Assessing the Performance and Emission Traits of Diesel Engine Utilizing Blends Derived from Waste Cooking Oil Biodiesel across Varied RPM Regimes: A Numerical Approach

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Abstract

Fostering sustainable energy in India is vital for economic growth. Collaboration among environmentalists, humanitarians, and scientists is essential to address growing demands. With fossil fuel depletion a concern, exploring alternative fuels like biodiesel is crucial. Biodiesel performs similarly to conventional diesel, making its integration for energy sustainability a pragmatic choice. Utilizing a numerical simulation tool, this study assesses the performance and emission parameters of a diesel engine powered by blends of waste-cooking oil biodiesel (WCO10, WCO20, WCO30, and WCO100) at various engine speeds (1500, 2000, 2500, and 3000 RPM) and these outcomes also compared with conventional diesel fuel. These findings emphasize the critical role of RPM management and the strategic composition of blends in mitigating emissions. Though particular blends may closely mimic diesel in terms of performance and emissions in specific facets, the pattern of reduced efficiency and fuel consumption at higher RPMs remains consistent across all WCO blends, including pure diesel, and higher RPMs also align with elevated emission levels. This approach aims to achieve an optimal balance between engine performance enhancement and the utilization of alternative fuel sources such as WCO blends.

Keywords: Waste cooking oil biodiesel, Variable RPM, CI engine, Biodiesel blends, Performance, Emission.

1. Introduction

The unsustainable use of fossil fuels has a detrimental impact on the environment. There is an urgent need for research into non-polluting energy sources and renewable fuels in order to protect the planet for future generations. Clean energy sources offer a viable solution and must be explored further [1], [2]. Given recent research from the energy information administration and global energy in the U.S., global energy consumption is increasing at an average rate of 1.6% annually. As such, it is of crucial importance that alternative fuel sources are identified in order to adequately meet the increased demand, while mitigating reliance on fossil fuels [3].

In the face of increasing energy rates and the adverse impacts of traditional fuel emissions on the environment, new alternative fuels are being explored. Biodiesel is an important renewable option that is both ecologically sustainable and cost-effective, providing a viable replacement for crude oil-based diesel. By using biodiesel as an alternative to diesel, we can effectively reduce emissions while maintaining affordability [4]. India is an economically growing nation and its expanding population requires reliable fuel sources. As conventional fuel reserves are dwindling, policy makers, environmentalists and experts are looking for sustainable alternatives that can meet the nation's needs. With this in mind, exploring new methods of alternative energy has become increasingly important to ensure the country's fuel requirements remain met [5].

Earlier studies by research institutions explored the possibility of biodiesel from various sources, such as rapeseed oil, trout-oil, waste cooking oil, bio-lipids like virgin vegetable oil, cottonseed oil, linseed seed oil, peanut seed oil, soybean oil and others; palm oil, neem oil, rice-bran; edible and nonedible types of biodiesel; jatropha biodiesel; waste tire pyrolysis oils; kerosene–biodiesel blends; animal fat-based oils; waste fish oils and many more. Algae biodiesel was also looked into as a potential alternative fuel for diesel engines [6]–[9]. Utilizing waste cooking oil for the production of biodiesel can be seen as an environmentally-friendly approach to renewable energy. When traditional cooking oil has reached the end of its lifespan, it can be used instead to produce biodiesel, creating more value out of a product that would otherwise go to waste. In comparison to conventional diesel, waste cooking oil biodiesel is known for its higher consistency and burning/heat release values [10], [11]

Our current research seeks to evaluate the emission and performance of waste cooking oil when using a variety of rotational speeds in a single-cylinder diesel engine. In this experimental investigation, the outcomes results were computed using varying RPM values while maintaining a consistent compression ratio of 17.5. The RPM values were incremented by 500 units and performance and emission results find out at the data points 1500, 2000, 2500, and 3000 RPM respectively. This study presents novel findings that have been compared against earlier findings on the use of diesel fuel. The potential outcomes of this research may lay a foundation for further explorations into renewable fuel sources.

2. Proposed Methodology

2.1.Fuel properties

The properties of waste cooking oil bio-diesel blends are using as a fuel in this study are determined through experimental tasting and some properties obtained from earlier research and properties were measured according to ASTM standard. The essential fuel properties of WCO biodiesel and its blends are given in Table 1. The chemical composition of the fuels affects the CI engine's performance and emissions characteristics.[9], [12]–[20]

Table 1: Properties of biodiesel and its blends

Properties	WCO10	WCO20	WCO30	Diesel
Density (kg/m^3)	834.28	840.71	846.33	830
Kinematic viscosity at 40^o C (mm^2/s)	2.753	3.084	3.301	2.542
Surface tension factor (N/m)	0.028	0.03122	0.03436	0.028
Low heating value (MJ/kg)	41.684	41.301	40.738	43.286

Properties	WCO10	WCO20	WCO30	Diesel
Cetane number	48.35	48.62	48.75	48
Diffusion factor (at atmospheric condition)	3.10E-10	3.10E-10	3.10E-10	3.10E-10
Fuel thermal capacity (J/kg*K)	1853	1853	1853	1853
Saturated vapour pressure PV at critical temperature 710 K (bar)	1.616	1.616	1.616	1.616
Activation energy (kJ/mol)	22	22	22	22
Saturated vapour pressure at low temperature at 480 K (bar)	0.04332	0.04091	0.0372	0.0477
Fuel temperature (K)	380	380	380	380

2.2.Engine Specifications and Experimental Procedure

The performance and emission parameters of CI engine at different RPM are obtained using numerical tool Diesel-RK. For the investigation of various characteristics, single-cylinder, water-cooled, a direct injection, four-stroke in-line diesel engine is used. The piston head and cylinder head material are made by aluminum. 1 bar of atmospheric pressure and 288 K of temperature were chosen. The iterations were carried out under full load conditions at compression ratio of 17.5 and a top clearance of 1 mm. The technical engine specification as depicted in Table 2. With a max pressure of injection of 220 bar, fuel injection starts at 23^0 b TDC. Table 3 shows the various fuel injection settings and test engine operational setup shows in Figure 1.

In this study, Firstly, by keeping the rpm value as 1500 and all other parameters fixed as mentioned, the performance, and emission parameters are calculated for different blends of waste cooking oil biodiesel and diesel fuel. Similarly, in the further steps these parameters were evaluated for different fuels at 2000 rpm, 2500 rpm, and 3000 rpm respectively, while all other engine parameters were kept constant as mentioned. Finally, the output from all the tests are analysed and all the blends were compared at different rpm separately and the optimum result is evaluated.

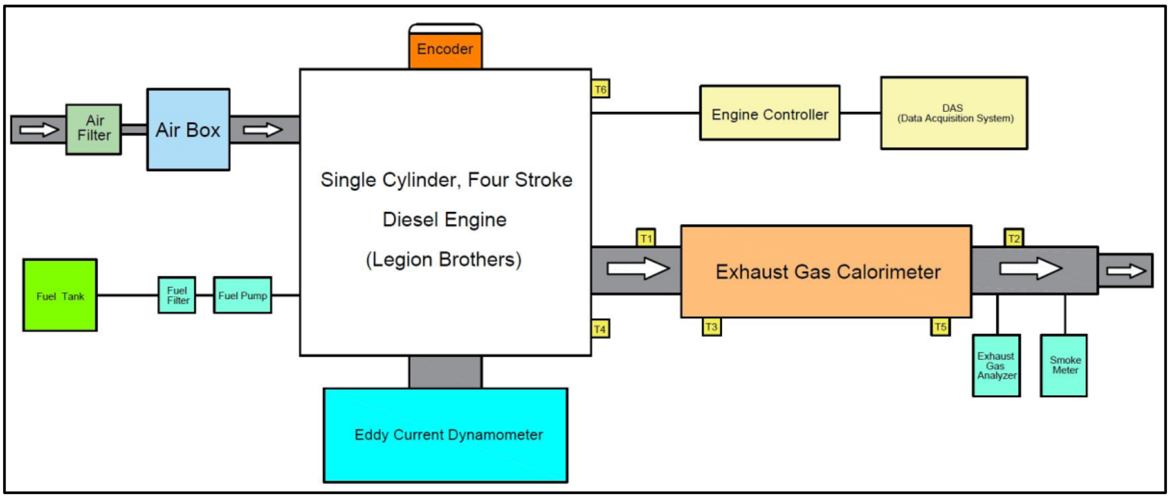

Figure 1. Operational setup of the test engine

Table 2: Test Engine Specifications

Description	Value

Engine type	Single cylinder, 4 - stroke
Bore diameter	80 mm
Stroke length	110 mm
Cooling type	Liquid cooled
Length of Connecting rod	235 mm
Cylinder head & Piston head Material	Aluminium
Engine Speed	Variable
Compression ratio (CR)	17.5
Piston type	Bowl shape
Lubrication system	Forced lubrication
Exhaust Valve Opening (before BDC)	60 deg.
Exhaust Valve Closing (after TDC)	15 deg.
Inlet Valve Closing (after BDC)	30 deg.
Inlet Valve Opening (before TDC)	28 deg.
Design of cylinder head	Two valves
Cylinder liner Mean temperature at TDC	400 K
Top clearance at TDC	1 mm
Length of exhaust manifold	160 mm
Diameter of Exhaust manifold	34 mm
Length of intake manifold	160 mm
Diameter of intake manifold	38.1 mm

Table 3. Fuel injection details.

Description	Value
No. of nozzles	3
Injector nozzles bore diameter	0.22 (mm)
Injection timing	23^0 b TDC
Injection duration	29 CA
Maximum injection pressure	220 bar
Distance between spray centre & bowl axis	2.5 mm
Air fuel equivalence ratio	1.75
Ambient temperature	288 K
Ambient pressure	1 bar
Nozzle discharge coefficient	0.77
Load	100%

2.3.Numerical method

The simulation tool employed in this study was Diesel-RK. This program considers a set of equations that involve the conservation of mass, energy, friction model, heat model, and NOx model. It uses the first law of thermodynamics to measure an internal combustion engine's optimized performance, combustion characteristics and ecological influence. Previous research reveals that Diesel-RK contains multiple zones divided into seven steps to compute combustion results while relying on the Zeldovich mechanism when computing NOx emissions. The governing equations of the numerical model used are listed in Table 4 in this study.

In the process of quantifying performance parameters like Brake Thermal Efficiency, Indicated Thermal Efficiency, Mechanical Efficiency, Volumetric Efficiency, Torque, Brake Mean Effective Pressure, and Brake Specific Fuel Consumption, the utilization of corresponding equations given in Table 5 is commonplace. [31], [32].

Table 4. Numerical model governing equations.

Equations used in numerical method		
Equation name	**Numerical model governing equations**	Reference
Conservation of mass	$\frac{dm}{dt}=\sum_j \dot{m}_J$	[21], [22]
Net generation rate of the i^{th} species	$\dot{s}_{gen}=\nu W_m \Omega_i$	
Species equations	$\frac{d(m_i Y)}{dt}=\sum_j Y_i^j \dot{m}_J+\dot{s}_{gen}$	
Species conservation equation	$\dot{Y}_i=\sum_j\left(\frac{\dot{m}_j}{m}\right)\left(Y_i^j-Y_i^{cyl}\right)+\frac{W_m\Omega_i}{\rho}$	
Conservation of energy	$\frac{d(mu)}{dt}=-p\frac{dv}{dt}+\frac{dQ_{ht}}{dt}+\sum_j\dot{m}_j h_j$	
Heat Release during ignition delay	$\tau=3.8\times10^{-6}(1-1.6\times10^{-4}.n)\sqrt{\frac{T}{p}}\,exp\left(\frac{E_a}{8.312T}\quad\frac{70}{25+CN}\right)$	[23]–[25]
Heat release rate during controlled combustion	$\frac{dx}{d\tau}=\Phi_0\times\left(A_0\left(\frac{m_f}{\nu_i}\right)\times(0.1\times\sigma_{ud}+x_0)\times(\sigma_{ud}-x_0)\right)+\Phi_1\times\left(\frac{d\sigma_u}{d\tau}\right)$	
Heat release rate during controlled combustion	$\frac{dx}{d\tau}=\Phi_1\times\left(\frac{d\sigma_u}{d\tau}\right)+\Phi_2\times\left(A_2\left(\frac{m_f}{\nu_c}\right)\times(\alpha-x)\times(\sigma_u-x)\right)$	
Heat release rate during late combustion phase	$\frac{dx}{d\tau}=(\alpha\xi_b-x)\times(1-x)\times\Phi_3A_3K_T$	
Zeldovich Mechanism	$O_2 \Leftrightarrow 2O$	[22], [26]–[29]
	$N_2+O \Leftrightarrow N+NO$	
	$N+O_2 \Leftrightarrow O+NO$	

Equations used in numerical method		
Equation name	**Numerical model governing equations**	Reference
NO concentration during the combustion	$\frac{d[NO]}{d\theta}=\frac{2.333\times10^{-7}.P.e^{-\frac{38020}{T_b}}[O]_e.[N_2]_e.\left\{1-\left(\frac{[NO]}{[NO]_e}\right)^2\right\}}{T_b.R.\left(1+\frac{2365}{T_b}.\frac{[NO]}{[O_2]_e}.e^{\frac{2365}{T_b}}\right)}\times\frac{1}{\omega}$	
Soot formation	$Smoke(Hartridge)=100\left[1-0.9545e^{(-2.4226[C])}\right]$	[22], [26], [30]
Hartridge smoke level	$\left(\frac{d[C]}{dt}\right)_K=0.004\frac{q_c}{V}\frac{dx}{dt}$	

Table 5. Equations for performance parameter.

Performance parameters	Equations	Reference
Heat Addition	$Q_{in}=m_f Q_{HV}\eta_c$	[31], [32].
Heat Addition in steady state condition	$\dot{Q}_{in}=\dot{m}_f Q_{HV}\eta_c$	
Amount of energy (power) available for use in an engine	$\dot{W}=\dot{m}_f Q_{HV}$	
Brake thermal efficiency	$(\eta_t)_{brake}=\dot{W}_b/\dot{m}_f Q_{HV}\eta_c$	
Indicated thermal efficiency	$(\eta_t)_{ind}=\dot{W}_i/\dot{m}_f Q_{HV}\eta_c$	
Mechanical efficiency	$\eta_m=\dot{W}_b/\dot{W}_i$	
	$\eta_m=(\eta_t)_{brake}/(\eta_t)_{ind}$	
	$\eta_m=\frac{BMEP}{IMEP}$	
Volumetric efficiency	$\eta_v=m_a/\rho_a V_d$	
	$\eta_v=n\dot{m}_a/\rho_a V_d N$	
Torque	$\tau=\frac{(BMEP)V_d}{2\pi n}$	
Brake Mean effective pressure	$BMEP=2\pi n\tau/V_d$	
Mean effective pressure	$MEP=n\dot{W}/V_d N$	
Brake Specific Fuel Consumption	$BSFC=\dot{m}_f/BP$	

3. Results and discussions

3.1.. Performance characteristics

3.1.1. . Brake power

Brake power measures the performance of an engine at its crankshaft. Diesel fuel can produce a higher brake power due to its higher calorific value and more efficient combustion, but biodiesel and its blends may not be as effective due to their higher viscosity, density, and lower heating value [33]–[35]

In this experimental study, the results for the brake power were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of brake power were found as 4.4359, 5.702, 6.401, and 6.6472 KW respectively for the WCO10 blend, 4.4359, 5.6624, 6.3563, and 6.4741 KW in case of WCO20 blend 4.4106, 5.6043, 6.231, and 6.2978 KW respectively for WCO30 blend 4.6024, 5.9203, 6.7175, and 6.8867 KW for Diesel. The maximum value of brake power for WCO10, WCO20, and WCO30 are found as 6.6472, 6.4741, and 6.2978 at 3000 RPM, and the minimum values are found as 4.4359, 4.4375, and 4.4106 at 1500 RPM respectively. While for Diesel the maximum and minimum value of brake power is 6.8867 and 4.6024 at 3000 and 1500 RPM respectively. The average brake power of the WCO blends B10, B20, and B30, respectively, were 3.571 %, 4.959 %, and 6.561% lower than Diesel.

Among all the blends, the Brake power values for WCO20 is found closest to diesel whose value is 4.4375 KW and it is about 3.582 % lower than diesel at 1500 RPM. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of brake power increases for the all blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel and all blends possess minimum difference at 1500 RPM while increasing the RPM this difference gets increase among them. It shows in Figure 2.

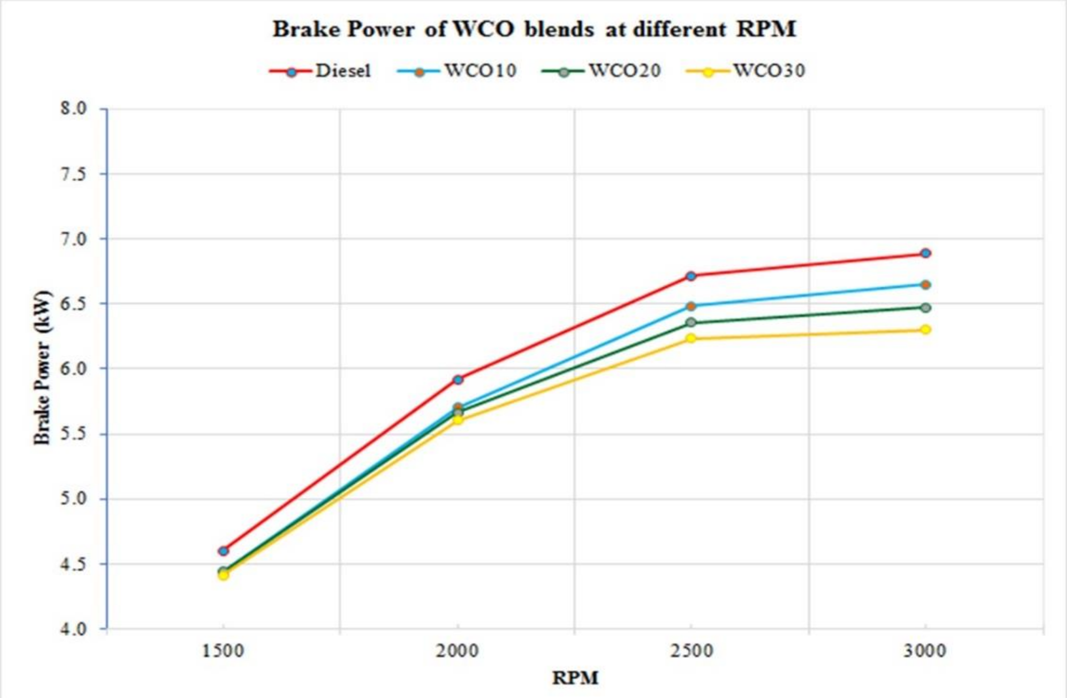

Figure 2. Variation of brake power of WCO blends with variable RPM

3.1.2. . Brake torque

Brake Torque (BT) at the transmission end of a crankshaft is used to calculate brake power. BT value is determined by engine load, engine speed, and other factors. BT will rise as engine load and speed decrease [36], [37].

In this experimental study, the results for the brake torque were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of brake torque were found as 28.242, 27.227, 24.754, and 21.16 Nm respectively for the WCO10 blend, 28.352, 27.038, 24.281, and 20.609 Nm in case of WCO20 blend 28.081, 26.761, 23.802 and 20.048 Nm respectively for WCO30 blend 29.302, 28.27, 25.661, and 21.923 Nm for Diesel. The maximum value of brake torque for WCO10, WCO20, and WCO30 are found as 28.242, 28.252, and 28.081 at 1500 RPM, and the minimum values are found as 21.16, 20.609, and 20.048 at 3000 RPM respectively. While for Diesel the maximum and minimum value of brake torque is 29.302 and 21.923 at 1500 and 3000 RPM respectively. The average brake torque of the WCO blends B10, B20, and B30, respectively, were 3.588%, 4.732%, and 6.147% lower than Diesel.

Among all the blends, the Brake torque values for WCO10 is found closest to diesel whose value is 21.16 Nm and it is about 3.480% lower than diesel at 3000 RPM. While comparing all the results, it was found that while increasing the value of RPM the corresponding value of brake torque decreases for the blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel and all blends possess minimum difference at 1500 RPM while increasing the RPM this difference gets increase among them. It shows in Figure **3**3.

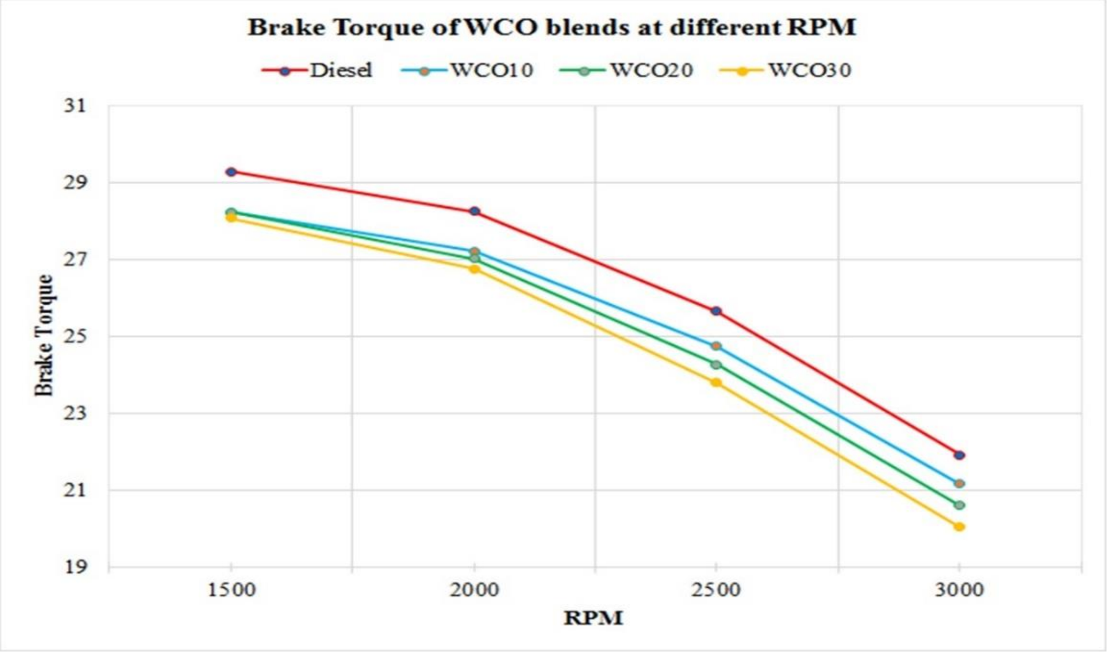

Figure 3. Variation of brake torque of WCO blends with variable RPM.

3.1.3. . Indicated efficiency

The efficiency of an engine is determined by how much power it generates before reaching the piston known as indicated efficiency, is figured out by comparing the energy outputted with indicated power about the energy put in through fuel input. When indicated efficiency values are high, it suggests that more power is transferred to the piston while expending less fuel energy [38], [39].

In this experimental study, the results for the Indicated efficiency were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of indicated efficiency were found as 0.43284 ,0.43872, 0.43147 and 0.4199 respectively for the WCO10 blend, 0.42991, 0.43379, 0.42341 and 0.41059 in case of WCO20 blend 0.42712, 0.42968, 0.41705 and 0.4029 respectively for WCO30 blend 0.43118, 0.43686, 0.42859 and 0.4159 for Diesel. The maximum value of indicated efficiency for WCO10, WCO20, and WCO30 are found as 0.43872, 0.43379, and 0.42968 at 2000 RPM, and the minimum values are found as 0.4199, 0.41059, and 0.4029 at 3000 RPM respectively. While for Diesel the maximum and minimum value of brake torque is 0.43686 and 0.4159 at 2000 and 3000 RPM respectively. The average indicated efficiency of the WCO biodiesel blends B10, B20, and B30 were 0.607% (higher), 0.865% (lower), and 2.089% (lower) than Diesel.

Among all the blends and different RPM the optimum value of Indicated efficiency is found 0.4199 at 3000 RPM for WCO10 biodiesel blend which is 0.961% higher than diesel. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of indicated efficiency increases for the blends WCO10, WCO20 & WCO30 from 1500-2000 RPM and then it started decreasing with increase of RPM and same trend is observed for pure diesel. It shows in Figure **4**4.

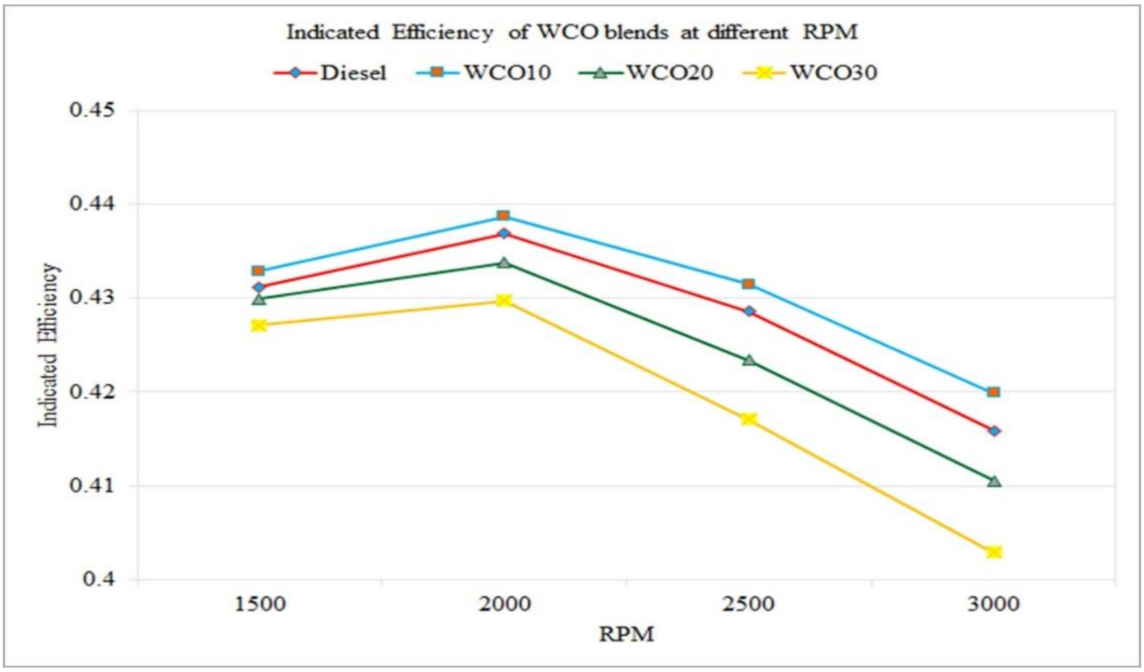

Figure 4. Variation of indicated efficiency of WCO blends with variable RPM.

3.1.4. Brake-specific fuel consumption

SFC is the amount of fuel required to generate power for an engine over a period of time. Factors that influence this calculation include calorific value, density and viscosity. Biodiesel and its blends tend to have higher SFC values than diesel because they have a higher density and lower calorific value and viscosity [40], [41].

In this experimental study, the results for the Brake-specific fuel consumption were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of brake specific fuel consumption were found as 0.24999, 0.2588, 0.2808, and 0.31659 kg/kWh respectively for the WCO10 blend, 0.25366, 0.26449, 0.29052, and 0.32993 kg/kWh in case of WCO20 blend 0.25908, 0.27127, 0.30082, and 0.34431 kg/kWh respectively for WCO30 blend 0.23983, 0.24807, 0.26963, and 0.30423 kg/kWh for Diesel. The maximum value of brake-specific fuel consumption for WCO10, WCO20, and WCO30 are found as 0.31659, 0.32993, and 0.34431 at 3000 RPM. While the minimum values are found as 0.24999, 0.25366, and 0.25908 kg/kWh at 1500 RPM respectively. While for Diesel the maximum and minimum value of brake-specific fuel consumption is 0.30423 kg/kWh and 0.23983 kg/kWh at 3000 and 1500 RPM respectively. The average brake-specific fuel consumption of the WCO blends B10, B20, and B30, respectively, were 4.183%, 7.237%, and 10.710% higher than Diesel.

Among all the blends and different RPM, the optimum value of brake-specific fuel consumption is found 0.24999 kg/kWh at 1500 RPM for WCO10 biodiesel blend which is 4.236 % higher than diesel. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of brake-specific fuel consumption increases for the blends WCO10, WCO20 & WCO30 increases and same trend is observed for pure diesel. It shows in Figure **5**5.

3.1.5. Brake mean effective pressure

The term BMEP describes the average uniform pressure acting on a piston when it moves from TDC to BDC. This pressure can be calculated by multiplying the mean effective pressure and mechanical efficiency. BMEP is also the work done per unit displacement volume of an engine [42], [43].

In this experimental study, the results for the Brake mean effective pressure were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of brake mean effective pressure were found as 6.4182, 6.1875, 5.6255, and 4.8088 bar respectively for the WCO10 blend, 6.4204, 6.1445, 5.518, and 4.6835 bar, in case of WCO20 blend 6.3815, 6.0815, 5.4092, and 4.5561 bar respectively for WCO30 blend 6.6591, 6.4245, 5.8316, and 4.982 bar for Diesel. The maximum value of brake mean effective pressure for WCO10, WCO20 and WCO30 are found as 6.4182, 6.4204, and 6.3815 respectively at 1500 RPM. While the minimum values are found as 4.8088, 4.6835, and 4.5561 at 3000 RPM respectively. While for Diesel the maximum and minimum value of brake mean effective pressure is 6.6591 and 4.982 bar at 1500 and 3000 RPM respectively. The average brake mean effective pressure of the WCO blends B10, B20, and B30, respectively were 3.587%, 4.731%, and 6.146%, lower than Diesel.

Among all the blends, the brake mean effective pressure values for WCO10 is found closest to diesel whose value is 4.8088 bar at 3000 RPM and it is about 3.476 % lower than diesel. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of brake mean effective pressure decreases for the blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel. It shows in Figure 6.

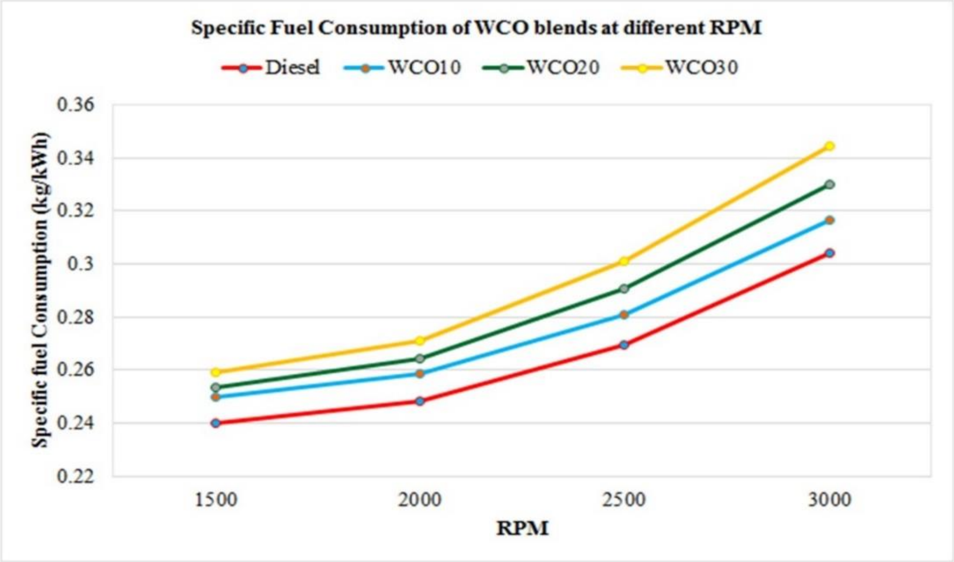

Figure 5. Variation of Brake-specific fuel consumption of WCO blends with variable RPM.

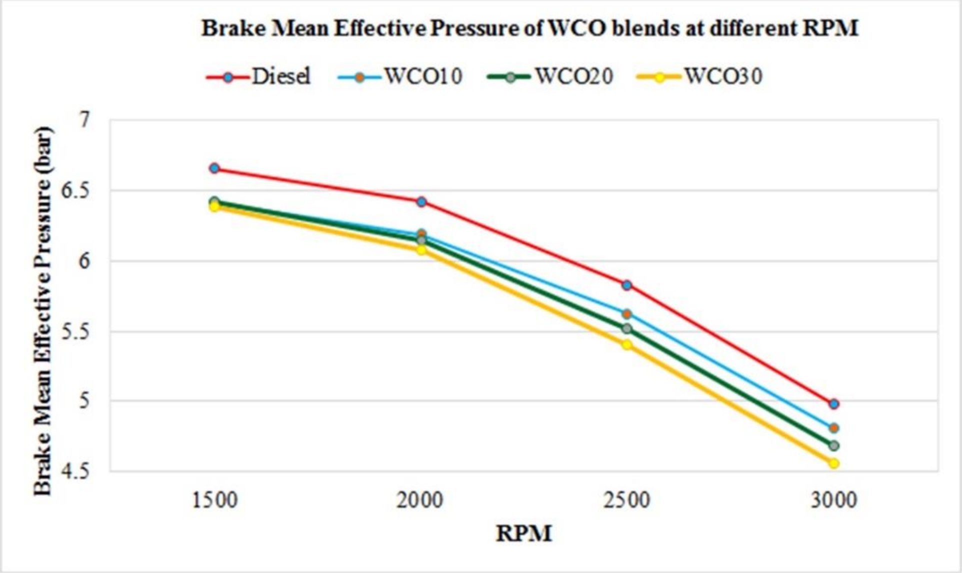

Figure 6. Variation of brake mean effective pressure of WCO blends with variable RPM.

3.2.Emission characteristics

3.2.1. CO2 Emission

Combustion is the process in which oxygen and carbon combine to create emissions. Diesel fuels are formulated to reduce this reaction's oxygen content, which helps decrease emissions; however, incomplete combustion can still create hazardous levels of CO [44]–[46].

In this experimental study, the results for the CO_2 Emission were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil (bio-diesel) of CO_2 emission were found as 796.55, 824.6, 894.73, and 1008.8 g/kWh respectively for the WCO10 blend, 798.55, 832.64, 914.59, and 1038.7 g/kWh in case of WCO20 blend 805.83, 843.75, 935.65, and 1070.9 g/kWh respectively for WCO30 blend 772.79, 799.33, 868.82, and 980.28 g/kWh for Diesel. The maximum value of CO_2

emission for WCO10, WCO20, and WCO30 are found as 1008.8, 1038.7, and 1070.9 g/kWh at 3000 RPM. While the minimum values are found as 796.55, 798.55, 805.83, and at 1500 RPM respectively. While for Diesel the maximum and minimum value of CO_2 emission is 980.28 and 772.79 g/kWh at 3000 and 1500 RPM respectively. The average CO_2 emission of the WCO blends B10, B20, and B30, respectively, were 3.024 %, 4.771 %, and 6.866 % higher than Diesel.

Among all the blends, the CO_2 emission values for WCO10 is found closest to diesel whose value is 1070.9 g/kWh and it is about 9.244 % higher than diesel at 3000 RPM. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of CO2 emission increases for all blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel. It shows in Figure **7** 7.

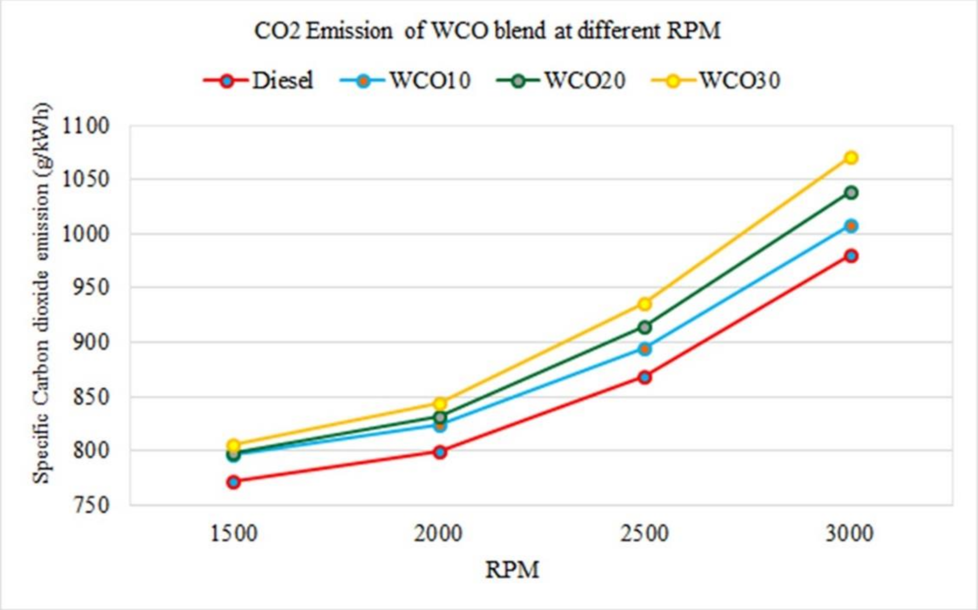

Figure 7. Variation of CO2 Emission of WCO blends with variable RPM.

3.2.2. SO2 Emission

Fuel containing sulphur produces Sulphur dioxide (SO_2) when burned. These emissions mix with oxygen, creating sulphur trioxide (SO_3). When the SO_2 and SO_3 mix with water vapour in the atmosphere, they form sulphuric acid - a toxic chemical that leads to environmental issues such as acid rain, reduced air quality and visibility, respiratory diseases, and inhibition of plant growth [10][47].

In this experimental study, the results for the CO2 Emission were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of SO_2 emission were found as 0.0095, 0.0098, 0.01067, and 0.01203 g/kWh respectively for the WCO10 blend, 0.00913, 0.00952, 0.01046, and 0.0118 g/kWh in case of WCO20 blend 0.00881, 0.00922, 0.01023, and 0.01171 respectively for WCO30 blend 0.00959, 0.00992, 0.01079, and 0.01217 g/kWh for Diesel. The maximum value of SO_2 emission for WCO10, WCO20, and WCO30 are found as 0.01203, 0.01188, and 0.01171 g/kWh at 3000 RPM. While the minimum values are found as 0.0095, 0.00913, and 0.00881 g/kWh at 1500 RPM respectively. While for Diesel the maximum and minimum value of SO2 emission is 0.01217 and 0.00959 g/kWh at 3000 and 1500 RPM respectively.

The average SO2 emission of the WCO blends B10, B20, and B30, respectively, were 1.036 %, 3.484 %, and 5.886 % lower than Diesel.

Among all the blends, the SO_2 emission values for WCO30 is found closest to diesel whose value is 0.00881 g/kWh and it is about 8.133 % lower than diesel at 1500 RPM. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of SO2 emission increases for all blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel. It shows in Figure **8**8.

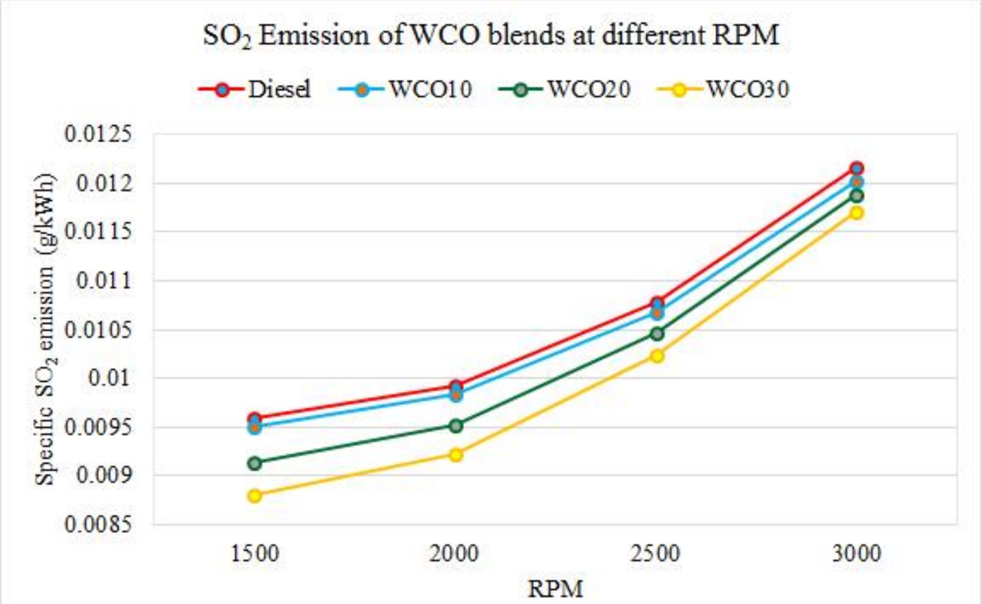

Figure 8. Variation of SO_2 Emission of WCO blends with variable RPM.

3.2.3. Fraction of wet NOx Emission

Biodiesel reduces NOx Emission compared to diesel, due to its higher oxygen content. This leads to better combustion of air and fuel, and reduced NO_X [10][46][48][28].

In this experimental study, the results for the Fraction of wet NOx Emission were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of NOx emission were found as 1020.5, 1079.6, 935.49, and 807.23 PPM respectively for the WCO10 blend, 1100.5, 1100.5, 1121.3, and 961 PPM in case of WCO20 blend 1132.5, 1250.5, 1234.9, and 1119.7 PPM respectively for WCO30 blend 1226.2, 1313.1, 1298.5 and 1195.8 PPM for Diesel. The maximum value of NOx emission for WCO10, WCO20, and WCO30 are found as 1079.6, 1185.6, and 1250.5 PPM at 2000 RPM. While the minimum values are found as 807.23, 961, and 1119.7 at 3000 RPM respectively. While for Diesel the maximum and minimum value of NOx emission is 1313.1 and 1195.8 PPM at 2000 and 3000 RPM respectively. The average fraction of wet NOx emission of the WCO biodiesel blends B10, B20, and B30 were 23.656 % (lower), 13.215 % (lower), and 5.880 % (lower) than Diesel.

Among all the blends and different RPM, the optimum value (max difference) of fraction of wet NOx emission is found 807.23 PPM at 3000 RPM for WCO10 biodiesel blend which is 32.494 % lower than diesel. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of fraction of wet NOx emission increases for the blends WCO10, WCO20 & WCO30 from 1500-2000 RPM and then decreases. It shows in Figure **9**9.

3.2.4. PM Emission

Particulate matter is commonly generated as a by-product of combustion when air interacts with fuel. These particles usually consist of soluble organic components and areas with reduced moisture.[48]

In this experimental study, the results for the Fraction of wet PM emissions were calculated at different values of RPM 1500, 2000, 2500, and 3000. The experimental values for different blends of waste cooking oil bio-diesel of PM emission were found as 0.59911, 0.65394, 1.0882, and 1.677 g/kWh respectively for the WCO10 blend, 0.66195, 0.74575, 1.2141, and 1.8227 g/kWh in case of WCO20 blend 0.73993, 0.84328, 1.3248, and 1.9682 g/kWh respectively for WCO30 blend 0.59611, 0.65144, 1.0832, and 1.6547 g/kWh for Diesel. The maximum value of PM emission for WCO10, WCO20, and WCO30 are found as 1.677, 1.8227, and 1.9682 at 3000 RPM. While the minimum values are found as 0.59911, 0.66195, and 0.73993 g/kWh at 1500 RPM respectively while for Diesel the maximum and minimum value of PM emission is 1.6547 and 0.59611 g/kWh at 3000 and 1500 RPM respectively. The average PM emission of the WCO blends B10, B20, and B30, respectively, were 0.822 %, 11.518 %, and 22.350 % higher than Diesel.

Among all the blends and different RPM, the optimum value of PM emissions is found 0.65394 g/kWh at 2000 RPM for WCO10 biodiesel blend which is 0.383 % higher than diesel. While comparing all the results, it was found that while increasing the value of RPM the corresponding values of PM emission increases for all blends WCO10, WCO20 & WCO30 and same trend is observed for pure diesel. It shows in Figure **10**10.

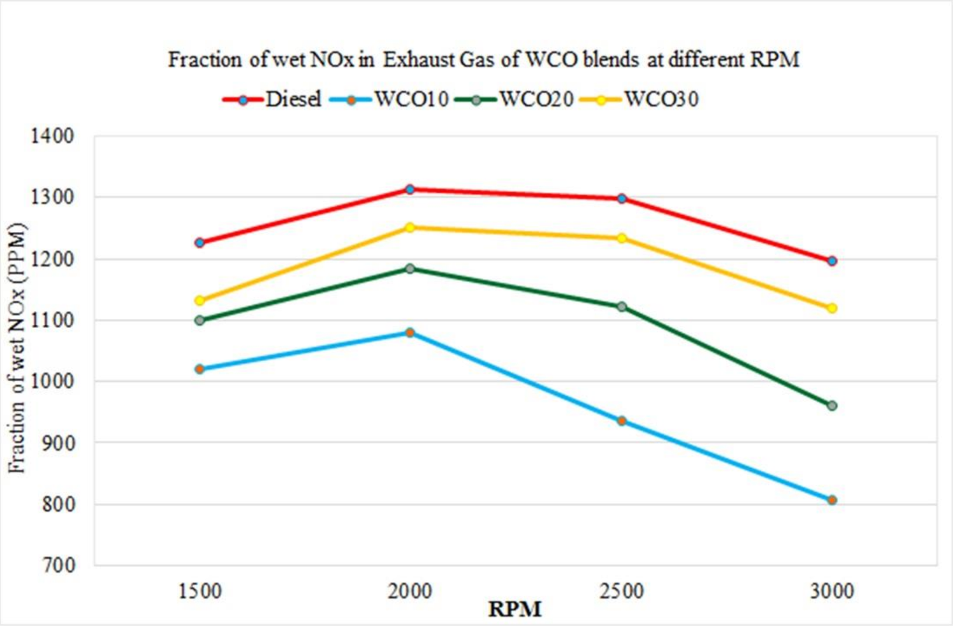

Figure 9. Variation of Fraction of wet NOx Emission of WCO blends with variable RPM.

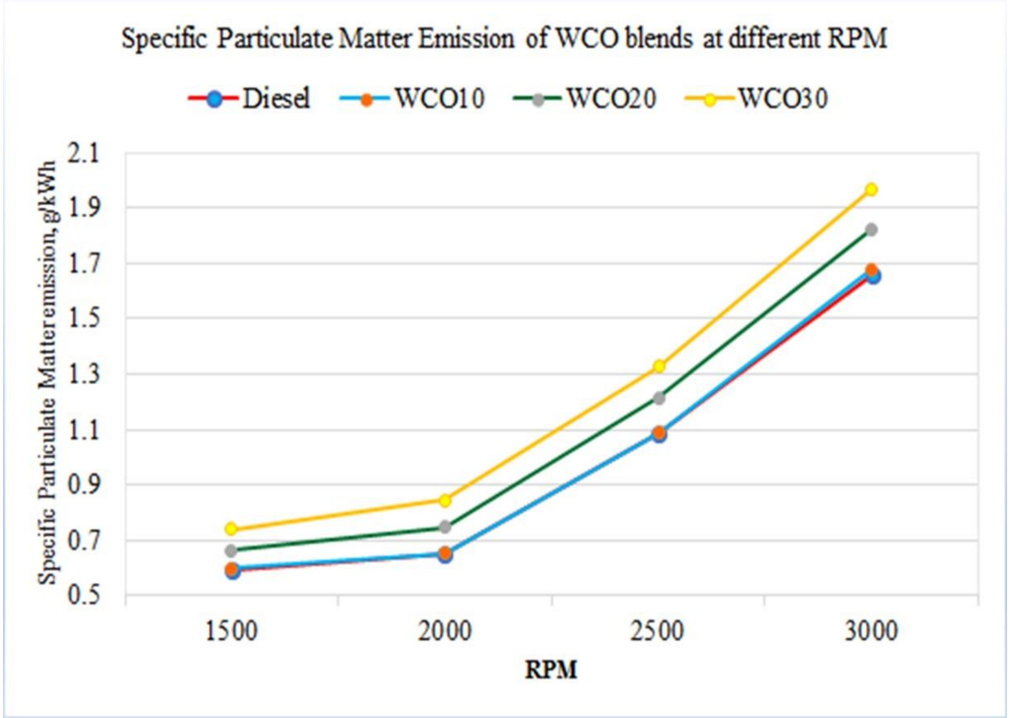

Figure 10. Variation of PM Emission of WCO blends with variable RPM.

3.3. Comprehensive analysis of WCO Blends at different RPMs

Through an extensive examination, the study sought to offer a comprehensive overview of the interactions between different WCO blends and RPM levels in terms of both their performance achievements and emission implications shows in Table 6.

Table 6. Findings regarding Performance and Emission traits of various WCO blends across RPM variations.

Findings regarding Performance and Emission traits of various WCO blends across RPM variations					
Engine Parameter	WCO blends Values find to closest to diesel				Remark
	Blends Name	At RPM	Value	Lower / Greater %	
Brake Power	WCO20	1500	4.4375 KW	3.582 % lower than diesel	Increasing the value of RPM, the corresponding values of brake power increases for the all blends.
Brake torque	WCO10	3000	21.16 Nm	3.480% lower than diesel	Increasing the value of RPM, the corresponding value of brake torque decreases for the all blends.
Indicated efficiency	WCO10	3000	0.4199	0.961% higher than diesel	IE rises as RPM increases from 1500 to 2000, but declines beyond 2000 up to 3000 RPM across all blends.

Findings regarding Performance and Emission traits of various WCO blends across RPM variations					
Engine Parameter	WCO blends Values find to closest to diesel				Remark
	Blends Name	At RPM	Value	Lower / Greater %	
Brake-specific fuel consumption	WCO10	1500	0.249 kg/kWh	4.236 % higher than diesel	Increasing the value of RPM, the corresponding values of BSFC increases for the blends.
Brake mean effective pressure	WCO10	3000	4.8088 bar	3.476 % lower than diesel	Increasing the value of RPM, the corresponding values of brake mean effective pressure decreases.
CO_2 emission	WCO10	3000	1070.9 g/kWh	9.244 % higher than diesel	increasing the value of RPM, the corresponding values of CO_2 emission increases for all blends.
SO_2 emission	WCO30	1500	0.00881 g/kWh	8.133 % lower than diesel	Increasing the value of RPM, the corresponding values of SO2 emission increases for all blends.
Fraction of wet NOx Emission	WCO10	3000	807.23 PPM	32.494 % lower than diesel	Increasing the value of RPM, the corresponding values of fraction of wet NOx emission increases.
PM emissions	WCO10	2000	0.6539 g/kWh	0.383 % higher than diesel	Increasing the value of RPM, the corresponding values of PM emission increases.

4. Conclusion

In conclusion, the comprehensive analysis of engine performance and emissions across different RPM values and various waste cooking oil (WCO) blends highlights several significant findings:

- The results indicate that among all WCO blends, WCO20 closely approximates diesel's brake power and torque at specific RPMs. At 1500 RPM, WCO20 exhibits a 3.582% lower brake power compared to diesel, while at 3000 RPM, WCO10 demonstrates a 3.480% lower brake torque.
- For WCO10, the highest indicated efficiency of 0.4199 is achieved at 3000 RPM, surpassing diesel by 0.961%. Nevertheless, an interesting trend emerges where, generally, increasing RPM elevates indicated efficiency up to 2000 RPM for WCO10, WCO20, and WCO30 blends. Beyond this point, efficiency declines with increasing RPM, echoing the behavior observed in pure diesel.

- The results highlight that the blends consistently exhibit higher brake-specific fuel consumption compared to pure diesel. WCO10 at 1500 RPM showcases a 4.236% increase in fuel consumption compared to diesel, aligning with the trend seen in other blends and higher RPMs.
- Among all the blends, WCO10 closely mirrors diesel's BMEP values, with a 3.476% difference at 3000 RPM. Notably, as RPM increases, the BMEP values decrease for all blends, reflecting the same pattern observed in the case of pure diesel.
- Among all blends, WCO10 closely mirrors diesel's CO_2 emission levels, albeit 9.244% higher at 3000 RPM. The analysis reveals that higher RPM settings correspond to increased CO_2 emissions across all blends, echoing the same trend observed in pure diesel.
- WCO30 showcases SO_2 emission values closest to diesel, with a reduction of about 8.133% at 1500 RPM. Correspondingly, increasing RPM results in higher SO_2 emissions across all WCO blends, mirroring the pattern seen in pure diesel.
- The optimal fraction of wet NO_X emission is achieved at 3000 RPM for WCO10, exhibiting a substantial reduction of 32.494 % compared to diesel. Notably, within the range of 1500-2000 RPM, NOx emissions rise for WCO10, WCO20, and WCO30, followed by a subsequent decline.
- WCO10 demonstrates the closest PM emission values to diesel, with a slight increase of 0.383% at 2000 RPM. Analogous to other emissions, as RPM increases, PM emissions also escalate for all WCO blends as well as pure diesel.

These observations collectively highlight that the performance and emission characteristics of the engine are influenced by both the type of WCO blends and the RPM setting. While specific blends closely resemble diesel's performance and emission in certain aspects, the trend of decreasing efficiency and increasing fuel consumption with higher RPMs is consistent across all blends, including pure diesel and elevated RPMs also correlate with increased emission values. These insights underscore the significance of RPM control and blend formulation in minimizing emissions while optimizing engine performance for alternative fuel sources such as WCO blends.

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Nomenclature			
$(\eta_t)_{ind}$	Indicated thermal efficiency	τ or BT	Brake Torque
$(\eta_t)_{brake}$	Brake thermal efficiency	N	Engine speed
η_c	Combustion efficiency	n	Number of revolutions per cycle
η_m	Mechanical efficiency	NO_X	Fraction of wet NO_X in exhaust gas
η_v	Volumetric efficiency	PM	Specific particulate matter emission
m_a	Mass of air into the engine for one cycle	BSN	Bosch smoke number
$\dot{m}_a$	steady-state flow of air into the engine	CO_2	Specific CO_2 emission
$\dot{W}$	Power	SO_2	Specific SO_2 emission
$\dot{W}_b$ or BP	Brake Power	BMEP	Brake Mean effective pressure
$\dot{W}_i$ or IP	Indicated Power	IMEP	Indicated Mean effective pressure
$\dot{m}_f$	Fuel flow rate into the engine	MEP	Mean effective pressure
Q_{HV}	Heating value of the fuel	BSFC	Brake Specific Fuel Consumption
η_c	Combustion efficiency	WCO10	10% waste cooking oil biodiesel +

			90% diesel
V_d	Displacement volume	WCO20	20% waste cooking oil biodiesel + 80% diesel
ρ_a	Air density	WCO30	30% waste cooking oil biodiesel + 70% diesel