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Experimental studies on in-cylinder combustion, exergy performance, and exhaust emission in a Compression Ignition engine fuelled with neat biodiesels

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ABSTRACT

In the last decade, the search for cleaner fuels like biodiesels is gaining wide popularity, and exergy analysis are widely used in design and performance evaluation to identify the various losses. In this study, three neat biodiesels are tested for energy and exergetic performance in a single-cylinder, four-stroke IDI diesel engine. The experiments are conducted for waste poultry fat biodiesel (WPFBD), palm oil biodiesel (POBD), and waste cooking oil biodiesel (WCOBD) at various loads by maintaining a fixed rpm of 1500. Parameters like exergetic efficiency, exergy destruction, and various heat loss factors are computed from the thermodynamic models. The in-cylinder combustion pressures, heat release rate, and fuel consumption are also measured. Results show that WCOBD dominates the other two biodiesels by achieving high exergetic efficiency (52.74%) and low exergetic destruction (3.74 kJ). The in-cylinder combustion pressures and net heat release for WCOBD show smoother combustion with better torque conversion. In contrast, POBD shows high fuel consumption and more unaccounted heat losses. Better utilization of heat input by converting it into useful work was achieved for WCOBD at 75 and 100% loads. Similarly, the exhaust emissions from WCOBD compared with diesel fuel at all the loads reveal that except for NOx, there is a drastic reduction of CO, UHC, and exhaust smoke.

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1. INTRODUCTION

The role of energy production and its utilization is vital in shaping the country's economy and living standards. However, the current energy resources are on the verge of extinction due to rapid consumption. With the increasing global population, the demand for energy sources like fossil fuels is increasing at a faster rate (Olalekan *et al.*, 2022). The statistical predictions reveal that fossil fuels will meet only 3/4th of the total energy demand by the year 2040 (Ebel *et al.*, 1996; Kivevele *et al.*, 2020).

Fossil fuels are prevalent in many applications of industries, transportation, and agriculture. Among these, the most sought-after fuels are petro-diesel. Although they satisfy most of our day-to-day needs, the exhaust emissions from petro-diesel-fueled engines increase environmental air pollution (Mirhashemi & Sadrnia, 2020). Inhaling these harmful pollutants can cause serious human health issues like respiratory malfunction, lung cancer, and cardiovascular as well as skin diseases (Bendtsen *et al.*, 2021).

To mitigate the challenges posed by fossil fuels, renewable fuels like biodiesel from different feedstocks are gaining wide popularity nowadays more than ever (Kolakoti *et al.*, 2021; Kolakoti, Prasadarao, *et al.*, 2021; Pambudi *et al.*, 2021; Setiyo *et al.*, 2021; Sule *et al.*, 2022; Supriyadi *et al.*, 2022). Several researchers (as shown in **Table 1**) are inclined toward biodiesel utilization due to their exceptional capability in lowering harmful exhaust emissions and, at the same time conquering fuel scarcity.

Biodiesels are known for their attractive properties like zero sulfur content, rich in oxygen, cetane content, high flash point, biodegradability, lubricity, and nontoxic (Singh *et al.*, 2020). The added advantage of no change in the design of the engine with direct usage of biodiesel marks its preference over others.

It is a known fact that almost one-third of energy is lost from the engine during the combustion process. This fact creates a great scope for improvement in the engines. Therefore, to estimate the lost energy, thermodynamic models like energy and exergy are utilized as a key tool in diesel engine performance diagnosis (Rangasamy *et al.*, 2020).

The benefits of energy and exergy analysis, among others, are:

(1) used as a tool to measure system sustainability;
(2) reflect the quality of the heat transfer process in a thermodynamic cycle;
(3) the effective utilization of energy from a particular source can be identified with the exergy analysis;
(4) identifying the various losses caused by the irreversibility in a thermodynamic cycle; and
(5) identifying the various losses aids in the identification of the root causes, thereby improving the thermodynamic cycle efficiency.

Energy analysis based on the first law of thermodynamics gives us the rate of energy conversion within a control volume. Only the conversion of energy with efficiency from the engine can be analyzed. In contrast, exergy analysis reveals the qualitative and quantitative losses in a system and determines the accurate location where the possible sources of irreversibilities may occur, and also provide significant information about the engine efficiencies (Canakci & Hosoz, 2006; Chahartaghi & Sheykhi, 2018; Li *et al.*, 2016).

Therefore, these features made the researchers rekindle exergy analysis.Another investigation by Wang *et al.* (2019) on exergy and energy distribution for hydrogen-fueled turbocharged engines shows that the efficiency of exergy due to exhaust has reached up to 23%, while the coolant energy was observed below 5%. This study shows that there will be a great scope for recovering the energy (23%) from the exhaust system.

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Table 1. Exhaust emissions from different biodiesels with additive blends.

Biodiesel Type	Emission Highlights	Authors
Mahua Biodiesel with methanol additive	Low exhaust emissions of HC (57%), CO (20%), NOx (14%), and smoke (27%) are observed for 3% additive in biodiesel than diesel fuel.	Rao & Rao (2014)
Rice bran biodiesel with isopropanol additive	Thermal efficiency was improved by 4.3%, and toxic emissions were reduced by 14% of CO, 36.5% of NOx, and 27.5% of smoke recorded for 2% of additive in biodiesel at full load.	Talamala *et al.*, (2017)
Di-Oxyethylene-Ether (DOEE) additive in Palm Kernel biodiesel	50% reduction of CO, 44% reduction of HC, and 21% reduction in NOx are observed for 3% additive in biodiesel.	Kolakoti (2022)
Neat biodiesels of Waste cooking and Animal fat	High NOx and fuel consumption were observed for both the biodiesels and diesel fuel. At maximum and 3/4th maximum loads, the exhaust emissions of smoke, CO, and HC are observed to be low for the biodiesels.	Kolakoti (2021)
Neat biodiesels of pongamia, mahua, and jatropha	At full load, NOx emissions were reduced by 18.41%, 17.46%, and 7.61% for jatropha, mahua, and jatropha biodiesels. Similarly, low CO and HC are observed for three biodiesels than diesel fuel.	Prasadarao *et al.*, (2021)

The exergy results of Jafarmadar & Nemati (2016) in an HCCI (homogeneously charged compression ignition) engine showed an improvement in exergy efficiency with biodiesels being added to the diesel fuel. Sayin Kul & Kahraman (2016) conducted experiments at various speeds on a water-cooled diesel engine using biodiesel-diesel blends containing 5% bioethanol. Results show that neat diesel fuel has high thermal and exergetic efficiencies than the biodiesel blend.

This may be due to the high calorific value of diesel fuel. Aghbashlo *et al.* (2015) found an important conclusion stating that engine speed and load affect the exergy parameters, and an increase in the speed of the engine had an adverse effect on the index of sustainability and exergy efficiency.

From these studies, it was evident that energy and exergy analysis shows a better insight into diesel engine combustion and performance predictions. Therefore, the present experimental investigation aims to analyze the energy and exergy contributions from three different neat biodiesels when they are tested at various loads in a 5.4 kW diesel engine.

To the best of the author's knowledge, the comparison of three different neat biodiesel applications in energy and exergy analysis with their emission studies is limited. Hence this study reveals the detailed analysis of the energy and exergetic performance of the three biodiesels the best performing biodiesel was identified, and its pollution levels were measured.

2. METHODS AND MATERIALS

2.1. Materials Used

In this endeavor, three different oils were chosen for experimentation, namely waste poultry fat oil (rendered from feathers, skin, offal, etc. of chickens and turkey), waste cooking oil (sunflower oil used in deep frying of potato), and palm oil. These raw oils were purchased from a local market in Visakhapatnam, India. The raw oils of waste poultry fat (WPFO), waste cooking (WCO), and palm (PO) were initially filtered to remove the unwanted sediments of dust, suspended particles, etc. This was with the help of a filter paper (Whatman GF/B grade) and stored at ambient room temperature in an air-tight glass beaker. Different analytical grade chemicals of methyl alcohol (CH_3OH), sodium hydroxide ($NaOH$), oil of vitriol (H_2SO_4), etc. were obtained from Sigma-Aldrich chemicals suppliers.

2.2. Transesterification Method

Transesterification is a widely used chemical treatment for reducing the high viscosity in raw oils (Ayu *et al.*, 2019; Kolakoti, Prasadarao, *et al*., 2021; Kolo *et al.*, 2022). It is also considered as one of the most economical methods to achieve maximum output yield (Kolakoti *et al.*, 2021; Kolakoti, Setiyo, *et al*., 2022; Kolakoti & Satish, 2020). Therefore, the transesterification process was implemented in this current research.

The chemical kinetics of the transesterification mechanism was well understood from **Figure 1**, which reveals that the triglycerides in chosen raw oils react with alcohol (methanol or ethanol) in the presence of strong catalysts (homogeneous or heterogeneous). As a result of the chemical reaction, a clear separation of ester and glycerol appeared, and the ester was known as biodiesel.

The filtered raw oils of WPFO, WCO, and PO were converted into biodiesel at our fuel testing laboratory by following a two-stage transesterification process (acid-catalyzed and alkali-catalyzed). In the first stage of acid-catalyzed, also called esterification, a sample of one-liter raw oil, 0.4 mL of H_2SO_4, and 100 mL of CH_3OH was mixed with the help of a temperature-controlled magnetic stirrer for 90 minutes, as shown in **Figure 2**.

The temperature maintained throughout the first stage was fixed at 55°C. After the desired reaction period, the mixture was transferred into a separating funnel and allowed to settle for 8 hours to make two distinct liquid phases.

The excess methanol in the top layer was removed, and unreacted triglycerides and methyl esters were used in the second phase of the alkaline transesterification process. In the second phase, a homogeneous catalyst was used to initiate the transesterification process. For this purpose, 8 grams of NaOH pellets were mixed with 100 mL of CH_3OH to form a methoxide solution.

The methoxide was mixed continuously with the first stage esters, and the temperature and reaction period was maintained at 60°C and 120 minutes. A clear separation of methyl ester and glycerol appeared after 8 hours of the settlement period, as shown in **Figure 2**.

The glycerol was separated, and leftover methyl esters were washed with deionized water until a neutral pH value and a clear separation of water and biodiesel appeared.

The same procedure was followed for converting the three raw oils into biodiesels. By following the two-stage trans-esterification process, maximum biodiesel yield was achieved, and the yield was calculated using Equation (1).

Finally, obtained waste poultry fat biodiesel (WPFBD), waste cooking oil biodiesel (WCOBD), and palm oil biodiesel (POBD) were tested for key fuel properties as per ASTM standards before the start of engine experiments are shown in **Table 2**.

$$\text{Biodiesel yield (\%)} = \frac{\text{Weight of the Biodiesel}}{\text{Weight of the Raw oil}} \times 100 \quad (1)$$

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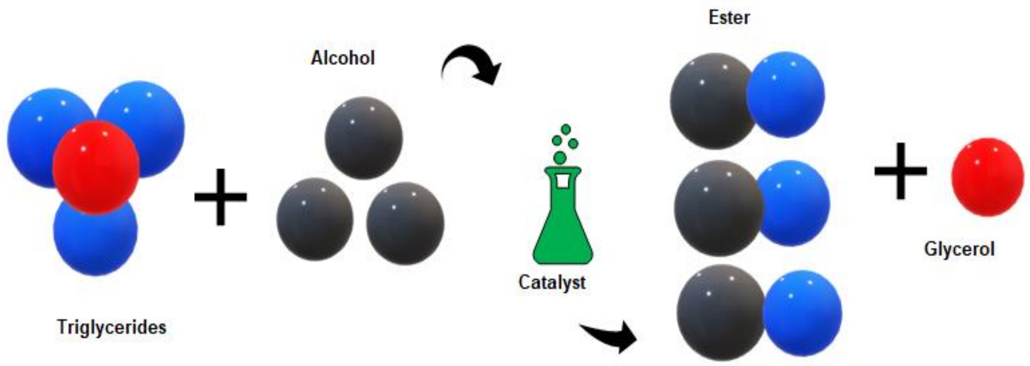

Figure 1. Transesterification mechanism.

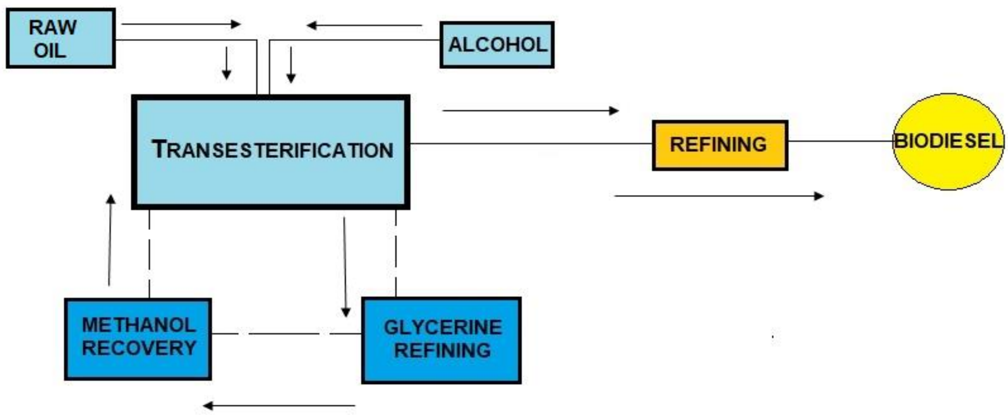

Figure 2. Biodiesel production flow chart.

Table 2. Diesel and Biodiesels characterization.

No	Property	ASTM	WPFBD	POBD	WCOBD	Diesel
1	Kinematic Viscosity (mm^2/s) at 40 °C	D445	4.6	4.5	4.2	2-3.7
2	Density at 25 °C (kg/m^3)	D1298	872	878	867	827
3	Calorific Value (MJ/kg)	D240	38.56	38.26	38.82	42.6
4	Cetane number	D613	52	51	53	47
5	Flashpoint (°C)	D93	170	180	163	54

2.3. Experiment method

Three neat biodiesels of WPFBD, WCOBD, and POBD were utilized for engine experimentation. The main aim of this experimental investigation is to test the combustion behavior, energy, exergy, and emission characteristics of neat biodiesels. For this purpose, a well-equipped single-cylinder 5.4 kW diesel engine was chosen for experimentation. The experimental testbed's schematic layout with the different instrumental arrangements is shown in **Figure 3**. The technical specification of the engine and other exhaust gas measuring components are shown in

Table 3.

The proposed experiments were started with the engine warm-up for 30 minutes with reference diesel fuel. During this duration, all the necessary connections of pressure pickup, crank angle encoder, fuel flow meter, coolant flow meter, air flow measuring unit, exhaust lines, data acquisition system, computer interface, and power connections were verified. Once the engine attains

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steady-state condition, energy and exergetic performance and emissions were measured at no load (0%) to full load (100%) by maintaining a fixed speed of 1500rpm. Eddy current dynamometer was used for applying the load on the engine and the combustion pressure data was measured with a least count of one degree with the help of a water-cooled pressure transducer. Engine exhaust gas temperatures were measured with K-type thermocouples and exhaust smoke, HC, CO, and NOx were measured with an AVL smoke meter and AVL five gas analyzers.

After recording the essential parameters from reference diesel fuel, the fuel lines were changed to neat biodiesels of WPFBD, WCOBD, and POBD. During the neat biodiesel applications, the test engine design parameters were not changed, and the injection pressures remain the same as per the manufacturer. The experimental procedure for each fuel sample was repeated multiple times (five) and the average results were taken for calculations. Furthermore, for each fuel change, the engine was run for 15 minutes, and all the measured parameters of combustion, performance, and exhaust emissions were recorded when the engine was in a thermal equilibrium state. As the experimental setup consists of several moving parts, therefore, the overall uncertainty of the measured parameters is calculated as per the standards and presented in **Table 4**.

Table 3. Research engine technical specifications.

Parameters	Specifications
Engine type	Single cylinder and four stroke
Bore (mm)	86
Stroke (mm)	77
Compression ratio	24:1
Rated speed (rpm)	1500
Ignition type	Compression
Injection pressure (bar)	142-148
Starting mode	Electrical
Loading	Eddy current dynamometer
Smoke meter	AVL 437C
CO, NOx, HC emission meter	AVL 444N

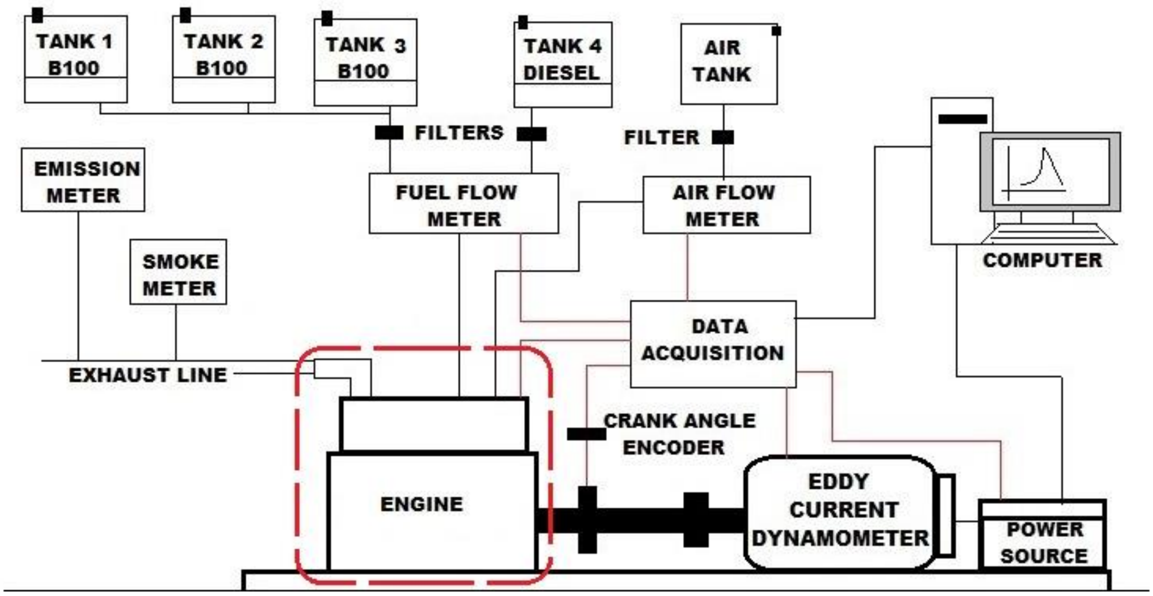

Figure 3. Experimental test rig and its components.

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Table 4. Measured uncertainty parameters.

No	Measurement	Uncertainty (%)
1	Torque	±1.5
2	Combustion Pressure	±0.12
3	Fuel consumption (BSFC)	±2.10
4	Brake thermal efficiency (BTE)	±1.93
5	Unburnt hydrocarbons (UHC)	±0.2
6	Carbon monoxide (CO)	±0.2
7	Smoke	±0.2
8	NOx	±0.2
9	Temperatures	±0.1

Furthermore, to predict the accurate heterogeneous combustion phenomena in diesel engines for the calculation of energy and exergy, few standard assumptions were considered for solving the complex equations. Air and fuel composition entering the experimental engine is assumed to be an ideal gas mixture.

The available air during the experimentations contains a fixed proportion of nitrogen (78%), oxygen (20.9%), carbon dioxide (0.03%), argon (0.09%), and other traces of gases (0.17%). The experimental engine is assumed as an adiabatic or insulated engine and it is operated under steady-state conditions. The system, as shown in **Figure 3** was assumed as an open system.

Therefore, the mass flow rate consisting of fuel and air is constant into and out of the system. The atmospheric temperature and pressure were considered as reference states for the calculation of energy and exergy balance (Rakopoulos & Giakoumis, 2006). The specific heat of the exhaust gases is assumed to be the specific heat of air at the mean exhaust temperature.

The unaccounted losses calculated were included based on the general calculations (Abedin *et al*., 2013) concerning the valve, spark plug, and combustion chamber locations. The lubricating oil losses were considered as unaccounted losses as per the available literature. Due to this, there will be fluctuations in the numerical results during the calculation of unaccounted losses, as agreed by different research groups (Abedin *et al*., 2013). Less significant losses were generated by changes in the kinetic and potential energy; hence they were neglected in the calculations.

From the simplified assumptions, the following mathematical equations were used for calculation. The molar concentration of individual gases in combustion was calculated by Equation (2). Where the coefficients α, β, γ, δ, ε, ζ, θ, φ, φ, and ψ are the mole fractions of the respective components and X is the number of moles of the measured products.

The heat energy released by the fuel was calculated by Equation (3). The output power (BP), Brake Thermal Efficiency (BTE), and Brake Specific Fuel Consumption (BSFC) were calculated by Equations (4) to (5). Then, the rate of mass flow balance and energy balance is calculated by Equations (6) and (7), respectively.

The exergy analysis was assumed to be calculated at the ambient temperature of 298K and one atm pressure at all conditions and the exergy balance was calculated by Equation (8), then the exergy destructed (Ex_d) was calculated by Equations (9) to (12). Where h,c,o, and s are the mass fractions of hydrogen, carbon, oxygen, and sulfur contents of the fuel, respectively. Finally, the second law efficiency was calculated by Equation (13).

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$$\alpha C_a H_b O_C + \beta(O_2 + 3.76N_2) \xrightarrow{yields} X(\gamma O_2 + \delta CO_2 + \varepsilon Co + \zeta H_2O + \theta HC + \phi NO + \varphi N_2 + \psi H_2) \quad (2)$$

$$\mathrm{E_f(kW)} = \mathrm{m_f} \times \mathrm{LHV} \quad (3)$$

$$\mathrm{BP\ (kW)} = \frac{2\pi NT}{60000} \quad (4)$$

$$\mathrm{BTE(\%)} = \frac{BP}{Q} \times 100 \quad (5)$$

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (6)$$

$$dQ - dW = dE \quad (7)$$

$$Ex_q + Ex_w = Ex_{in} + Ex_{out} - Ex_d \quad (8)$$

$$Ex_d = Ex_{in} - \left(Ex_w + Ex_c + Ex_{eg}\right) \quad (9)$$

$$Ex_{in} = \left[1.0401 + 0.1728\left(\frac{h}{c}\right) + 0.0432\left(\frac{o}{h}\right) + 0.2169\ \frac{s}{o}\left(1 - 2.0628\frac{h}{c}\right)\right] \times m_f \times LHV \quad (10)$$

$$Ex_c = \sum\left(1 - \frac{T_0}{T_w}\right)Q_w \quad (11)$$

$$Ex_{eg} = Q_{eg} + m_{eg}T_0\left[C_p \ln\left(\frac{T_0}{T_{eg}}\right) - R\left(\frac{P_0}{P_{eg}}\right)\right] \quad (12)$$

$$\eta_{II} = \left(1 - \frac{Ex_d}{Ex_{in}}\right) \times 100 \quad (13)$$

3. RESULTS AND DISCUSSION

3.1. In-cylinder Pressure and Net Heat Release Rate Analysis

Combustion pressures were measured at every degree of crank angle for all the tested fuels of neat diesel and biodiesels. **Figure 4** and **Figure 5** represent the variations of in-cylinder combustion pressure (bar) and net heat release rate (J/degree) as a function of the crank angle at 75% and 100% loads. Compared to neat biodiesels, diesel fuel exhibits maximum in-cylinder pressure at the tested loads.

It was a known fact that the heating value for diesel fuel was superior to biodiesels, which helps in achieving the maximum pressure rise during combustion. At the same time, biodiesels show belated combustion in reaching peak pressure late due to higher latent heat and self-ignition temperatures. Compared to WPFBD and POBD, WCOBD shows a leading pressure rise during the combustion, and it almost competes with diesel fuel, as shown in **Figure 5**. In contrast, the lowest in-cylinder pressure was recorded for POBD at both loads.

As the combustion process in diesel engines was categorized into premixed and diffused modes, the net heat release rate (NHR) plots at 75%, and 100% loads reveal the premixed combustion was promoted for neat biodiesel application. Higher heat release for neat biodiesels may be acclaimed for improved cetane index and low ignition delay, which promotes smooth combustion with better torque conversion ability. The same can be witnessed for WCOBD and WPFBD at maximum load.

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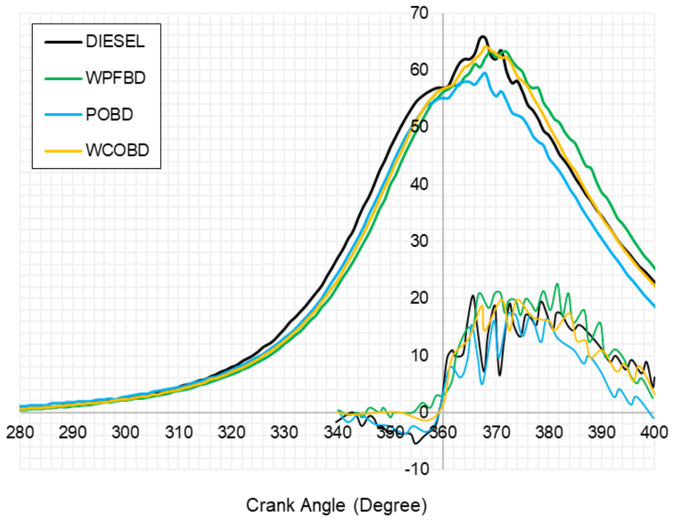

Figure 4. In-cylinder combustion pressure and heat release rate measurement at 75% load.

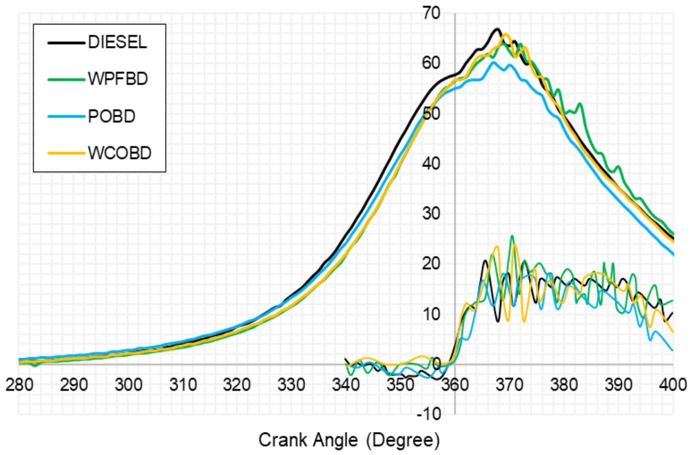

Figure 5. In-cylinder combustion pressure and heat release rate measurement at 100% load.

3.2. Exergetic Efficiency

To identify how effectively the fuel energy (heat input) was utilized for the conversion of useful work, exergy analysis plays a significant role. Exergy gives us a qualitative analysis of outcomes and the scope for improvement. Therefore, the exergetic efficiency for the three biodiesels was computed as Equation (13) stated in the methodology section. The results yielded in the exergy analysis (exergetic efficiency) in a control volume for the three biodiesels at various loads are shown in **Figure 6**. The results reveal that the exergetic efficiency increased with the load on the engine and maximum efficiency of 52.74% was observed at 75% load for WPFBD and WCOBD. Further increase in the engine load (at 100%) the efficiency was reduced by 6.99% and 5.61% for WPFBD and WCOBD. Whereas for POME, the exergetic efficiency of 48.85% and 50.12% were recorded at 75% and 100% loads. It is a known fact that at peak load operation (100%), the speed of the engine decreases, thereby producing lesser rotational power or torque. Hence lesser efficiency was recorded than that of 75% load. Similarly, at lower loads, the torque produced is low, or the output brake power is lower, which results in lesser efficiency at 25% loads. The other factors like the density and viscosity of tested biodiesels are also affecting this performance value. The obtained results are at hand with the experimental finding of Canakci & Hoşöz (2006), Sayin Kul & Kahraman (2016), and Khoobbakht *et al* (2016).

3.3. Exergy Destruction

Exergy destruction indicates the amount of lost opportunity which could have been overcome. Therefore exergy destruction is an important tool in finding the amount of utilization of energy in an engine. The exergy destruction for the combustion process of the three biodiesels was found using the equations stated in the methodology section (Eq. 9). Initially, the values of exergy associated with the input, work output, coolant, and exhaust gases were found. The input exergy was found using the chemical exergy equations (2,10) of the hydrocarbons (Chaudhary & Gakkhar, 2021). The work output exergy readings were obtained from the values of the engine using the rated brake power of the engine and the actual output obtained. The exergy obtained from the engine coolant was given by Eq.(11). The exergy developed due to exhaust gases is obtained from Eq. (12). By substituting all these equations, exergy destruction was obtained (Eq. (9)). Similarly, at various loads of 25, 50, 75, and 100%, the exergy destruction was calculated and present in **Figure 7**.

From **Figure 7**, it was observed that the exergy destruction increased with the increase in load for all the three biodiesels viz. (WPFBD, PBOD, WCOBD). Compared to the other biodiesels, WCOBD was recorded as low exergy destruction at measured loads and it was evident at 75% load. This shows that maximum chemical energy in the WCOBD has successfully converted into useful work. Low exergy destruction for WCOBD may be due to the improved fuel properties of high cetane number and low viscosity, which helps in regulating the delay period.

Furthermore, WPFBD was observed as the highest destruction at measured loads. Low exergy destruction is always desirable; however, due to combustion irreversibilities and incomplete combustion of fuel during the combustion process increases the exergy destruction. Furthermore, during the combustion process, the chemical exergy in the fuel is reduced due to the diversion of available exergy associated with work transfer, heat transfer, and exergy destruction. Experimental studies (Mahabadipour *et al*., 2019) show that 14% of chemical exergy in the fuel will escape as exhaust in the form of physical exergy during the start of the injection process. This 14% loss can be regulated by adjusting the degree of crank angle.

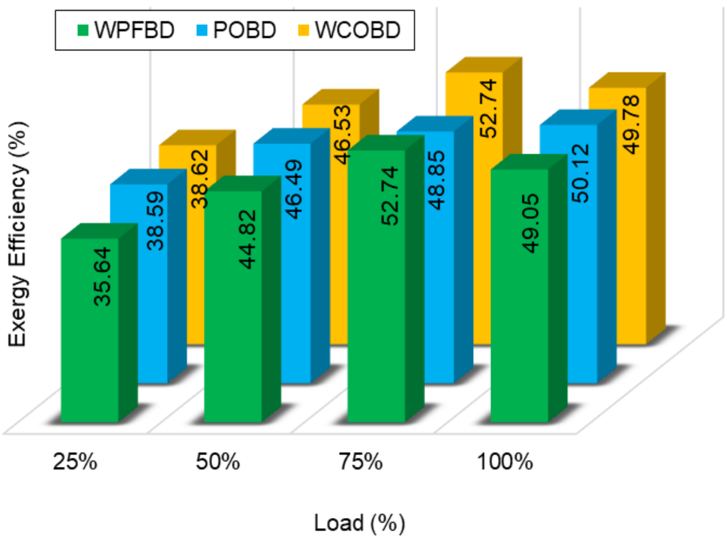

Figure 6. Exergy efficiency at various loads.

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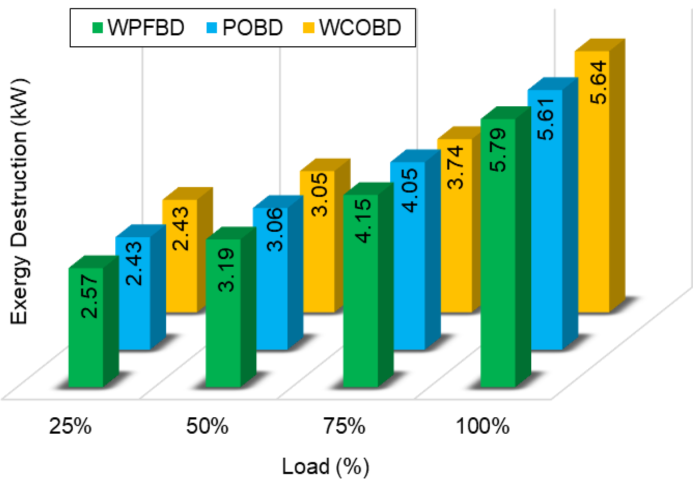

Figure 7. Exergy destruction at various loads.

3.4. Fuel consumption analysis

The brake-specific fuel consumption (BSFC) for three neat biodiesels was compared with diesel fuel are, shown in **Figure 8** reveals that BSFC of diesel fuel was observed to be minimum at all the loads, whereas biodiesels are recorded as high. An increase in fuel consumption for tested biodiesels is due to their fuel properties of high viscosity and density. At 75% and 100% loads, an average increment of 10.34% and 3.12% fuel consumption was observed for WPFBD and WCOBD compared with diesel fuel, and at the same loads, there is not much difference in fuel consumption observed for WPFBD and WCOBD. In contrast, POBD was observed as the highest fuel consumption among the three biodiesels at maximum and next lower loads.

3.5. Analysis of loss factors

Finding the losses in an engine is of utmost importance, as the basic definition states that a heat engine is a device that converts heat into work. Therefore, to achieve maximum work output, the engine must convert the heat supplied to work output most efficiently. However, during the network output conversion, some amount of the energy was lost in the form of exhaust, coolant, and unaccounted.

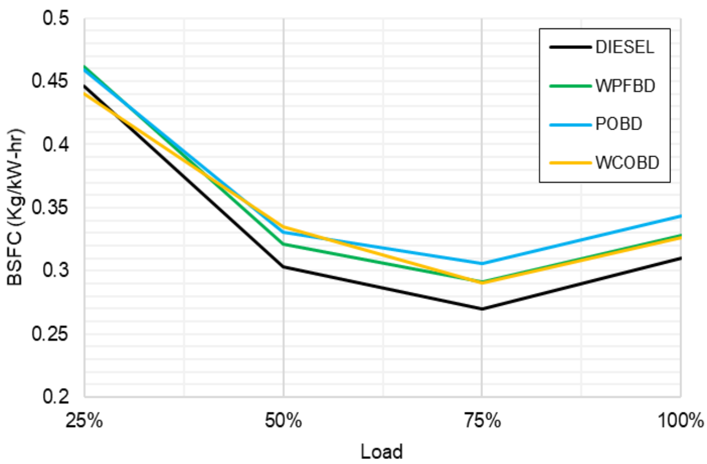

Figure 8. Brake specific fuel consumption at various loads.

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Figure 9 and **Figure 10** represent these losses from the tested biodiesels at 75% and 100% loads. The useful work is also called heat equivalent to brake power (BP) is observed to be high for WPFBD and WCOBD at measured loads compared to POBD. An average improvement of 0.23% and 2.30% was observed for WPFBD compared with WCOBD and POBD at 100%. Similarly, 0.25% and 2.23% improvement were observed for WPFBD at 75% load, respectively.

The unaccounted heat losses, which include convection, radiation, lubrication, etc., are observed to be high for POBD, followed by WPFBD and WCOBD at 75% and 100% loads. Due to high unaccounted losses, the useful work was reduced for the tested biodiesels and this can be mitigated with the proper insulation on the top of the piston, engine cylinder head, and walls with ceramic coatings (Abedin *et al*., 2013). Furthermore, exhaust heat losses are computed by considering that the specific heat of the air and exhaust gas is the same as the mean exhaust gas temperature. As per the computed results, WCOBD has observed relatively high exhaust losses than WPFBD and POBD at 75% and 100% loads.

The cooling heat losses are observed below 3.06% for the tested biodiesels at 75% load. Whereas at 100% load WCOBD was recorded higher than WPFBD and POBD. Several parameters account for the energy balance analysis and the accurate prediction of the root causes for these losses is still challenging due to the heterogeneous combustion in diesel engines and the varying fuel properties in tested biodiesels like bulk modulus, heating values, viscosity, cetane number, presence of molecular oxygen, etc.

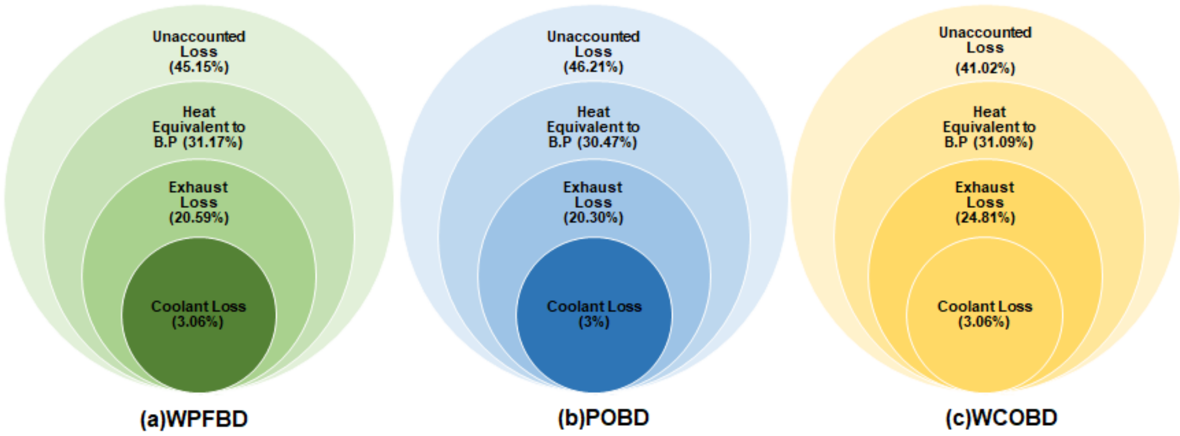

Figure 9. Energy distribution for three fuels at 75% load.

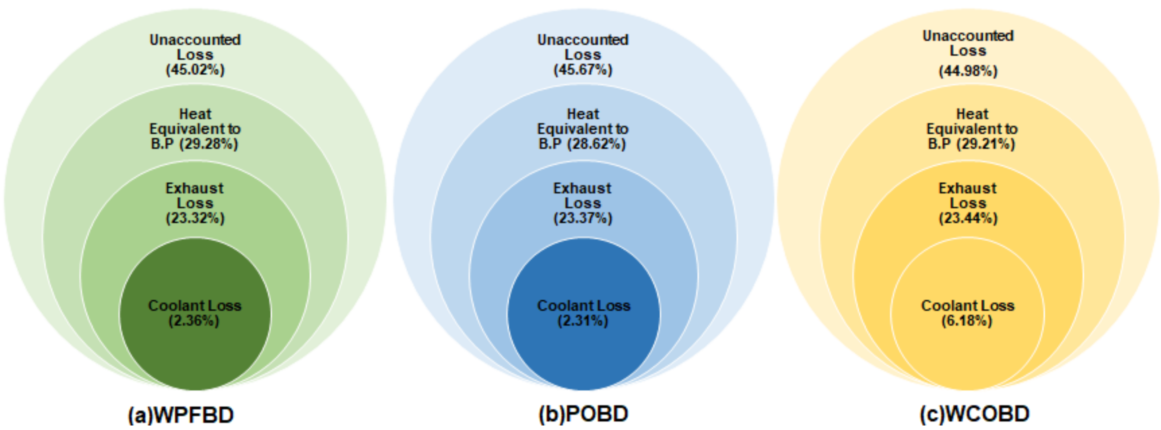

Figure 10. Energy distribution for three fuels at 100% load.

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3.6. Exhaust Emission Analysis

The combustion and exergetic performance analysis of WCOBD are observed as better fuels among the WPFBD and POBD. Therefore, exhaust emissions tests were carried out to check the pollution levels from neat WCOBD and compare the same with neat diesel fuel. The exhaust emissions of unburnt hydrocarbons (UHC), carbon monoxide (CO), nitrogen oxides (NOx), and smoke are measured at all loads by maintaining a constant speed of 1500 rpm. The variations in UHC emissions measured at different loads (**Figure 11**) reveal that with the increase in load, low UHC is recorded. The low emission for WCOBD may acclaim due to the presence of molecular oxygen and high cetane index, which helps in refining the combustion. Different studies (Abed *et al*., 2019; Kolakoti & Rao, 2020) proved that biodiesel utilization regulates UHC emissions, and the same can be witnessed in this experimental investigation. At 75 and 100% loads, the UHC emissions are reduced by 38.46 and 42.42% compared to diesel fuel. The UHC emissions are caused due to incomplete combustion, and a longer ignition delay promotes incomplete combustion. Biodiesel regulates the longer ignition because of improved cetane number, thus controlling the UHC emissions. **Figure 12** represents the measured CO emissions at five varying loads. The results show that compared to diesel fuel, low CO emissions are reported for WCOBD. At 75 and 100% loads, CO emissions are decreased by 25 and 60%. Low combustion temperature and lack of available oxygen result in incomplete combustion and produce CO emissions. The other factors which promote CO formation during the combustion process are poor atomization of fuel, injection timing, injection pressures, and air-fuel equivalency ratios. As biodiesel possesses in-built molecular oxygen (11% approximate) helps in the formation of peroxides and hydro-peroxides (Prasadarao *et al*., 2021) during the combustion process and results in maintaining low CO emissions. Whereas for diesel fuel, the absence of molecular oxygen leads to incomplete combustion and produces more CO emissions than biodiesel.

Furthermore, **Figure 13** represents the exhaust smoke emission measured at varying loads for diesel and WCOBD. With the increase in load, there is a drastic reduction of smoke emission observed for WCOBD than diesel fuel. A maximum reduction of 66.67 and 68.42% was recorded at 75 and 100% loads, respectively. This can be attributed to refined fuel properties of low carbon content, and the presence of molecular oxygen in biodiesel helps to reduce the smoke formation by achieving complete combustion. Due to improved cetane number and low ignition delay biodiesel also helps in burning a large part of the fuel during the first phase of the combustion, promotes complete combustion, and generates low smoke emissions. Finally, the variations in NOx emissions for diesel fuel and WCOBD are illustrated in **Figure 14**. Unlike the UHC, CO, and smoke emissions, NOx emissions are observed to be relatively high (2.64%) than diesel fuel at maximum load and decreased by 0.87 at 75% load. At lower loads also, NOx pollutants are recorded high for WCOBD than diesel fuel. An increase in NOx emissions for biodiesel-fueled engines is observed in many experimental studies (Abed *et al*., 2019; Talamala *et al*., 2017). This is due to the presence of molecular oxygen in biodiesel which boosts combustion and results in an increase in in-cylinder temperatures. Therefore, high in-cylinder combustion temperatures promote the formation of NOx emissions as governed by the Zeldovich mechanism (Muzio & Quartucy, 1997; Talamala *et al*., 2017). The other factors which promote high in-cylinder combustion temperature are high bulk modulus, density, long-chain fatty acids, sound velocities, etc.

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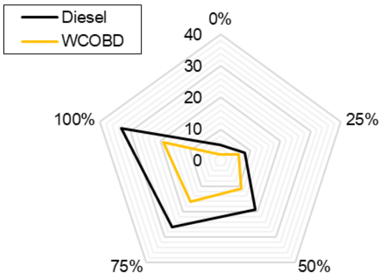

Figure 11. Unburnt hydrocarbon emissions measurement at various loads.

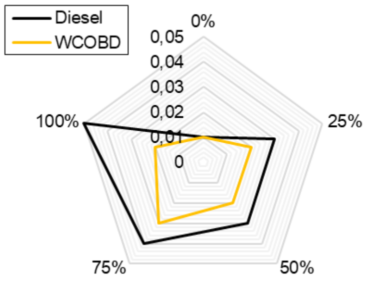

Figure 12. CO emissions measurement at various loads.

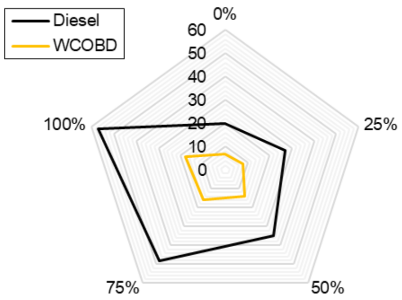

Figure 13. Exhaust smoke emissions measurement at various loads.

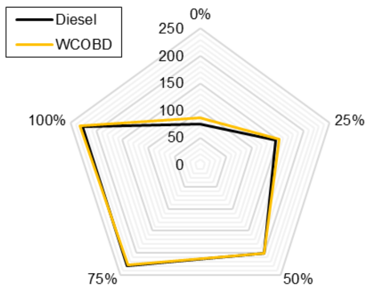

Figure 14. NO_X emissions measurement at various loads.

4. CONCLUSION

Energy and exergy analysis is considered as a powerful tool to identify the significant losses in a thermodynamic system. Identifying the various losses in a system helps to design a better efficient energy system by lowering its inefficiencies. This study attempted to analyze the exergetic performance, combustion, and emissions in a diesel engine fuelled with three neat biodiesels. Based on the experimental results, the following conclusions were obtained.

- The exergetic efficiency computed in a control volume shows that at 75% load WCOBD and WPFBD achieve maximum exergetic efficiency of 52.74%. At the same time, POBD was observed highest efficiency of 50.12 at 100% load.
- The highest exergy destruction of 4.15 kW and 5.79 kW was observed for WPFBD at 75% and 100% loads, respectively. The lowest destruction of 3.74 kW was achieved for WCOBD at 75% load.
- The in-cylinder combustion pressures measured with a least count of one degree at 75% and 100% loads show that WCOBD exhibits on far with diesel fuel. Similarly, the net heat release rate for WCOBD represents smooth combustion with better torque conversion when compared to other biodiesels.
- Due to the high viscosity and density in neat biodiesels, the fuel consumption was observed to be high for all the biodiesels compared to diesel fuel.
- Compared to POBD, WCOBD and WPFBD show a high heat equivalent to BP, and low unaccounted heat losses were observed for WCOBD at measured loads. This shows that WCOBD converts the maximum fuel energy into useful work.
- Except for NOx emissions, the UHC, CO, and exhaust smoke emissions are recorded low for WCOBD at all the measured loads compared to diesel fuel.

From the above summary of main conclusions, it can be concluded as WCOBD has the potential to replace the existing diesel fuel, and utilizing the WCO for biodiesel production can promote sustainable development.

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5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

Nomenclature		
$\dot{m}_i / \dot{m}_o$	Mass flow rates into/out of the engine	[kg/s]
C_p	Specific heat of exhaust gases	[kJ/kg.K]
E_f	Heat energy released by the fuel	[kW]
Ex_c	Rate of Exergy destroyed due to coolant	[kW]
Ex_{eg}	Rate of Exergy destroyed due to exhaust gases	[kW]
P_0	Reference pressure	[Bars]
P_{eg}	Pressure of exhaust gas	[Bar]
Q_{eg}	Heat leaving the control volume through engine exhaust	[kW]
Q_w	Heat leaving the control volume through the engine coolant	[kW]
T_0	Temperatures of the reference environment	[K]
T_{eg}	Temperature of exhaust gas	[K]
T_w	Temperatures of the coolant	[K]
m_{eg}	Mass flow rate of exhaust gases	[kg/s]
m_f	Mass flow rate of the fuel in engine	[kg/s]
dE	Rate of energy transfer	[kW]
dQ	Rate of heat transfer	[kW]
dW	Rate of work transfer	[kW]
LHE	Lower heating value	[kJ/kg]
N	Engine speed	[rpm]
Q	Heat supplied to the engine	[kW]
R	Gas constant	[kJ/kg.K]
T	Torque	[N-m or J]
Ex_d	Rate of exergy destroyed	[kW]
Ex_{in}	Rate of input exergy	[kW]
Ex_{out}	Rate of exergy output	[kW]
Ex_q	Rate of exergy transfer due to heat	[kW]
Ex_w	Rate of exergy transfer due to work	[kW]

Abbreviation	
η_{II}	Second law or exegetic efficiency
°C	Degree Centigrade
ASTM	American Society for Testing and Materials
CO	Carbon Monoxide
CI	Compression Ignition
HC/UHC	Unburnt Hydrocarbons
IDI	In-direct Injection
J/kJ	Joules/kilo Joules
Kg	kilo grams
kW	kilo Watt
Mm	Millimeter
Nm	Newton meter
NOx	Nitrogen oxide
POBD	Palm Oil Biodiesel
rpm	Revolutions per minute
s	Seconds
WCOBD	Waste Cooking Oil Biodiesel
WPFBD	Waste Poultry Fat Biodiesel

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