Performance and Emission analysis of Deccan Hemp Seed Cake Pyrolysis Bio oil-Diesel blends in a Single Cylinder Diesel Engine: A Comprehensive Study

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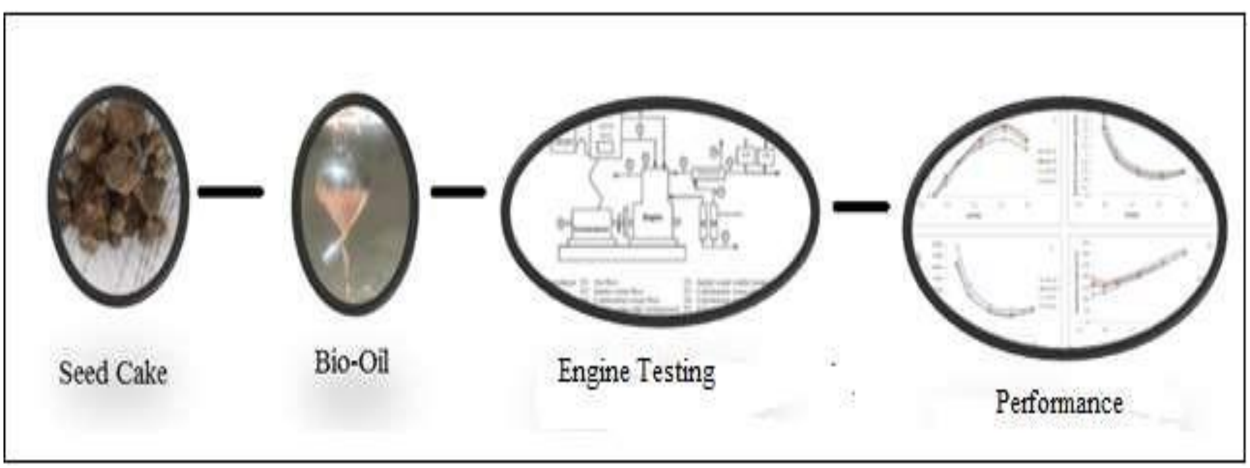
Abstract
The rising demand for fuel presents a major challenge to globalization. However, transportation business has advanced remarkably in mitigating this issue by commercializing alternative fuels like ethanol, biodiesel, liquefied petroleum gas, and compressed natural gas. In the current investigation the prospective utilization of blends of pyrolysis bio-oil and diesel is ascertained as a substitute fuel for powering diesel engine. Blends, which consist of 10% to 30% pyrolysis bio-oil, are referred to as BO10, BO20, and BO30. The bio-oil was produced from pyrolysis of deccan hemp seed-cake. The study analyzed various performances, emission and combustion parameters, including brake thermal efficiency, exhaust gas temperature, carbon monoxide, and hydrocarbon, oxides of nitrogen emissions, heat release rate and rate of pressure rise. Results showed that the variance of brake thermal efficiency between diesel and BO20 blend was only 2.61%. Exhaust gas temperature for the BO20 blend was also lower compared to diesel. Carbon monoxide, hydrocarbon, oxides of nitrogen and smoke emissions were in proportion to diesel emissions. Based on engine test results, the BO20 blend has the potentiality to serve as substitute fuel, with a 20% blending ratio into diesel. This research provides understanding the feasibility of using pyrolysis bio-oil as a sustainable alternative to diesel fuel.
Keywords: *Bio oil- diesel blend; Diesel engine; Emission; Performance; Pyrolysis.*

Graphical Abstract



1. Introduction

India, amongst world's rapidly developing economies and an emerging country, heavily rely on imported oil to fulfill its energy requirements. Diesel is the primary transportation fuel in India, which has resulted in increased diesel consumption, significant capital outflows, and growing concerns related to climate change. To address these issues, there is pressing need to explore alternative sources for diesel fuel (DF). One promising approach is converting biomass and its residues into more sustainable energy sources using different approaches viz. mechanical, biological, and thermal methods. Among these methods, pyrolysis, a thermal process, is gaining attention as a means of converting biomass into bio-fuel. The resulting product of biomass pyrolysis, bio-oil, has the potential to take over DF.

Pyrolysis is the process of decomposing biomass via heat in an oxygen-depleted environment. The procedure necessitates utilization of outside heat source to biomass inside a confined vessel. The condensed volatile substance that emerges in the chamber can be retrieved to get a more concentrated product consisting of gases, liquids, and solids, such as fuels and chemicals. The bio-oil, the liquid output, as substitute to DF is supported by its reproducibility and environmentally friendly nature [1].

In the light of subpar quality of crude bio-oil, it is inapt to use it directly in diesel-engines, as it exhibits hydrophilic properties and contains high concentration of moisture [2]. Therefore, upgrading the bio-oil is necessary before it could be utilized in diesel-engines as fuel. Various mechanisms, like hydro-treating, catalytic-cracking, solvent-addition, emulsification and steam reformation, are adapted to upgrade bio-oil [3]. In the present research work, gravity separation was employed to distinguish bio-oil fuel layer and organic fluid obtained from deccan hemp seed cake (DHSC) pyrolysis. This technique separates the two layers based on their differing densities, with the denser fuel layer located on top and the water and organic fluid constituents, which are usually composed of carbohydrate-derived compounds, situated beneath it. Following the separation process, the denser upper layer is heated to eliminate any residual moisture in the bio-oil. The temperature employed for upgrading ranges from 100 to 110°C.

After the upgrade, varying proportions of pyrolysis-oil were blended with diesel. In the present investigation a single-cylinder, four-stroke, direct injection (DI) diesel engine is used to assess its combustion characteristics, performance and emission properties. The study also explores the optimal bio-oil to diesel blend ratio to serve as diesel-engine fuel, are discussed and compared to diesel. The utilization of pyrolysis-derived bio-oil to power diesel engines, given its practicality, versatility, and ability to be produced from waste materials was studied.

The following literature study examines how pyrolysis bio-oil is typically used by blending with diesel in an ideal ratio and can serve as fuel source for diesel-engines.

The mahua bio-oil (MBO)-diesel emulsion performance in DI diesel-engine, indicated higher brake thermal efficiency (BTE), lower smoke, nitrogen oxide (NO) emissions, and exhaust gas temperature (EGT) [4]. Exploration on DI diesel-engine powered with blend of DF and bio-oil from aegle marmelos seedcake, found improved BTE and reduced carbon monoxide/oxides of nitrogen (CO/NO_x) emissions, but decreased brake specific energy consumption (BSEC) compared to DF [5]. The investigation on sweet-lime empty fruit bunch bio-oil mixed with diesel in diesel engines culminated that increasing bio-oil percentage reduced BTE and increased specific fuel consumption (SFC) because of heterogeneous air-fuel mixture, exhaust emissions were similar to diesel, but with higher CO and hydrocarbon (HC) emissions [6]. To increase cetane-number and evaluate exhaust and performance characteristics, [7] added waste-plastic pyrolysis oil (WPPO) and diethyl ether (DEE) to DF and observed that WPPO mix had superior performance with reasonable exhaust emissions compared to diesel at different loads.

A liquid oil blend from waste polymeric substances and neem-de-oiled-cake (NDC) showed lower BTE and improved brake specific fuel consumption (BSFC) at increasing blend proportions, but better performance at higher engine loads [8]. An investigation was performed on a blend of plastic-pyrolysis oil (PPO) and camphor oil in DI diesel engine, finding low BSFC, large heat release rate (HRR), reduced unburned hydrocarbon (UBHC) emissions, and elevated NO emissions. The blend resulted in increased smoke opacity due to improper combustion [9]. The impact of cottonseed bio-oil blended with diesel on engine performance was explored which showed maximum efficiency and minimum fuel consumption for blend of 5% bio-oil and 95% diesel. However, NO_x emissions marked up with higher loads, compression ratio (CR) and blend ratios, while CO as well as HC emissions went up with lower blend ratios and CRs at higher loads. Smoke opacity decreased with higher load, CR, and blend ratio [10].

The study is intended to assess utility of bio-oil-diesel blend as an alternate energy source in a single-cylinder diesel engine.

2. Materials and Methods

2.1 Pyrolysis bio-oil

The current study comprises collecting seed cake, a byproduct of extracting oil from the non-edible seeds of deccan hemp. The cake was dried in sun before being ground using a kitchen mixer. The pyrolysis reactor was loaded with ground seed cake of particular-size, and process was allowed to progress at a specific temperature. Reactor is constructed using mild-steel and lined with refractory materials to minimize heat-loss. Grinded, dried seed cake weighing 2 kilogram's is introduced into the reactor. Optimal temperature for maximizing bio-oil production during the seedcake biomass pyrolysis process was revealed to be 450°C [as ascertained from thermo-gravimetric analysis (TGA) for seed cake]. Figure 1 depicts flow-chart of seedcake pyrolysis process. At ideal temperature of 450°C and particle-size of 1.5 mm maximum yield of bio-oil 49.5 wt% and bio-char was 36.5 wt%.

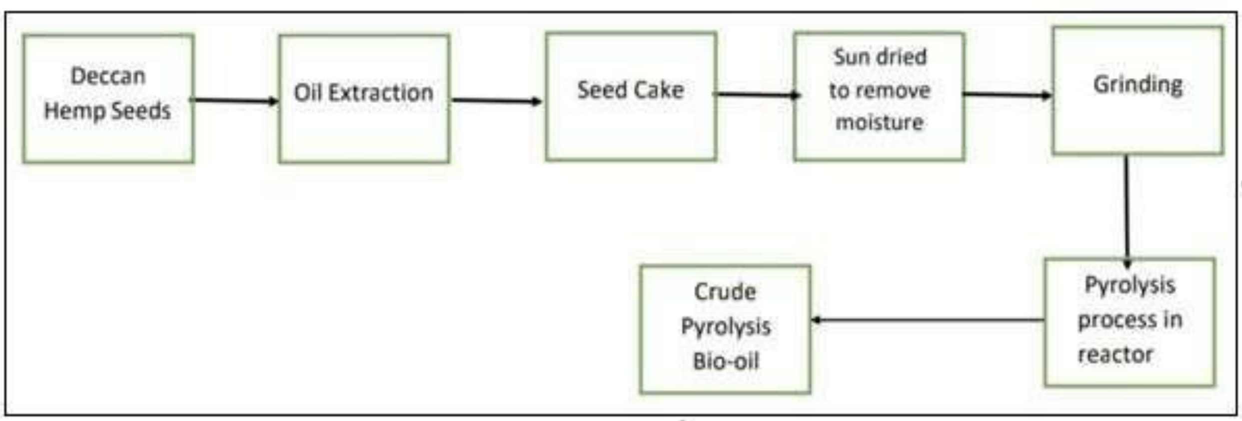


Fig. 1. Flow-chart of pyrolysis of seed cake

2.2 Bio-oil up-gradation

The up-gradation process of condensed crude bio-oil involves two steps, gravity separation and moisture elimination. The gravity separation step involves separating the bio-oil into two layers, an upper dense layer and a lower aqueous layer. The second step involves eliminating the moisture from the upper dense layer by heating it within a specific temperature, between 100 to 110°C. To better understand the qualities of upgraded bio-oil, several analyses were performed to evaluate its physical, chemical, and thermal properties. A major outcome was that, density of upgraded bio-oil was closer to diesel than the original crude bio-oil. Figure 2 depicts the flow chart of process of bio-oil up-gradation.

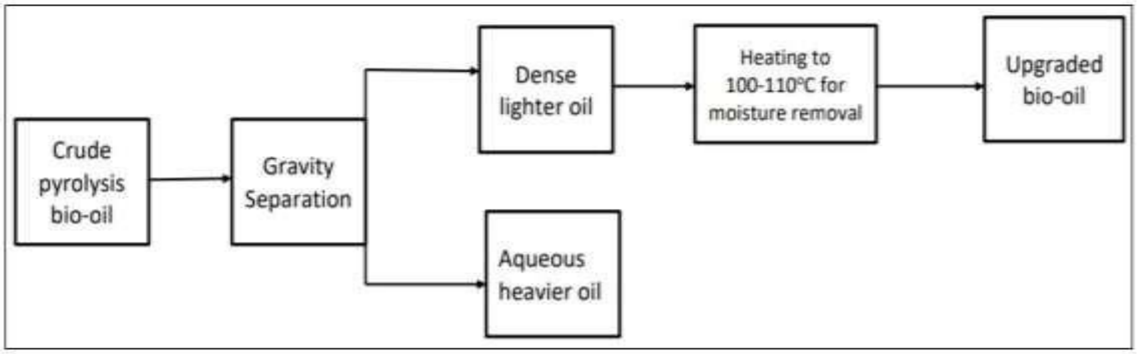


Fig. 2. Flow chart of bio-oil up-gradation process

2.3 Experimentation

Diesel engine employed for experimentation has a power output of 3.5 kW and is a normally aspirated, water-cooled, single-cylinder, four stroke DI diesel-engine. Table 1 depicts engine specifications. Figure 3 illustrates experimental setup's image and schematic layout. The experimental set-up primarily comprises of test bed, a diesel-engine, an eddy-current dynamometer used to load the test engine, a data-acquisition device, a computer, and an operation-panel. To analyze exhaust gas composition, five-gas analyzer is utilized, the details of which are provided in Table 2. Additionally, Table 3 displays the details of smoke-meter employed for measuring smoke emissions.

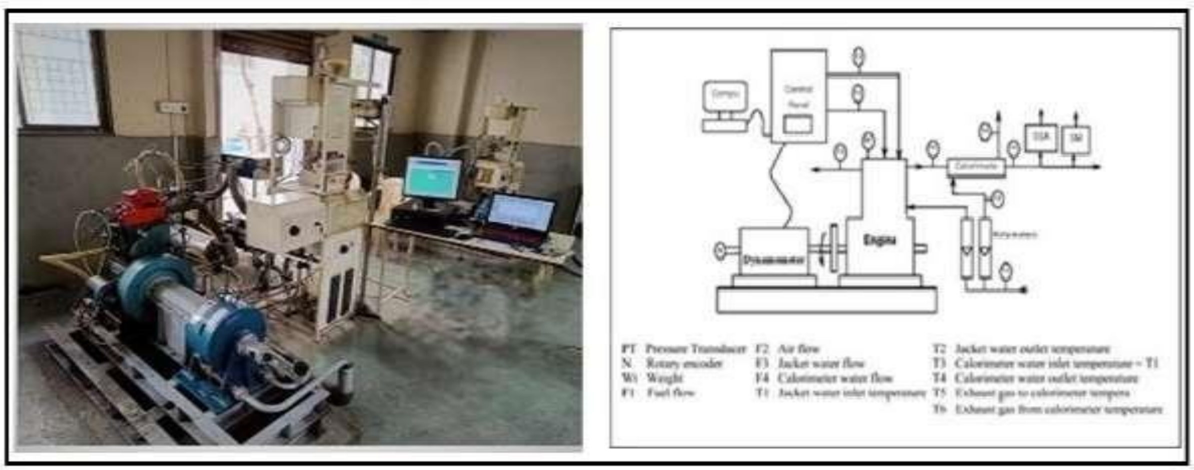


Fig. 3. Image of experimental set-up with schematic representation

Table 1. Engine Specifications

Manufacturer	Kirloskar
Model	TV1
Engine	Single cylinder, DI
Bore	87.5 mm
Stroke	110 mm
Compression ratio	17.5:1

Rated power	3.5 kW
Speed	1500 RPM
Injection pressure	210bar/23° before TDC
Cooling	Water cooled
Type of sensor	Piezo sensor, Range 5000PSI, with low noise cable.
Dynamometer	Eddy current, water cooled
Load indicator	Digital, Range 0-50 kg
Load sensor	Load cell, strain gauge, range 0-50kg
Crank angle sensor	Resolution 1 Deg, Speed 5500 RPM with TDC pulse
Calorimeter	Type pipe in pipe
Data acquisition device	NI USB-6210, 16 bit, 250 kS/s
Temperature sensor	Type RTD, PT100 and Thermocouple, Type K
Temperature transmitter	RTD PT100, Range 1-100°C,3Nos; Thermocouple, Range 0-1200°C, 2Nos
Rotameter	Engine cooling 40-400 LPH; Calorimeter 25-250 LPH
Software	"Enginesoft" Engine performance analysis software

Table 2. Five-gas analyzer specifications

Technical specification		
Manufacturer	M/s AVL India Pvt. Ltd.	
Model	AVL DiGas 444N	
Display	LCD display	
Interface	USB	
Operating voltage	100-300V AC, 50-60Hz	
Power consumption	Max.10W	
Dimension (wxhxl)	270x85x320 mm	
Weight	4.5kg	
Approval (India)	ARAI Pune	
Gas bench	OIML, Class O/CE/ISO	
Measurement data		
	Measurement	**Resolution**
CO	0-1% Vol.	0.001% Vol.
HC	0-20000 ppm Vol.	1 ppm/10ppm (0-2000 ppm)/(>2000 ppm)
CO_2	0-20 % Vol.	0.1 % Vol.
O_2	0-25 % Vol.	0.01 % Vol.
NO	0-5000 ppm Vol.	1 ppm Vol.
Engine speed	400-6000 rpm	1 rpm
Oil temperature	0°C -125°C	1°C
Lambda (λ)	0-9.999	0.001

Table 3. Smoke meter specifications

Technical specification	
Manufacturer	M/s AVL India Pvt. Ltd.
Model	AVL 437
Measurement range	Opacity : 0 – 100% Absorption : 0 – 99.99 m^{-1}
Resolution	Opacity: 0.1 % Absorption : 0.01 m^{-1}
Accuracy	Better than ± 0.1 m^{-1} of measurement value
Operating temperature	5°C - 50°C
Linearity check	50 % of measurement range (automatic)
Measurement length	0.43 mm ± 0.005 mm
Dimension	570x1250x500 mm
Weight	50 kg
Power supply	220 V, 50Hz 11.5 – 36 V DC

2.4 Experimental procedure

Four test oils have been set about for the engine trials. The first one is DF and the other three are BO10, BO20 and BO30. Physical properties of BO10, BO20 and BO30 are collated for diesel in Table 4.
BO10 – 10% upgraded bio-oil and 90% diesel
BO20 – 20% upgraded bio-oil and 80% diesel
BO30 – 30% upgraded bio-oil and 70% diesel

Table 4. Physical properties of bio-oil blends

Properties	Test-Method	Diesel	Upgraded bio-oil	Blends		
				BO10*	**BO20***	**BO30***
Density, kg/m^3	ASTM D1298	830	978	844.8	859.6	874.4
Viscosity, cSt	ASTM D445	3.05	86.41	11.39	19.72	28.06
Flash point, °C	ASTM D93	98	50	93	88.4	83.6
Calorific Value, kJ/kg	ASTM D4868	42000	22440	40044	38088	36132

*Computed Values

Testing of engine was performed under varying engine loads of 0, 0.35, 0.9, 1.8, 2.6 and 3.5 kW at constant rated speed of 1500 revolutions per minute (RPM), at standard crank angle setting of 23° before top-dead-centre (BTDC) and injection opening pressure (IOP) of 210 bar. First diesel was used as fuel for the trails at different loads. After completion of the tests on diesel, the same test procedure is reiterated for BO10, BO20 and BO30 and the results accomplished are compared to DF. The data is recorded and calibrated from 50 successive cycles.

3. Results and discussion

3.1 Performance

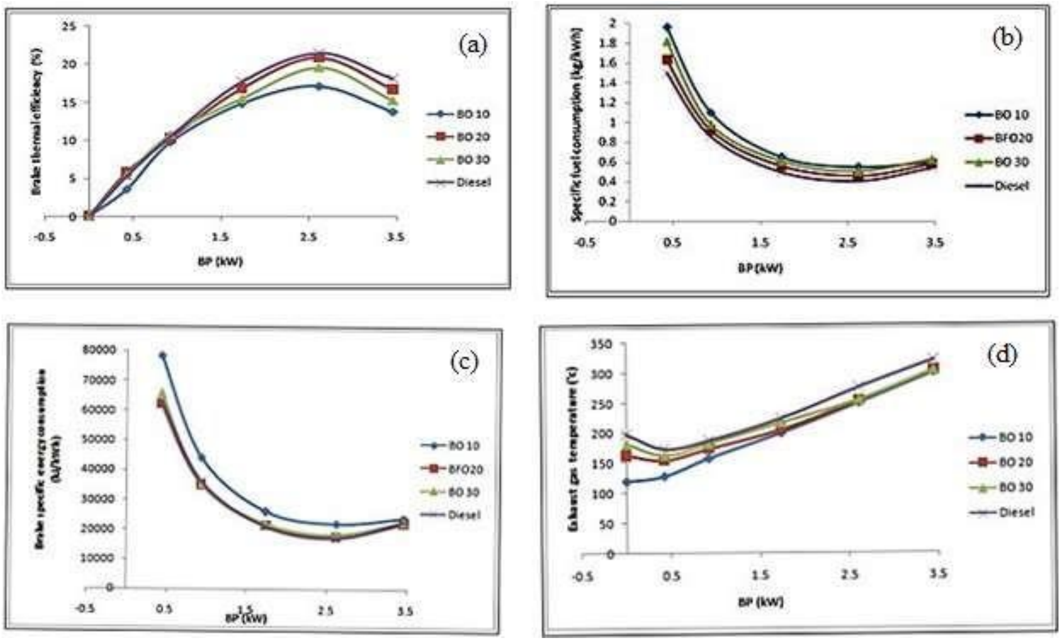


Fig. 4. (a) BTE Vs BP (b) SFC Vs BP (c) BSEC Vs BP (d) EGT Vs BP

Figure 4 (a) illustrates relationship between BTE for diesel and bio-oil blend fuel with brake power (BP). BTE represents the proportion of fuel energy input that is converted into useful power output [11]. As the load increases, BTE of DF and blends increases because of less heat loss at higher loads. The BTE was higher at 75% load owing to better combustion characteristics. The recorded BTE at 75% load of BO10, BO20, BO30 and DF were 17.12, 20.88, 19.57 and 21.44%. The difference in BTE between diesel and BO20 blend could potentially be ascribed to variance in their oxygen content. Higher viscosity, spray-characteristics and a low calorific-value are all related to lower BTE for bio-oil blends [12, 13].

Figure 4 (b) depicts variation of SFC for diesel and blends with BP. SFC decreases as the load increases but slightly increases at full-load for bio-oil blends and diesel. SFC recorded at 75% load for BO10, BO20, BO30 and diesel was 0.55, 0.46, 0.51 and 0.41 kg/kWh. On account of higher calorific-value and lower mass, diesel noted lowest SFC while all blends showed higher SFC by virtue of lesser calorific-value and greater viscosity [14, 15]. Since BO20 has larger oxygen content, makes it a superior blend, with SFC values which resemble closely to diesel.

Figure 4 (c) illustrates variation in BSEC for diesel and blends with BP. BSEC is a vital factor being considered while choosing a fuel mix. BSEC of BO10 and BO30 is superior to DF. This could possibly due to mixture's decreased calorific value plus incorrect fuel atomization and vaporization, which culminates in a weak spray and inefficient combustion. Furthermore, existence of aromatic compounds in bio-oil requires a higher levels of energy to separate double bounded carbon (C=C) [16], therefore more fuel must be burned to produce appropriate amount of power [17]. The lowest BSEC was at 75% load, and recorded values for BO10, BO20, BO30 and diesel are 22024, 17521, 18606 and 17220 kJ/kWh. With the outcomes it is evident that BSEC of BO20 is well comparable with diesel.

Figure 4 (d) illustrates variation in EGT for diesel and blends with BP. An engine's EGT can serve as an indicator of amount of heat that has been utilized to accomplish work. The chart clearly shows that under part load, the EGT's of various bio-oil-diesel blends are lower relative to DF. This is possibly due to lower calorific-value of bio-oil-diesel blends relative to DF and their tendency to quench due to water content [18]. As the load increases, EGT of different blends increased and was quite comparable to DF. At 75% load, EGT of BO10, BO20, BO30 and diesel are 250, 254, 256 and 275°C.

3.2 Emissions

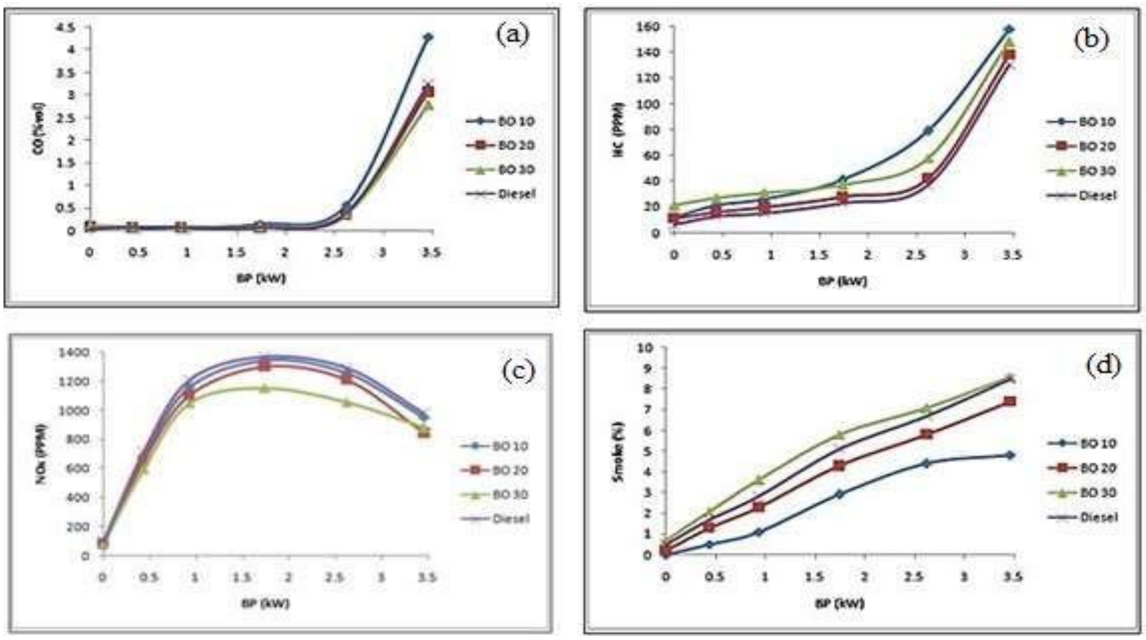


Fig. 5. (a) CO Vs BP (b) HC Vs BP (c) NO_x Vs BP (d) Smoke emissions Vs BP

Figure 5 (a) depicts CO emission variation with BP for diesel and blends. It is noticed that, up-to 75% of the load CO emissions are very low and almost constant later raise from 75% to full load. This is because of incomplete combustion in diesel-engines due to lower flame temperatures and less oxygen, which can result in emergence of CO [19]. At 75% engine load, CO emissions for BO10, BO20, BO30 and diesel are 0.56, 0.35, 0.38 and 0.40 % volume respectively. CO emissions were found to be lower with BO20 blend in comparison to DF may be ascribed to occurrence of oxygen that facilitates improved combustion [20].

Figure 5 (b) illustrates HC emission variation with BP for DF and blends. The illustration makes it quite evident that as load amplifies the HC emissions also raise. A greater level of HC emissions is caused by poor combustion of fuel-air mixture. Throughout the entire operation range, all blends exhibit higher levels of HC emissions than DF. HC emissions are higher in blends, potentially by virtue of high viscosity and density. Poor combustion is the consequence of greater viscosity because of imperfect atomization [19, 21]. At 75% load the noted HC emissions for BO10, BO20, BO30 and diesel are 79, 42, 58 and 37 parts per million (PPM). Observations indicate that, HC emissions of BO20 are close to DF

Figure 5 (c) depicts how NO_x emissions vary with BP for diesel and blends. NO_x production is impacted by components like, availability of oxygen and combustion temperature in diesel engines [22, 23, 24]. In comparison to diesel, it is observed that all blends exhibit lower levels of NO_x emissions. The lower NO_x emissions in bio-oil blends may be ascribed to the prevalence of water that has high latent-heat of vaporization, plus the inherent oxygen content in bio-oil, which helps to limit NO_x formation. Due to higher latent-heat of water vaporization in bio-oil blends, the cylinder temperature can be reduced, leading to lower NO_x emissions. At 75% load NO_x emissions of BO10, BO20, BO30 and diesel are 1253, 1210, 1054 and 1288 PPM

Figure 5 (d) depicts how the smoke quantity varies with BP for blends and diesel. For diesel engines smoke is a very important performance parameter. The opacity of smoke appears to be rising, in the light of increase in load for different blends. When load on engine is increased, additional fuel is consumed per cycle, ensuing poor combustion and increased formation of smoke [25]. The bio-oil blends, except BO30, have lower smoke opacity in contrast to diesel because of greater levels of oxygen and concentration of hydrogen and oxygen (OH) radicals. These factors promote higher combustibility and reduce smoke formation [26, 27]. The heavy compounds present in bio-oils have higher molecular weight and are more complex in structure, that effect adversely for complete burning in the combustion-chamber of diesel engine. This incomplete combustion leads to development of particulate matter, which is the main component of smoke. Therefore, bio-oil blends may have a higher tendency to produce smoke than diesel. Higher water-content in bio-oil blends can usher to longer ignition delay, incomplete-combustion, and promote smoke emissions. This is due to the fact that the water content can quench the flame and reduce the temperature of combustion, leading to incomplete-combustion and smoke generation. At 75% load, smoke opacity of BO10, BO20, BO30 and diesel are 4.4, 5.8, 7.1 and 6.7% respectively.

3.3 Combustion Parameters

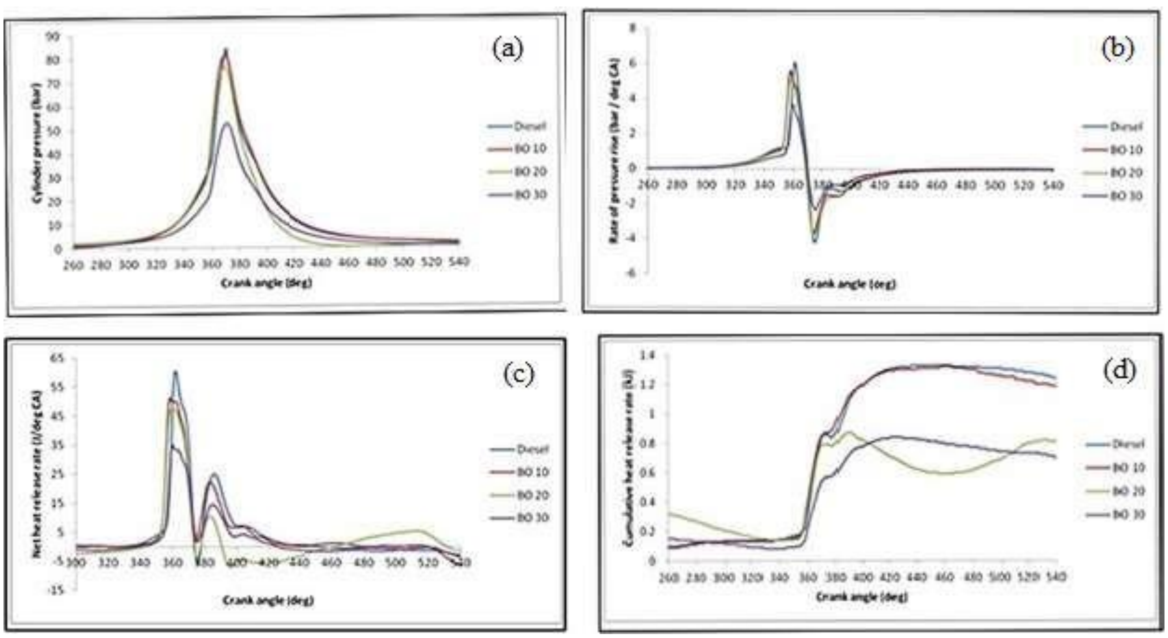


Fig. 6. (a) CP Vs CA (b) RPR Vs CA (c) NHRR Vs CA (d) CHRR Vs CA

Variation in cylinder pressure (CP) with crank angle (CA) is illustrated in Figure 6 (a) for diesel and blends at 75% engine load. It is crucial to monitor CP to assess both performance of engine and combustion behavior inside the combustion chamber. According to observations, the CP rises as the load does. In comparison to other bio-oil blends, diesel showed higher CP for all engine running situations. When operating at 75% load, the cylinder-peak pressures for BO10, BO20, BO30, and diesel fuels are 81.92, 76.55, 52.72, and 84.21 bar, respectively. Cylinder-peak pressure for bio-oil blends was lower than DF. This is likely attributed to enhanced viscosity and reduced volatility for blends of bio-oil [28].

Figure 6 (b) illustrates the deviation in rate of pressure rise (RPR) alongside CA for diesel and blends at 75% load. RPR signify the knocking tendency (abnormal combustion) in diesel engine. Furthermore, generation of NO_x emissions impended from diesel-engines is determined by maximum RPR [29] should be articulated that when engine load rose, the maximum RPR values also climbed. At 75% load the RPR for BO10, BO20, BO30 and diesel are 5.61, 5.08, 3.65 and 6.07bar/°CA respectively. Observations indicate that under all engine working situation, the maximum RPR of bio-oil blends is lower than DF. The possible reason being enhanced viscosity and reduced volatility of bio-oil. To bring down noise and to extend engine life the RPR should be as low as possible.

Figure 6 (c) exemplifies the variation in net heat release rate (NHRR) alongside CA for DF and blends at 75% engine load. NHRR represents heat energy release-rate per unit time and space during chemical reactions which is a crucial physical parameter in the review of combustion mechanisms. In comparison to bio-oil blends it is established that DF exhibits faster heat energy release rate. At 75% load, the NHRR for BO10, BO20, BO30, and diesel are 51.33, 47.03, 35.15, and 60.41 J/°CA, respectively. Diesel has a higher peak-heat release rate in comparison to other bio-oil blends owing to prolonged delay period, which leads to the accumulation of fuel and subsequent enhanced heat release during pre-mixed combustion [30]. The NHRR decreases as percentage of bio-oil in blends is raised. This is due to shorter ignition delays of bio-oil blends, resulting in reduced calorific-value and CP.

The variation in cumulative heat release rate (CHRR) with CA is illustrated in Figure 6 (d) for diesel and blends at 75% engine load. CHRR is crucial indicator of how effectively the combustion process performs. It is noted at 75% load the CHRR for BO10, BO20, BO30 and diesel are 1.31, 0.82, 0.84 and 1.32 kJ respectively. The figure indicates that CHRR of diesel is superior to all blends possibly owing to greater viscosity and bio-oil density [25]. The CHRR tends to rise as the load does, which is a discernible pattern [31, 32].

4. Conclusion

The use of pyrolysis to extract bio-oil from biomass remains a viable approach. However, the resulting deccan hemp seed cake (DHSC) bio-oil is notably viscous, dense, and has a lower calorific-value than fossil fuels, making it unsuitable for diesel engine applications without further processing. The main challenge with bio-oil is high moisture-content that can be eliminated by heating the oil above 100°C. Once the moisture has been removed, the bio-oil can be cooled to room temperature and blended with DF to produce BO10, BO20, and BO30 fuel blends.

The conclusion of current investigation on combustion, emission, and performance attributes of diesel engines powered by diesel and bio-oil diesel blends can be summarized at optimum operating load of 75% engine load.

From above investigations, among the bio-oil blends tested, BO20 blend was able to produce BTE, SFC, BSEC and EGT comparable to diesel. Thermal- efficiency of BO20 bio-oil blend is 2.61% lower as compared to DF. The BO20 bio-oil blend produced lower CO, NOx, HC and smoke emissions are comparative to diesel. Combustion parameters of BO20 bio-oil blend are analogues to DF. Inline to the aforementioned findings it is finally concluded that, bio-oil derived, utilizing DHSC pyrolysis may serve as partial replacement for DF with 20% blend without requiring any engine alteration.

References

[1] Aghbashlo, M., Tabatabaei, M., Mohammadi, P., Khoshnevisan, B., Rajaeifar, M.A. et al. (2017). Neat diesel beats waste-oriented biodiesel from the exergoeconomic and exergoenvironmental point of views. *Energy Conversion and Management*, *148*, pp.1-15.

[2] de Luna, M.D.G., Cruz, L.A.D., Chen, W.H., et al. (2017). Improving the stability of diesel emulsions with high

pyrolysis bio-oil content by alcohol co-surfactants and high shear mixing strategies. *Energy*, *141*, pp.1416-1428.

[3] Yuan, X., Leng, L., Xiao, Z., Lai, C., Jiang, L., et al. (2016). Pyrolysis and combustion kinetics of glycerol-in-diesel hybrid fuel using thermogravimetric analysis. *Fuel*, *182*, pp.502-508.

[4] Mulimani, H. and Navindgi, M.C., (2017). An experimental investigation of DI diesel engine fuelled with emulsions of Mahua bio-oil. *International Journal of Science and Research*, *6*(1), pp.1781-1785.

[5] Paramasivam, B., Kasimani, R. and Rajamohan, S., (2018). Characterization of pyrolysis bio-oil derived from intermediate pyrolysis of Aegle marmelos de-oiled cake: study on performance and emission characteristics of CI engine fueled with Aegle marmelos pyrolysis oil-blends. *Environmental Science and Pollution Research*, *25*, pp.33806-33819.

[6] Sukumar, V., Manieniyan, V. and Sivaprakasam, S., (2019). Experimental studies on DI diesel engine fueled in sweet lime pyrolysis oil with biodiesel. *Int J Appl Eng Res*, *14*(5), pp.1145-1150.

[7] Selvam, M.A.J., Sambandam, P. and Sujeesh, K.J., (2022). Investigation of performance and emission characteristics of single-cylinder DI diesel engine with plastic pyrolysis oil and diethyl ether blends. *International Journal of Ambient Energy*, *43*(1), pp.3810-3814.

[8] Raguraman, D., Kumar, A., Prasanna Raj Yadav, S., Patil, P.Y., Samson Isaac, J., et al. (2021). Performance and emission characteristics of pyrolysis oil obtained from neem de Oiled cake and waste polystyrene in a compression ignition engine. *Advances in Materials Science and Engineering*, *2021*, pp.1-10.

[9] Kasiraman, G., Manoharan, A. and Sai, M.C., (2021). Effect of camphor oil on a plastic pyrolysis oil fueled DI diesel engine. In Journal of Physics: Conference Series (Vol. 2054, No. 1, p. 012045). IOP Publishing.

[10] Rajamohan, S., Suresh, S., Mallinathan, S., Harigopal, A., Engel, D., et al. (2022). Optimization of operating parameters for diesel engine fuelled with bio-oil derived from cottonseed pyrolysis. *Sustainable Energy Technologies and Assessments*, *52*, p.102202.

[11] Krishna, S.M., Salam, P.A., Tongroon, M. and Chollacoop, N., (2019). Performance and emission assessment of optimally blended biodiesel-diesel-ethanol in diesel engine generator. *Applied Thermal Engineering*, *155*, pp.525-533.

[12] Kavitha, M.S. and Murugavelh, S., (2019). Optimization and transesterification of sterculia oil: Assessment of engine performance, emission and combustion analysis. *Journal of Cleaner Production*, *234*, pp.1192-1209.

[13] Prasad K.M. and Murugavelh, S., (2020). Experimental investigation and kinetics of tomato peel pyrolysis: Performance, combustion and emission characteristics of bio-oil blends in diesel engine. *Journal of Cleaner Production*, *254*, p.120115.

[14]] Dewangan, A., Yadav, A.K., Mallick, A., Pal, A. and Singh, S., (2022). Comparative study of Manilkara zapota and Karanja based biodiesel properties and its effect on diesel engine characteristics. *Energy Sources, Part*

A: Recovery, Utilization, and Environmental Effects, *44*(2), pp.5143-5153.

[15] Yadav, A.K., Dewangan, A. and Mallick, A., (2018). Effect of n-butanol and diethyl ether on performance and emission characteristics of a diesel engine fueled with diesel–Pongamia biodiesel blend. *Journal of Energy Engineering*, *144*(6), p.04018062.

[16] Mangesh, V.L., Padmanabhan, S., Tamizhdurai, P. and Ramesh, A., (2020). Experimental investigation to identify the type of waste plastic pyrolysis oil suitable for conversion to diesel engine fuel. *Journal of Cleaner Production*, *246*, p.119066.

[17] Bhaskar, K., Nagarajan, G. and Sampath, S., (2013). Optimization of FOME (fish oil methyl esters) blend and EGR (exhaust gas recirculation) for simultaneous control of NOx and particulate matter emissions in diesel engines. *Energy*, *62*, pp.224-234.

[18] Bibin, C., Seeni, K.P. and Devan, P.K., (2020). Performance, emission and combustion characteristics of a direct injection diesel engine using blends of punnai oil biodiesel and diesel as fuel. *Thermal Science*, *24*(1A), p.13.

[19] Kumar, S., Prakash, R., Murugan, S. and Singh, R.K., (2013). Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine. *Energy conversion and management*, *74*, pp.323-331.

[20] Damanik, N., Ong, H.C., Tong, C.W., Mahlia, T.M.I. and Silitonga, A.S., (2018). A review on the engine performance and exhaust emission characteristics of diesel engines fueled with biodiesel blends. *Environmental Science and Pollution Research*, *25*, pp.15307-15325.

[21] Sharifzadeh, M., Sadeqzadeh, M., Guo, M., Borhani, T.N., Konda, N.M., et al. (2019). The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions. *Progress in Energy and Combustion Science*, *71*, pp.1-80.

[22] Buyukkaya, E. and Cerit, M., (2008). Experimental study of NOx emissions and injection timing of a low heat rejection diesel engine. *International journal of thermal sciences*, *47*(8), pp.1096-1106.

[23] Senthilkumar, P. and Sankaranarayanan, G., (2016). Effect of Jatropha methyl ester on waste plastic oil fueled DI diesel engine. *Journal of the Energy Institute*, *89*(4), pp.504-512.

[24] Saifuddin, M. and Boyce, A.N., (2016). Biodiesel production from waste cooking sunflower oil and environmental impact analysis. *Kuwait Journal of science*, *43*(3).

[25] Agarwal, A.K., (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in energy and combustion science*, *33*(3), pp.233-271

[26] Fu, P., Bai, X., Yi, W., Li, Z., Li, Y. and Wang, L., (2017). Assessment on performance, combustion and emission characteristics of diesel engine fuelled with corn stalk pyrolysis bio-oil/diesel emulsions with Ce0. 7Zr0. 3O2 nanoadditive. *Fuel Processing Technology*, *167*, pp.474-483.

[27] Vijayakumar, M. and Mukesh Kumar, P.C., (2017). Performance enhancement and emissions analysis of diesel engine with biodiesel, n-propanol and 1-butanol blend. *Journal of Applied Fluid Mechanics*, *10*(Special Issue)), pp.79-84.

[28] Vaishnavi, N. and Pugazhvadivu, M., (2020). Engine performance and emission analysis using pyrolytic liquid as a partial substitute for diesel fuel. In *AIP Conference Proceedings* (Vol. 2225, No. 1). AIP Publishing.

[29] Shrivastava, P., Verma, T.N. and Pugazhendhi, A., (2019). An experimental evaluation of engine performance and emisssion characteristics of CI engine operated with Roselle and Karanja biodiesel. *Fuel*, *254*, p.115652.

[30] Ramalingam, S. and Rajendran, S., (2019). Assessment of performance, combustion, and emission behavior of novel annona biodiesel-operated diesel engine. In *Advances in eco-fuels for a sustainable environment* (pp. 391-405). Woodhead Publishing.

[31] Yilbaşi, Z., Yesilyurt, M.K., Yaman, H. and Arslan, M., (2022). The industrial-grade hemp (Cannabis sativa L.) seed oil biodiesel application in a diesel engine: combustion, harmful pollutants, and performance characteristics. *Science and Technology for Energy Transition*, *77*, p.15.

[32] Asokan, M.A., Prabu, S.S., Bade, P.K.K., Nekkanti, V.M., et al. (2019). Performance, combustion and emission characteristics of juliflora biodiesel fuelled DI diesel engine. *Energy*, *173*, pp.883-892.