ramp rate of 2°C/min, flow rate of 2 μ l/min and split ratio of 80:1. Certainly, the major constituent of CC-CNSL, as evident from figure 3, was found to be 2-methyl phenol, an aromatic oxygenate that is deemed to promote the combustion process. Reportedly, all aromatic oxygenated are deemed to promote fuel oxidation and combustion process [24, 25], given the oxygen present in it is loosely bonded and would actively participate in the combustion process. Further, it also features the presence of few esters along with other hydrocarbons, so as to materialize as a potential fuel for diesel engine.

Normally, trans-esterification reaction is reported to produce methyl ester of fatty acids, which possess inherent oxygen and several double bonds within it. In the event of increased degree of unsaturation, the viscosity of it is higher and the presence of innate oxygen lowers the calorific value. However, from the composition of CC-CNSL, it is certain that the composition of it is unique with relatively lower proportion of methyl ester than CNSL biodiesel and thereby reducing the degree of unsaturation of fuel. Predominantly, CC-CNSL is composed of 2-methyl phenol, which has had influenced the fuel properties, as the molecular structure and group

contribution parameters of the constituents of fuel has an effect on fuel properties. In light of this, the fuel properties such as viscosity and calorific value of CC-CNSL are improved than CNSL and CNSL biodiesel, as shown in table 1.

3. Experimental setup and arrangement

The test engine used in the current study is a stationary single cylinder diesel engine, used mainly for agricultural application and in industries for generating electricity. The engine is coupled with an eddy current dynamometer for applying loads by adjusting the current supplied to it and while doing this; the fuel pump rack position is adjusted so as to maintain a constant speed of 1500 rpm. The injector that we used for the experimentation is a three-hole mechanical injector with pump-nozzle injection system, having a nozzle hole size of 300 microns. Of course, the fuel pump is a mechanical inline pump that could pressurize fuel from 200 to 300 bar. With regards to combustion chamber, a hemispherical bowl in piston type combustion chamber has been used with the bowl depth of 2.5 cm. All other engine specifications are listed in table 2 and the arrangement of engine setup has been depicted in figure 4.

The fuel flow rate was measured manually using a burette and stopwatch, and the airflow rate was measured using an orifice meter, installed in the intake air supply system. Measurement of combustion chamber pressure was obtained by installing an AVL pressure transducer with the sensitivity of 16:11 pC/bar. The in-cylinder pressure was recorded for 100 cycles using AVL 619 Indimeter hardware and Indwin software version 2.2, and the recorded pressure signals are then processed to estimate the heat release rate. Exhaust emissions such as HC (Hydrocarbon), CO (Carbon monoxide), NO_x (oxides of nitrogen), and O₂ (oxygen) were measured using AVL 444 digas analyzer, which works on NDIR (non-dispersive infrared) principle by selective

absorption. The exhaust sample to be evaluated was passed through a cold trap (moisture separator) and filter element to prevent water vapor and particulates entering into the analyzer. Notably, the gaseous emissions such as HC and NO_x were measured in ppm (parts per million), while CO and O₂ emissions were measured in terms of percentage volume. Smoke level in the exhaust was measured in terms of HSU (hartridge smoke unit) using a standard AVL 437C smoke meter based on light extinction principle. Finally, EGT (Exhaust gas temperature) has been measured after deploying a K-type thermocouple in the engine exhaust pipe and monitoring the temperature in a digital indicator.

3.1 Test Procedure

Prior to testing the engine with CC-CNSL20 (20% CC-CNSL and 80% diesel), the engine is made to run with diesel for 30 minutes so as to attain steady state condition. During this period, the engine warms up and this is ensured by the engine coolant and lubrication oil temperature. Once the engine is set to operate, it is fueled by the test fuels and all the experiments were carried out at ambient conditions. Care is exercised to purge out the previously used fuel from the fuel lines and other associated equipment's prior to experimenting the engine with a new test fuel. Categorically, all the measurements pertaining to the engine experiment were repeated for five times to ensure the accuracy of the obtained results and the average values were used for computation and analysis. The repeatability of the measurements pertaining to experimentation holds good and it was well with in the standards.

In the engine optimization study, fuel injection pressure was increased from manufacturer default injection pressure of 200bar in an attempt to improve the atomization characteristics of the blend fuel, CC-CNSL20. As such, CC-CNSL20 has been tested at three different injection

pressures viz 235bar, 270bar and 300bar. To help realize this, nozzle-opening pressure of the mechanical injector being used is varied by adjusting the stiffness of the spring in the injector. A screw over the top of the injector assembly is manually adjusted and the desired injection pressure was set after it was ensured in mechanical pressure gauge system. Also, the thickness of washer placed at the intersection of nozzle and spring is varied to obtain the required injection pressure. Methodologically, for each and every injection pressure, the engine performance and emission measurements are realized and data are analyzed subsequently.

3.2 ISO standard test cycle for emission measurement

The engine characteristics were evaluated for the operation of CC-CNSL20 in a diesel engine at a constant speed of 1500 rpm and five different modes viz. 10%, 25%, 50%, 75% and 100% loading conditions. Strikingly, the load applied has been kept in compliance with ISO 8178 D2 standard test cycle used for the emission measurement of genset. It is noteworthy to point out that ISO 8178 D2 test cycle examines the engine emissions at five different modes and each mode has been accorded a separate weighing factor, as listed in table 3, which are being used for the calculation of composite emissions as follows,

$$E_{comp} = \frac{\sum_{i=1}^n (WF_i * E_i)}{\sum_{i=1}^n (WF_i * P_i)}$$

Where E_{comp} is weighted composite emissions in g/kWh, WF_i is weighting factor for mode i, E_i is the emissions for mode i (g/h), P_i is the power for mode i (kW) and n is the number of modes.

Since a genset is being used for current experimentation, we have decidedly chosen to operate the engine at the reported test cycle, dictated by Indian legislation standards. Normally,

for the investigation of alternate fuels in a non-road test engine like the one used in the current study, emission results are examined by plotting them against brake power, while compliance of exhaust emissions with legislative norms are seldom considered. Therefore, to verify the exhaust emissions with legislations levied, composite emissions were evaluated as per ISO 8178 D2 standard test cycle and the results are comprehensively analyzed. Characteristically, Indian emission standards proposed for genset diesel engines, producing the power output of less than 19kW, are 3.5 g/kWh for CO, 1.3 g/kWh for HC, 9.2 g/kWh for NO_x and 0.7 m⁻¹ for smoke [26]. Notably, the standard value reported for smoke emission is the measurement at full load condition, while other gaseous emissions such HC, CO and NO_x are composite emissions that are being computed according to the standard test cycle.

Since the emissions of HC, CO and NO_x are required to be furnished in g/h in the above formulation, those emissions measured in ppm were converted into g/h based on the correction factors, which has been clearly elucidated in our previous publication [27]. Also, for the estimation of NO_x emission, factors such as ambient temperature and humidity were accounted and required correction factors were incorporated. In general, researchers tend to capture NO_x emission using gas analyzers and present the conditions of measurement to be ambient. However, the temperature of the ambient air is bound to fluctuate, depending on the geography, climatic conditions and the time of measurement and depiction of NO_x emission as such would mislead this trend. Therefore, in the current work, correction factors are invoked as per the standard test cycle so as to make the composite emission analysis more accurate. Further, the smoke emission, measured in terms of HSU, has been converted into k coefficient of light absorption (m⁻¹) so as to compare with the legislative emissions.

3.3 Error analysis

The errors and uncertainties prop up from the selection of instruments, environment, observation and operating condition. Therefore, some uncertainty with the instruments used for the experiments persist, which are listed in table 4. Using the percentage uncertainty of various instruments, the percentage uncertainty of several parameters like BP (brake power), BSFC (brake specific fuel consumption), BTE (brake thermal efficiency) and others were determined by method of propagation of errors, prescribed by Holman [28]. The total uncertainty of the experiment was computed to be $\pm 2.26\%$, based on the uncertainty of various parameters

4. Results and discussion

4.1 Analysis of performance characteristics

Performance of the engine is examined by analyzing the parameters like BSFC and BTE. Figure 5 indicates the variation of BSFC for diesel and CC-CNSL20 at all loading conditions. It could be observed from the figure that BSFC for CC-CNSL20 at manufacturers default injection pressure of 200 bar is slightly lower than that of diesel. Obviously, this is because of the promotion in combustion process caused by the supplementation of oxygen inherently present in CC-CNSL. At the same time, it can be seen from table 1 that the flow properties of CC-CNSL are believed to be conducive for effective fuel atomization and air/fuel mixing process, which is deemed to favor the combustion process for CC-CNSL20 and thereby, decreasing the fuel consumption. In general, when biodiesel is being used in a diesel engine, due to its lower energy density, BSFC is ought to be higher so as to affect the engine performance [29]. However, herein, BSFC for CC-CNSL20 is perceived to be lower than diesel, given the calorific value of

CC-CNSL is approachable to that of diesel. Evidently, the comparable calorific value of CC-CNSL stems from its unique composition and this has seemingly contributed to the enhancement in combustion process on the whole. Reports on decrease in fuel consumption for fuels having calorific value akin to that of diesel have been surfaced before [30, 31], justifying the conclusion drawn from the current study using CC-CNSL in a diesel engine.

Figure 5 also depicts the variation of BSFC for CC-CNSL20 at various fuel injection pressures viz 200 bar, 235 bar, 270 bar and 300 bar. A close observation of the figure dictates a reduction in BSFC with the increase in fuel injection pressure and introspectively, it has been noted to be decreased progressively from the default injection pressure of 200 bar up to the injection pressure of 300 bar. This decrease is attributed to the improvement in fuel atomization process, which has had a positive impact on the combustion process. Also, finer dispersion of fuel molecules at higher fuel injection pressure is expected to decrease the spray momentum, decreasing the penetration so as to avoid wall impingement and thereby, reducing the fuel consumption. Notably, BSFC of the engine is reduced by 6.6% and 11.3% for CC-CNSL20 at 300 bar injection pressure than that of diesel at low and full load conditions, respectively.

Figure 6 depicts the variation of brake thermal efficiency with respect to engine power output for CC-CNSL20 at various fuel injection pressures. It can be observed from the figure that CC-CNSL20 shows slightly higher thermal efficiency than that of diesel at default injection pressure of 200 bar. In a measure to improve BTE further for CC-CNSL20, fuel injection pressure was increased and the effect of this on engine performance has been duly analyzed at all loading condition. Notably, BTE for CC-CNSL20 at 300 bar injection pressure is increased by 7.8% than that at 200 bar injection pressure. Past studies on optimizing the fuel injection

pressure hold the view that with the increase in injection pressure, the fuel droplets are finely atomized which subsequently improves the fuel evaporation rate and its mixing with air, resulting in better combustion [32, 33]. In compliance with this, combustion is perceived to have been improved for CC-CNSL20, as the fuel injection pressure is increased and as such, the performance of engine is improved. Further, the fact that CC-CNSL has inherent oxygen emerges as one of the crucial factors, besides the improved fuel properties of CC-CNSL, to uplift the engine performance. Substantially, the decrease in EGT with the increase in fuel injection pressure, as shown in figure 7, is in synonymous with the improvement in BTE, signifying the enhancement in combustion process and rules out the prospect of late burning in tail pipe.

4.2 Analysis of combustion characteristics

The heat release rate for CC-CNSL20 at various fuel injection pressures under full load condition has been shown in figure 8a. Close scrutiny of the heat release rate curve tends to confirm that the peak heat release rate for CC-CNSL20 at an injection pressure of 300 bar is higher than that at all other fuel injection pressures. It is noteworthy to find that CC-CNSL20 has lower viscosity than conventional biodiesel and it is also an oxygenated biofuel: both of these has had promoted fuel oxidation and subsequent combustion process. Further, since CC-CNSL does not suffer a drop in calorific value in the likes of biodiesel, it does not inflict a drop in amount of energy being released and as such, peak heat release for CC-CNSL20 is higher. Notably, the magnitude of peak heat release rate for CC-CNSL20 is found to be comparable to diesel at default injection pressure of 200bar and it happens to increase with the increase in fuel injection pressure. Notably, the peak heat release rate for CC-CNSL20 at an injection pressure of 300 bar is observed to be 17.4% higher than that at default injection pressure of 200 bar.

Though substantial amount of heat is being released during combustion for CC-CNSL20, it seemingly have an effect on ignition delay that defines SOC (start of combustion). In general, the delay in SOC for CC-CNSL20 at default fuel injection pressure of 200 bar is conceivable; this is because of the lower cetane number of CC-CNSL. However, with the increase in fuel injection pressure, the delay in SOC further increases, which is due to the delay in start of dynamic fuel injection timing for fuels at higher fuel injection pressure. In wake of this, the amount of fuel being burnt in premixed combustion phase is increased and this is why the magnitude of the heat release rate is increased for CC-CNSL20 at higher fuel injection pressure. Past studies on the optimization of fuel injection pressure for the operation of biofuels have also asserted higher peak heat release rate and delayed SOC because of the interpretations that have been put forth in the current study [27].

To get better insight on the combustion process for the operation of CC-CNSL20 in a diesel engine, variation of in-cylinder pressure with respect to crank angle has been drawn and is shown in figure 8b. As inferred from in-cylinder pressure curve, it could be adjudged that the peak in-cylinder pressure increases with the increase in fuel injection pressure based on the judgments as explained above. It is rationale to witness the indifference in peak pressure of diesel and CC-CNSL20 at lower injection pressure, as there isn't much deviation in the energy density for both the fuels. This conclusion is in antagonistic with the results for vegetable oils and its derivative, wherein drop in peak heat release rate and in-cylinder pressure were reported in light of lower calorific value [34]. Even raw and trans-esterified CNSL that were used as alternate fuel in a diesel engine also capitulates to drop in in-cylinder pressure and peak heat release rate because of the reported lower calorific value [13, 15]. However, herein, the improved extraction and processing methods of CNSL such as steam treatment and catalytic cracking

process has helped in the improvement of fuel properties. In particular, besides the favorable viscosity and betterment of calorific value, the evaporation attribute of CC-CNSL20 is improved, as evident from the flash point of the fuel. Seemingly, atomization and the subsequent air/fuel mixing process are believed to be enhanced, enriching the engine performance and combustion process on the whole.

4.3 Analysis of emission characteristics

The exhaust emissions such as HC, CO, NO_x and smoke are measured for CC-CNSL20 at various fuel injection pressures initially and followed by this, they are represented in terms of composite emission so as to compare with the emission limits of genset. The methodology for the estimation of composite emission, based on weighing and correction factors, were portrayed in the previous section. The composite emission of HC and CO for diesel and CC-CNSL20 at various fuel injection pressures has been discerned in figure 9. The formation of HC in engine exhaust is a clear evidence of incomplete combustion [35, 36] and in this case, it has been noticed to be lower for CC-CNSL20, given the inherent presence of oxygen and enhancement in fuel properties after cracking has favored the combustion process in the right accord. Categorically, composite HC emission has been noted to be within the limit of 1.3 g/kWh for all the test fuels and is noted to descend further with the increase in fuel injection pressure. Notably, from the standard limit, the composite HC emission is decreased by 76.3% for diesel, while it is noted to be much lower of about 84.6% for CC-CNSL20 at an injection pressure of 300bar. In justification, Gumus et al [32] have shown that higher fuel injection pressure enhances fuel mixing process, resulting in a reduced HC emission.

CO emission is affected by various parameters such as air fuel equivalence ratio, fuel type, combustion chamber design, atomization rate, start of injection timing, injection pressure, engine load and speed [37]. In this case, fuel to air equivalence ratio for CC-CNSL20 is expected to decrease with the increase in fuel injection pressure due to the improvement in air/fuel mixing process. This intended decreased fuel to air equivalence ratio, in addition to other factors such as presence of oxygen within CC-CNSL and increased heat release rate, has had favored the oxidation of CO and thus, CO emission decreases with the increase in fuel injection pressure for CC-CNSL20, as inferred from figure 9. Though the composite CO emission for diesel is found at the legislative norm of 3.5 g/kWh, it is observed to be lower for CC-CNSL20 at an injection pressure of 200 bar and is further decreased to a value of 3 g/kWh at higher fuel injection pressure of 300 bar.

While composite NO_x emission, as observed from figure 10, shows an increasing trend for CC-CNSL20 with the increase in injection pressure, composite smoke emission perhaps evinces a decreasing trend. Oxides of nitrogen are chemical compound formed by the reaction of nitrogen and oxygen under extremely high temperature [38, 39]. Accordingly, higher temperature and increased oxygen content have increased NO_x emission for CC-CNSL20. Further, since the magnitude of peak heat release rate is higher for CC-CNSL20, peak in-cylinder temperature attained during combustion process would also be higher and thus favoring NO_x formation. Also, with the increase in fuel injection pressure, NO_x formation is further triggered due to the improvement in combustion process and it slightly exceeds the standard limit of 9.3 g/kWh for CC-CNSL20 at a higher injection pressure of 300 bar. However, at all other injection pressures, composite NO_x emission is envisaged to be within the nominal values for CC-

CNSL20, while diesel shows a much lower composite NO_x emission, given combustion is less appreciated for this hydrocarbon fuel in relevance to oxygenated CC-CNSL.

On the other hand, composite smoke emission is seen to be below the standard emission limit for CC-CNSL20 at various injection pressures from figure 10. While it was observed to be 0.6 m^{-1} for CC-CNSL20 at an injection pressure of 200 bar as against the limit of 0.7 m^{-1} , it was noted to be 0.5 m^{-1} at a higher fuel injection pressure of 300 bar. In general, when the magnitude of premixed combustion is more pronounced, smoke emission will be reduced at the expense of increased NO_x emission in an unmodified diesel engine [40]. In concurrence with this, more pronounced premixed combustion phase for CC-CNSL20 at higher fuel injection pressure has resulted in better oxidation of soot precursors in the flame region. This has been further supported by the presence of excess oxygen within the confines of combustion chamber and improvement in fuel atomization as well as air/fuel mixing process, thereby lowering the smoke emission for CC-CNSL20 at higher fuel injection pressure. Previously, reduction in smoke emission has been well established for oxygenated fuels [41] and documentation of reduced smoke emission for CC-CNSL20 at different injection pressures augurs well herein.

5. Conclusion

With the intent to improve the fuel properties of CNSL, an economically viable alternate fuel from cashew nut outer shells, so as to facilitate its effective use in a diesel engine, this research work has been incepted in the right accord. Having realized that catalytic cracking of CNSL has not been accomplished before, we have cracked it using zeolite as a catalyst and strikingly, a different approach of steam treatment process followed by mechanical crushing has been employed to extract CNSL from cashew nut outer shells. Seemingly, both the extraction

and processing methods has had a complementary effect on fuel properties, improving the viscosity and calorific value of the synthesized CC-CNSL. Also, the compositional analysis of CC-CNSL revealed the existence of 2 methyl phenol as the prime constituent, besides the presence of methyl esters and other hydrocarbons. Categorically, at manufacturers default injection pressure of 200 bar, CC-CNSL20 showed engine characteristics closer to diesel, while with the increase in injection pressure, both BTE and BSFC were noted to be improved than diesel. Further, the emission results of HC, CO, smoke and NO_x were reported in terms of composite emission in a measure to make the analysis unique and more meaningful. Based on the analysis, the composite emissions, estimated as per ISO 8178 D2 standard test cycle, were noted to be well within the legislative standard limit of genset for CC-CNSL20. In future, apart from the optimization of fuel injection parameters, engine design such as combustion bowl geometry, compression ratio and nozzle hole geometry could be modified to utilize higher blends of CC-CNSL effectively in a diesel engine.

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Tables

Table 1

Thermal and physical properties of CNSL, CNSL biodiesel and CC-CNSL

Property	Diesel	CNSL	CNSL biodiesel [13]	CC-CNSL
Acidity, Inorganic	Nil	Nil	Nil	Nil
Density (kg/m ³)	822	956.4	909.3	890.0
Kinematic viscosity (m ² /s)	3.6 * 10 ⁻⁶	43.1 * 10 ⁻⁶	10.3 * 10 ⁻⁶	4.1 * 10 ⁻⁶
Flash point (°C)	74	226	170	94
Pour point (°C)	-23	-12	-1	-5
Cloud point (°C)	-10	-7	-5	-8
Copper strip corrosion @100°C for 3 hours	Not worse than NO 1	Not worse than NO 1	Not worse than NO 1	Not worse than NO 1
Gross calorific value (kJ/kg)	42700	38681	34300	42500
Sulphur content (%)	-	Less than 0.005	Less than 0.05	Less than 0.05
Calculated cetane index	52	33	41	48

Table 2

Engine specification

Type	Four stroke, Kirloskar make, compression ignition, direct injection ,constant speed ,vertical, water cooled
No of cylinders	One
Bore	87.5mm
Stroke	110mm
Cylinder displacement	661cc
Compression Ratio	17.5:1
Rated Power	5.2kW
Rated Speed	1500rpm
Dynamometer	Eddy current
Start of injection	23°CA BTDC
Injection pressure	200 bar, 235 bar, 270 bar and 300 bar
Type of injection	Mechanical pump-nozzle injection
Lubricating oil	SAE40

Table 3

Power weighting factors for FTP 5-mode test cycle (ISO 8178 D2) composite emission calculations

Test Mode	Torque (%)	Speed (rpm)	Weighting Factor (%)
1	100	1500	5
2	75	1500	25
3	50	1500	30
4	25	1500	30
5	10	1500	10

Table4

Uncertainties and measurement methods of instruments used in the experimentation

Measurement	Accuracy	% Uncertainty	Measurement technique
Load	$\pm 10\text{N}$	± 0.2	Strain gauge type load cell
Speed	$\pm 10\text{rpm}$	± 0.1	Magnetic pickup principle
Burette fuel measurement	$\pm 0.1\text{cc}$	± 1	Volumetric measurement
Time	$\pm 0.1\text{s}$	± 0.2	Manual stop watch
Manometer	$\pm 1\text{mm of Hg}$	± 1	Principle of balancing column of liquid
CO	$\pm 0.02\%$	± 0.2	NDIR technique
HC	$\pm 10\text{ppm}$	± 0.1	NDIR technique
NO _x	$\pm 12\text{ppm}$	± 0.2	NDIR technique
Smoke	$\pm 1\text{HSU}$	± 1	Opacimeter
EGT indicator	$\pm 1^\circ\text{C}$	± 0.15	K-type thermocouple
Pressure Pick up	$\pm 0.1\text{bar}$	± 0.1	Piezo electric effect
Crank angle encoder	$\pm 1^\circ$	± 0.2	Magnetic pickup principle

Figure captions

Figure 1. Extraction and processing of CNSL

Figure 2. Schematic diagram of the catalytic cracking reactor system

Figure 3. Chemical composition of CC-CNSL

Figure 4. Schematic diagram of the experimental setup

Figure 5. Variation of BSFC (brake specific fuel consumption) for diesel and CC-CNSL20 at various fuel injection pressure

Figure 6. Variation of BTE (brake thermal efficiency) for diesel and CC-CNSL20 at various fuel injection pressure

Figure 7. Variation of EGT (Exhaust gas temperature) for diesel and CC-CNSL20 at various fuel injection pressure

Figure 8. Variation of a) heat release rate and b) in-cylinder pressure for diesel and CC-CNSL20 at various fuel injection pressure under full load conditions

Figure 9. Variation of composite HC (hydrocarbon) and CO (carbon monoxide) emission for diesel and CC-CNSL20 at various fuel injection pressure

Figure 10. Variation of composite NO_x (oxides of nitrogen) and Smoke emission for diesel and CC-CNSL20 at various fuel injection pressure

Highlights

- CNSL has been processed effectively by catalytic cracking process for the first time
- 2-methyl phenol has been figured out to be the major constituent of CC-CNSL
- Viscosity and calorific value of CC-CNSL were simultaneously improved
- BTE and peak heat release rate were found to be higher for CC-CNSL20 at 300 bar
- Composite HC, CO, NO_x and smoke emission were within ISO emission standard