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Evaluation of Engine Performance and Emissions with Biodiesel Blends Containing Polymer Waste Additives

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Abstract

The increasing awareness of fossil fuel depletion and environmental pollution has spurred interest in alternative fuels, notably biodiesel. However, biodiesel's performance and emissions can be influenced by intrinsic factors, such as viscosity and energy content. The research assesses the feasibility of enhancing engine performance and reducing emissions by integrating polymer waste additives (PWA) into biodiesel blends (B5). The maximum dissolution capacity of PWA in biodiesel was established, resulting in a uniform fuel composition. Subsequently, various biodiesel-diesel blends (B5) with differing PWA concentrations (30/60/90g) were evaluated in an engine under standardized operating conditions. The engine performance characteristics of braking power (BP), brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC) were evaluated statistically in addition to lowering emissions of CO, CO_2, and NOx. Incorporating dissolved PWA into biodiesel-diesel blends sustained engine performance in acceptable parameters, while simultaneously yielding notable reductions in emissions. These results demonstrate how PWA concentrations in biodiesel blends can be optimized to increase energy efficiency and reduce emissions. Integrating dissolved PWA into biodiesel-diesel blends presents a dual advantage of promoting sustainable PWA while enhancing fuel characteristics. This innovative approach holds significant potential for improving diesel engine performance and reducing emissions, making it a promising adoption for energy recovery applications.

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Introduction

The significance of alternative fuels, such as biodiesel, has grown concerns about energy security and environmental sustainability (Vijayan et al., 2022). Biodiesel is a sustainable and biodegradable fuel derived from vegetable and animal fats, capable of partially or fully replacing conventional diesel (Dinesh, 2024). However, modifications should be made to improve oxidation stability, cold flow properties, and emissions that cause environmental pollution (Gaur et al., 2022; Elkelawy et al., 2022). Biodiesel is rapidly gaining worldwide attention due to its biodegradability and lower overall greenhouse gas emissions, which lead to environmental pollution. Biodegradation of biodiesel is less pronounced compared to conventional fossil fuels and does not generate high amounts of hazardous sulfur oxides (SOx). Additionally, its production from plant oils and animal fats contributed to energy security and promoted rural economic growth (Rony et al., 2023). While biodiesel offers several advantages, it also has disadvantages, such as high viscosity can cause clogging in injectors, and poor cold flow properties, leading to gelling at lower temperatures. Oxidation instability can degrade fuel quality over time, requiring modifications and additives to improve performance (Hassan et al., 2022). Additives like cold flow improver, cetane enhancer, and antioxidants increase the biodiesel's stability and effectiveness. These additives optimize combustion characteristics and minimize engine wear, and reduce emissions in the atmosphere, so blending into biodiesel make its more compatible for widespread public consumption (Nagappan et al., 2022). Recycling polymer waste as an additive in biodiesel offers a promising solution to mitigate plastic pollution (Saifi, 2018). These polymer-based additives can improve cold-flow characteristics, oxidation stability, and viscosity, which are benefits of using biodiesel in traditional diesel engines (Jena et al., 2023). Polymer additives in biodiesel blends tend to be in BTE, BSFC, and combustion pressure with the engine (Sivasubramanian & Gomathi, 2019). Such blends contribute to improved fuel economy and power while ensuring the smooth operation of the engine (Hasan et al., 2023). These blends help compliance with stringent emission regulations and help reduce air pollution, environmental pollution by encouraging cleaner combustion (Dong et al., 2022).

Three different fuels were investigated by (Yakın & Behçet, 2021). E20 (20 percent ethanol and 80 percent gasoline mix), G100 pure gasoline, and ES20 (20 percent sodium borohydride added ethanol solution and 80 percent gasoline). According to the data, motor torque climbed by 1.87% with E20 combined fuel and declined by 1.64% with ES20 combined fuel as compared to clean gasoline. Standard engine fuels are used, which was creating competition for more environmentally friendly engine fuels that protect the environment (Mohammed et al., 2021). It was possible to use an ultrasonic bath to mix gasoline and alcohol fuel in different proportions. Analysis of one-cylinder, four-stroke, and spark ignition engines revealed ethanol concentration increases thermal efficiency, power, and brake-specific fuel consumption while lowering volumetric efficiency. Motor and octane numbers are increased by ethanol, but it also lowers dangerous exhaust particles.

Mourad et al., (2021) examine the emissions from heated biodiesel fuel for diesel engines about exhaust gas recirculation (EGR). The air-cooled, single-cylinder diesel engine featured variable EGR rates of up to 25%. The findings showed that at 25% EGR, there was a small gain in engine performance and a 22.2% decrease in pollutants, particularly NOx emissions. The biodiesel blends utilized in the investigation to evaluate the emission and performance of a CI engine contains three different types of nanoparticles (Fayaz et al., 2021). The response surface approach was used to improve the biodiesel made from palm oil. CNT, TiO2, and Al2O3 nanoparticles were mixed with the B30 mix to create the nano fuel blends. At different engine speeds and under full load, the engine's performance and emission characteristics were assessed. According to the research, fuel characteristics, engine performance, and emissions are all impacted by rising PWA concentrations in biodiesel (Razzaq et al,2021).

Das et al., (2021) assess a diesel engine's thermal balance using waste plastic oil, fuel, ethanol, and nano graphene (Knežević et al., 2018). The engine was tested under a range of loading conditions, and the findings showed that adding nanographene to the diesel increased its energy and exergy efficiency under higher operating load conditions, adding ethanol to the diesel fuel mixture increased the thermal efficiency of the brakes while lowering fuel consumption specific to the brakes (Walid & Makram, 2018). Fuel exergy increases at 18.57% the maximum load in comparison to diesel, while exhaust and exergy were destroyed. By using Al2O3 nanoparticles as a catalyst to enhance the emulsion properties and performance of biodiesel made from spirulina microalgae (Ge et al., 2022). Both pure diesel and various fuel mixtures were tested. The results showed adding Al2O3 nanoparticles to B15 biodiesel enhanced combustion characteristics and reduced emissions of harmful gases. In comparison to other blends, fuels B15N and B30N demonstrated higher BTE and lower fuel usage.

The particular topics are the blendability of Al2O3 nano-particles and the performance of pyrolyzed plastic oil in engines under exhaust gas recirculation (EGR) conditions (Selvan et al., 2022). After mixing commercial diesel with different mixtures of plastic pyrolyzed oil, factors like mechanical efficiency, CO, Co_2, and NO_x emissions, brake mean effective pressure, brake thermal efficiency, and indicated thermal efficiency were investigated. In the P30 mix with 50 ppm of Al2O3, the brake mean effective pressure and brake thermal efficiency were the highest. The performance and emission properties of biodiesel blends including 10% v/v dimethyl carbonate (DMC) and graphene oxide nanoplatelets (GNPs) as fuel additives were investigated in the research (Razz et al., 2021). The nanofuels were made with varying concentrations of GNPs and a sodium dodecyl sulfate surfactant. The nanofuels showed the maximum stability in biodiesel and reduced BSFC, BTE, HC, CO, and NOx in a four-stroke compression ignition engine. GNP and DMC together demonstrated encouraging possibilities for diesel engine operation.

Research Contributions

- Set the maximum PWA dissolution capability in biodiesel; thus, a uniform and stable fuel blend was ensured.
- Determined the braking performance under PWA about its variations in concentrations through BP, BTE, and BSFC measurements.
- To evaluate the environmental pollution of PWA-modified biodiesel blends, CO, CO_2, and NOx emissions were measured.
- Systematic evaluation of different biodiesel-diesel blends (B5) with variable PWA concentrations (30g, 60g, 90g) under standardized conditions of engine running to evaluate performance and emissions produced cause environmental pollution.

Materials and Methods

The process uses a systematic technique to evaluate how PWA affects the environmental pollution and performance of B5 biodiesel-diesel blends in diesel engines. Each stage is explained in Figure 1.

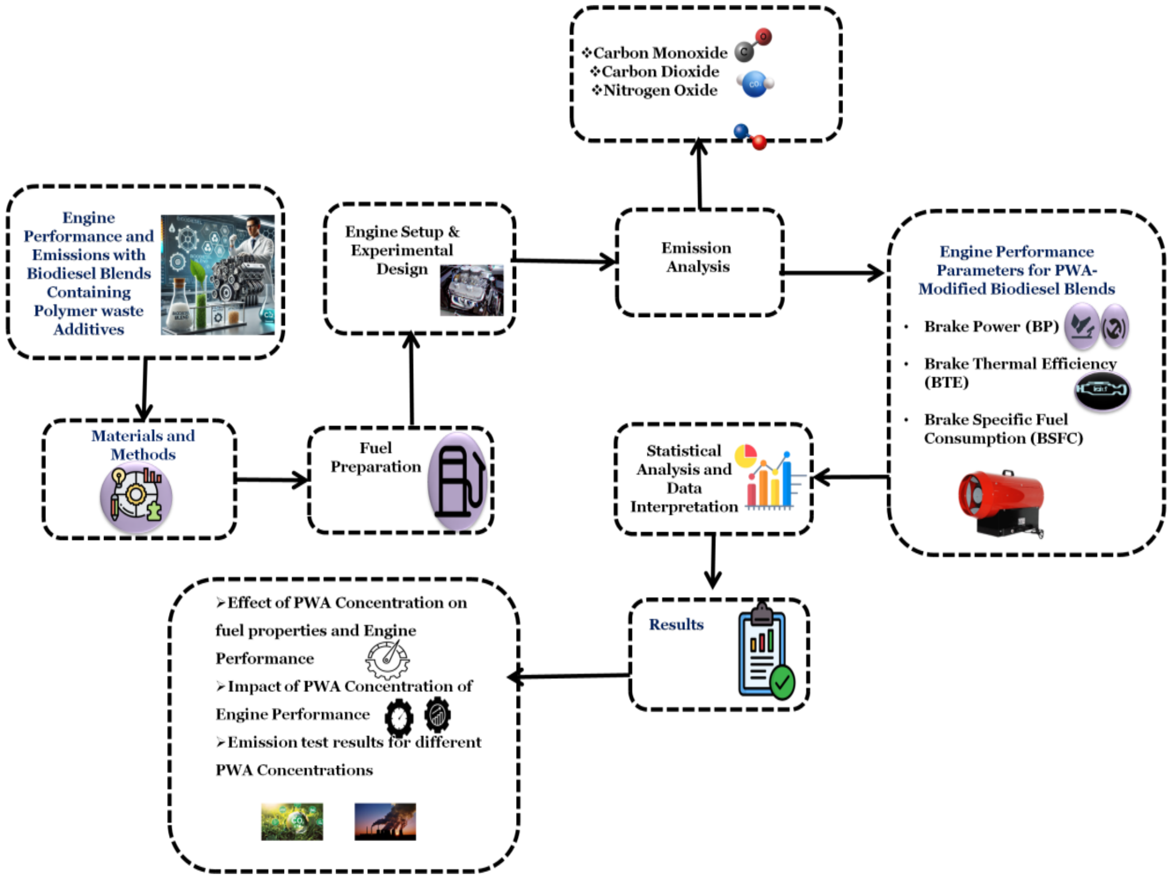

Figure 1. Overall research flow for engine performance and emissions with biodiesel blends containing

Fuel Preparation

The research's initial phase involves choosing and preparing biodiesel blends using polymer waste additions (PWA). A B5 standard biodiesel blend, which contains 5% biodiesel and 95% diesel, is the base fuel. This blend is commonly accepted in diesel engines without modifications. The various polymer wastes are sourced and processed. The chosen polymers should be stable chemically and have a high ability to dissolve in biodiesel without showing phase separation. It is crushed into small pieces to improve solubility. The highest possible solubility of PWA in biodiesel is quantified by adding different concentrations step by step until the biodiesel is uniformly mixed without settling. Once the solubility limit is established, different biodiesel blends with concentrations of PWA at 30g, 60g, and 90g per fixed volume are prepared. During blending, homogeneity is maintained and samples are kept under controlled conditions to maintain consistency before a test is conducted.

Engine Setup & Experimental Design

A single-cylinder or multi-cylinder diesel engine is selected for testing. It must pass the industrial standards for biodiesel performance evaluation. Sensors and monitoring systems are mounted on the engine to capture precise performance and emission data. The engine is run under standardized conditions to ensure reproducibility: fixed engine speed, constant fuel injection pressure, and a controlled cooling system to prevent overheating. These factors help cancel out variations and skew results. Each blended fuel prepared in B5+PWA 30g, 60g, and 90g is tested using the same experimental conditions, whereas data is generated at various load conditions to develop performance trends. A baseline experiment with conventional B5 biodiesel is conducted.

Emission Analysis

The research also employs a gas analyzer to assess how adding PWA affects exhaust emissions.

- **Carbon monoxide (CO):** CO emissions are caused by incomplete combustion resulting from improper air-fuel mixing or an insufficient supply of oxygen. A reduction in CO emissions would indicate better oxidation properties, but an increase would indicate that PWA negatively affects combustion efficiency.
- **Carbon dioxide (CO_2):** The direct result of full combustion is CO_2. While a large drop in CO_2 emissions can indicate insufficient fuel use, an increase in emissions often indicates improved combustion efficiency.
- **Nitrogen oxides (NOx):** NOx emissions are produced at high combustion temperatures because of the reaction of nitrogen with oxygen. Higher temperatures and longer combustion times result in higher NOx levels, which contribute to environmental pollution like air pollution and health issues. If NOx emissions decrease with PWA, it can be due to a lower combustion temperature as a result of changed fuel properties.

The research assesses whether PWA improves or degrades the environmental sustainability of biodiesel by comparing environmental pollution from various mixes.

Engine Performance Parameters for PWA-modified Biodiesel Blends

To determine the feasibility of including PWA in biodiesel blends, the research evaluates key engine performance metrics.

- **BP:** It is the actual power produced at the engine shaft. A dynamometer measures the torque and rotational speed; higher brake power implies good performance from an engine, but too much polymer content might interfere with combustion efficiency.
- **BTE:** BTE is the measure by which an engine converts fuel energy into useful work efficiency. It is calculated as a brake power ratio and input fuel energy. High BTE indicates the fuel is well combusted, but lower efficiency indicates some combustion problems due to PWA modification.
- **BSFC:** The BSFC is the metric that gives fuel consumption for the generation of one unit of energy (gram/kilowatt-hour). A lower BSFC value translates to more efficient fuel use with an improvement in energy consumption. A high increase in BSFC with increased PWA concentration signifies perhaps insufficiently combusted fuel or a reduced energy content of the fuel.

Statistical Analysis & Data Interpretation

Statistical methods like ANOVA and regression analysis have been used to analyze the data concerning performance and emissions to find any significant differences among the various fuel blends. The ANOVA tests determine whether any change in the concentration of PWA has a significant effect on the performance and emissions of the engine. Regression analysis, attempts to highlight trends and correlations. The results from the modified fuel blends compared to those of the baseline B5 blend to determine whether the addition of PWA leads to causes any noticeable improvement. To improve validity and reduce errors in the experiments, multiple readings are taken for all measurements. IBM SPSS version 29 was utilized for statistical analysis.

Results

The PWA was incorporated into biodiesel-diesel blends to eliminate pollution according to the standards.

PWA Concentration's Impact on Engine Performance and Fuel Properties

The physical and chemical characteristics of the blend of biodiesel with varying PWA levels are important. It includes important properties such as density, viscosity, calorific value, and flash point, which can directly influence combustion and performance. The combustion properties of PWA-modified blends have a substantial effect on engine performance and the enhancement factors of the three main performance metrics BP, BTE, and BSFC; these measures are affected by the effect of PWA concentration on fuel properties and engine performance is shown in Figure 2.

Table 1. Fuel properties for different PWA concentrations

PWA Concentration (g per fixed volume)	Density (kg/m^3)	Viscosity (mm^2/s at 40°C)	Calorific Value (MJ/kg)	Flash Point (°C)
0g (Baseline B5)	860	4.2	42.5	78
30g PWA	865	4.5	41.8	82
60g PWA	872	4.9	40.9	86
90g PWA	880	5.4	39.7	89

Table 1 illustrates the effects of raising the PWA concentration on the fuel's essential characteristics. Adding PWA to the biodiesel mix raises its density, viscosity, and flash point while lowering its calorific value. Due to polymer breakdown, density rises from 860 kg/m^3 for B5 to 880 kg/m^3 for 90g PWA, which can be a sign of a higher molecular weight composition. The viscosity increased from 4.2 mm^2/s to 5.4 mm^2/s. This would increase the injection time, affecting the atomization of fuel, and reducing combustion efficiency in diesel engines. The calorific value or the energy contained in the fuel decreases from 42.5 MJ/kg for B5 to 39.7 MJ/kg for 90g PWA. The energy per unit mass is lower for PWA-modified fuels, which means it decreases the overall engine performance. However, the flash point increases from 78°C (B5) to 89°C (90g PWA), improving fuel safety by reducing volatility, which is beneficial for storage and handling. While these changes indicate PWA can be safely blended with biodiesel, the reduction in calorific value and increased viscosity can negatively impact engine efficiency, and the concentration is too high.

Table 2. Engine performance metrics for different PWA concentrations

PWA Concentration (g per fixed volume)	Brake Power (BP) (kW)	Brake Thermal Efficiency (BTE) (%)	BSFC (g/kWh)
0g (Baseline B5)	5.8	28.5	320
30g PWA	5.7	28.1	325
60g PWA	5.5	27.6	335
90g PWA	5.3	26.8	350

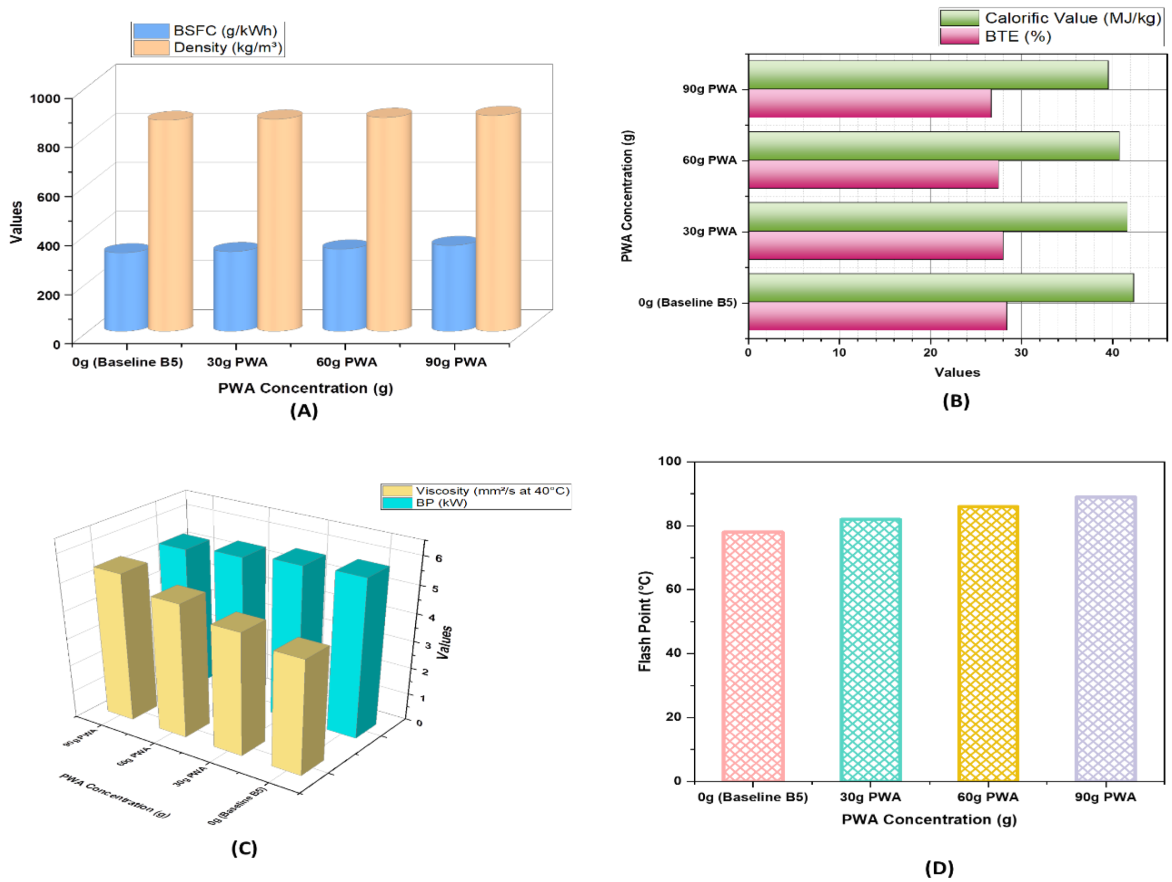

Figure 2. Fuel properties and engine performance for PWA concentration (A) Density, BSFC, (B) Calorific value, viscosity, (C) Viscosity, BP, (D) Flash point

As the PWA concentration rises, Table 2 displays how the engine performance metrics, BP, Brake BTE, and BSFC change. There is a trade-off between sustainability and performance as BP and BTE fall when PWA concentration rises concurrently with BSFC. The reduced calorific value of PWA-modified fuel is mostly responsible for the drop in BP from 5.8 kW (B5) to 5.3 kW (90g PWA). The drop in BP suggests a higher proportion of PWA lowers the energy for combustion, which lowers engine performance because energy content has a direct effect on power production. BTE also follows a similar pattern but decreases from 28.5% for the B5 to 26.8% for the 90g PWA. BTE indicates how well the engine is converting fuel energy into useful work, this reduction implies PWA additives cause the combustion process to be less efficient, most probably because of increased viscosity and decreased fuel atomization quality. BSFC is a measure of the mass of fuel consumed per unit of power generated; it rises from 320 g/kWh for B5 to 350 g/kWh for 90g PWA. The higher BSFC would mean more fuel to burn at the same power output, hence less energy conversion efficiency. This is expected; the PWA-modified biodiesel has lower energy density, and more fuel has to be burned to compensate for the lower calorific value.

Impact of PWA Concentration on Engine Performance

The variations of BP, BTE, and BSFC due to the concentrations of PWA are statistically significant according to ANOVA. Regression analysis tests the association between the independent variable, which is the concentration of PWA, and the dependent variables: BP, BTE, and BSFC.

Table 3. ANOVA table for engine performance metrics

Source of Variation	SS	df	MS	P- Statistic	F-Statistic	Significance (α = 0.05)
BP (Brake Power)	0.56	3	0.187	0.015	12.33	Significant
BTE (Brake Thermal Efficiency)	4.3	3	1.43	0.011	14.75	Significant
BSFC (Brake Specific Fuel Consumption)	250	3	83.33	0.008	19.25	Significant
Error (Residuals)	0.52	8	0.065	-	-	-
Total	5.81	11	-	-	-	-

Note: F-statistic, P-statistic, Mean Square (MS), Degrees of Freedom (df), Sum of Squares (SS), and P-statistic

Table 3 examines whether the variations in BP, Brake BTE, and Brake Specific Fuel BSFC across different PWA concentrations are statistically significant. Table 3 illustrates the SS for BP, BTE, and BSFC and represents the total variation in these parameters due to changes in PWA concentration. The df is 3 for the treatment (PWA concentration levels) and 8 for the residual error, so the total df = 11. MS is calculated as SS divided by df, and the F-value determines the significance of the variations. BTE (0.011), BSFC (0.008), and BP (0.015) all have P-statistics below the significance level ($\alpha = 0.05$). Therefore, this indicates PWA concentration has a statistically significant effect on engine performance. Large F-values (BP = 12.33, BTE = 14.75, BSFC = 19.25) further increasing PWA concentration will have a statistically significant effect on the metrics shown above. Error SS = 0.52 and error mean square = 0.065 show the variations in very less, implying the changes revealed are more affected by PWA concentrations rather than random variations.

Table 4. Regression analysis for engine performance vs. PWA concentration

Regression Equation	Intercept (β_0)	Slope (β_1)	R^2 (Coefficient of Determination)	P-Value
BP (kW) = $\beta_0 + \beta_1$(PWA)	5.85	-0.0065	0.92	0.013
BTE (%) = $\beta_0 + \beta_1$(PWA)	28.6	-0.02	0.95	0.009
BSFC (g/kWh) = $\beta_0 + \beta_1$(PWA)	318	+0.35	0.97	0.006

The association between PWA concentration and engine performance parameters is investigated by the regression analysis in Table 4. Because the decreased calorific value and greater viscosity impair combustion efficiency, the regression equation for Brake Power (BP = 5.85 - 0.0065(PWA)) indicates a negative connection, with rising PWA concentration lowering BP. The P-value of 0.013 (< 0.05) validates statistical significance, and the strong R^2 value of 0.92 shows PWA concentration accounts for 92% of BP changes. The Brake Thermal Efficiency regression equation (BTE = 28.6 - 0.02(PWA)) also exhibits a negative trend, indicating greater PWA concentrations result in worse thermal efficiency, most likely as a result of poorer atomization and decreased combustion efficiency. The R^2 value of 0.95 indicates a strong connection, while the P-value of 0.009 confirms significance. There is a positive association between Brake Specific Fuel Consumption (BSFC = 318 + 0.35(PWA)) and PWA concentration, suggesting more fuel is needed per unit of power output. With a P-value of 0.006, the statistical significance is further supported by the R^2 value of 0.97, which indicates PWA concentration accounts for 97% of BSFC changes.

Emission Test Results for Different PWA Concentrations

The results of the emission test demonstrate the effects of PWA concentration on the primary exhaust pollutants, namely CO, CO_2, and NOx. These emissions were measured using a Chemiluminescence Analyzer (CLA) for NOx and Non-Dispersive Infrared (NDIR) sensors for CO and CO_2.

Table 5. Emission test results

PWA Concentration (g)	CO (ppm) - NDIR	CO_2 (%) - NDIR	NOx (ppm) - CLA
0g (Baseline B5)	0.46	12.8	740
30g PWA	0.42	12.5	720
60g PWA	0.38	12.3	710
90g PWA	0.35	12.1	695

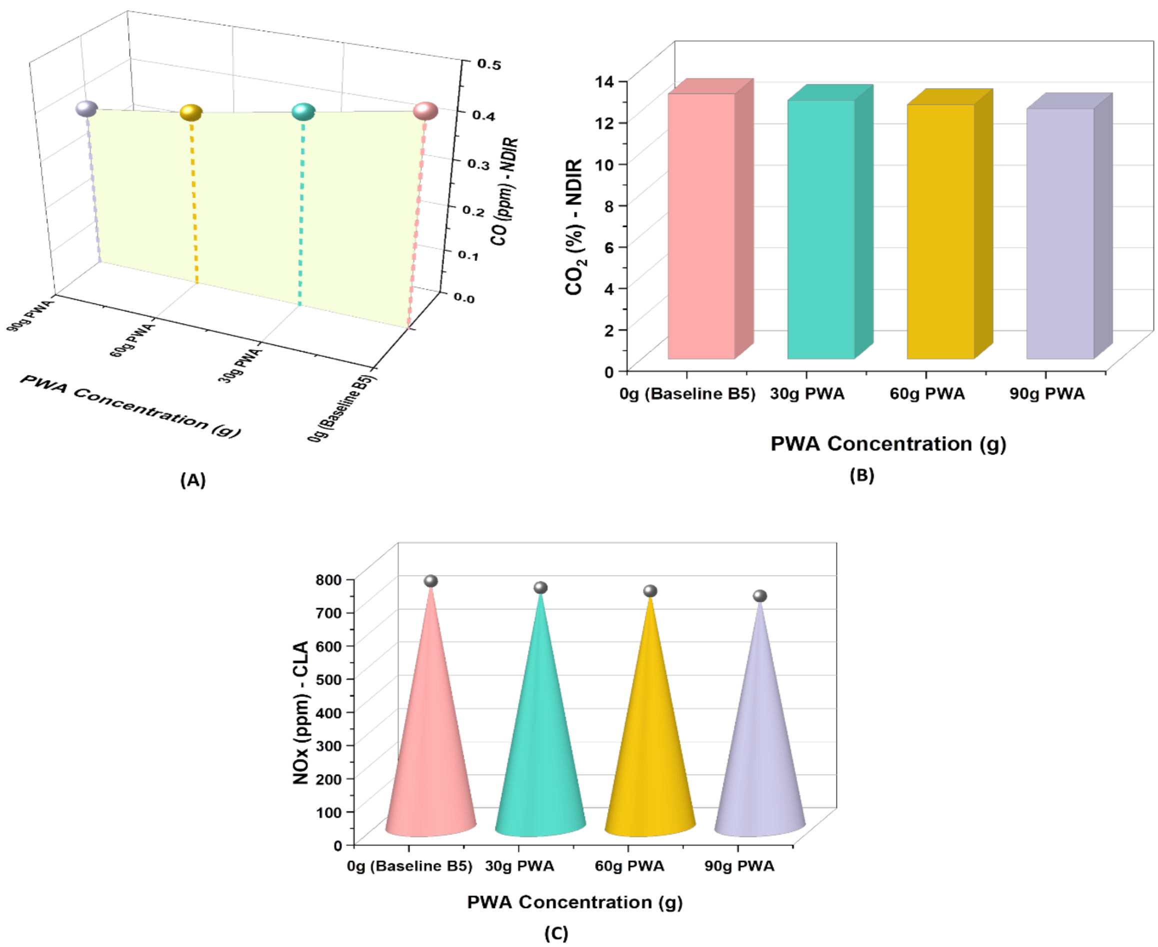

Figure 3. Engine emissions and performance comparison with PWA in biodiesel blends 9 A), CO, (B) CO_2, and (C) NO_x

CO is a byproduct of low combustion efficiency, as seen in Table 5 and Figure 3, and it usually rises as fuel combustion efficiency decreases. Test results indicate there is a stepwise reduction in CO emissions as the PWA concentration is increased. B5 baseline fuel recorded a CO emission of 0.46 ppm, while the same dropped to 0.42 ppm at 30g PWA, 0.38 ppm at 60g PWA, and 0.35 ppm at 90g PWA. This trend indicates that the addition of PWA in the biodiesel blend enhances better combustion, and this is believed to be mainly due to increased atomization of the fuel along with oxygen within the fuel. CO_2 is an important emission indicator of complete combustion, where higher CO_2 emissions are an indication of greater fuel oxidation. The base fuel B5 showed 12.8% CO_2, and this gradually went down to 12.5% at 30g PWA, to 12.3% at 60g PWA, and to 12.1% at 90g PWA. The slight dip in the emissions of CO_2 is indicative; though combustion is relatively efficient, the rising PWA content might weaken the content of fuel energy slightly and thus marginally diminish oxidation levels. NOx formation takes place due to elevated temperatures of combustion and due to excess oxygen present. The results show NOx forming lower levels as the content of PWA increased. The baseline B5 fuel (0g PWA) produced 740 ppm of NOx, which decreased to 720 ppm at 30g PWA, 710 ppm at 60g PWA, and 695 ppm at 90g PWA. This drop in NOx emissions is a sign PWA has raised the fuel's peak combustion temperature, but it might also be the result of certain altered fuel characteristics, like viscosity and calorific value.

Discussion

The PWA concentration of biodiesel is evaluated in relation to its effects on emissions, engine performance, and fuel properties. The experiment discovered that increasing PWA concentrations in biodiesel had an effect on emissions, engine performance, and fuel properties. Higher PWA increases density and viscosity but lowers the calorific value, impacting combustion efficiency. Brake power and thermal efficiency decrease, while fuel consumption increases with more PWA. ANOVA shows changes are statistically significant, with strong correlations found in the regression analysis. The emission results reveal lower levels of CO and NOx, indicating better combustion and reduced environmental pollution. The small decrease in CO_2 emissions indicates a minor change in the oxidation efficiency. The reduction in the emission of NOx shows a decrease in temperature during combustion, which is considered good for air quality. Though PWA supports sustainable performance, excessive amounts can harm engine performance. More research is necessary to address indications of problems with performance improvement while optimizing PWA's environmental advantages.

Conclusion

The effects of these additives on fuel combustion, efficiency, and pollutant emissions could be studied by a PWA. The insights thus gained are applicable to sustaining fuel alternatives and their environmental pollution. Optimizing PWA concentrations in biodiesel blends lead to increased energy efficiencies at reduced emissions. This approach improves the conditions of wastes in sustainable polymerism disposal and the properties of fuel, which is a potential solution for energy recovery purposes. At the same time, biodiesel blending with PWA has significant disadvantages, such as poor engine compatibility, increased deposits resulting from incomplete combustion, and varying fuel properties that can affect engine performance. Future research would refine additive formulations with improved combustion efficiency toward less emission by advanced catalytic converters and long-term engine durability tests to ensure reliability.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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