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Environmental Sustainability Improvement on Polycarbonate Fuel with Nano-additives for Cleaner Engine Performance

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ABSTRACT

The increasing plastic waste has posed an environmental challenge that calls for radical, innovative measures in the form of a pyrolysis process to convert plastics into alternative fuels. This reduces detritus waste and provides renewable energy. Nano-additives enhance the performance of recovered fuel properties and comply with strict emission standards. In this research, a supplementary fuel recovered from polycarbonate (PC) plastic waste along with magnesium oxide (MgO) was investigated in a diesel engine. This investigation tested the performance of a 20% blend ratio of polycarbonate fuel with 50 and 100 ppm of MgO. A 20% blend ratio of polycarbonate fuel with 50 ppm of MgO resulted in increased combustion efficiency and reductions of harmful emissions such as hydrocarbons (HC), carbon monoxide (CO), and specific fuel consumption (SFC). This study also explored the impact of engine load and nanoparticle concentration on the environmental sustainability of hydrocarbons and carbon monoxide using contour plots. All these advancements should contribute to achieving global sustainability goals, promoting cleaner energy solutions, and significantly reducing the impact of plastic wastes associated with fuel emissions.

Keywords: Magnesium oxide; Environmental sustainability; Hydrocarbons; Carbon monoxide; Contour plots; Polycarbonate waste.

1. INTRODUCTION

Nowadays, plastic waste is a significant menace in the world since many tons of plastic are thrown away annually, posing serious environmental threats to ecosystems, wildlife, and human health. Traditional approaches to manage waste that have been in the mainstream such as landfilling and incineration, are also failing and often end in causing soil, water, and air pollution (Kibria *et al.* 2023; Williams and Rangel, 2022). Alternative fuels derived from plastics using pyrolysis and similar processes are another bright hope toward a solution, for waste turns into an energy resource (Miandad *et al*. 2019). It addresses the long-standing need for confrontations related to urgent issues in sustainable waste management that meet the need to reduce the plastic pollution crisis and reliance on fossil fuel resources. Since the trend of controlling emissions around the globe is becoming more intensive, it becomes necessary to develop new technologies that would enhance the combustibility of such fuels, that is, making them more efficient and less pollutant, such as by incorporating nano-additives (Hariadi *et al.* 2021). Pyrolysis is an environmentally friendly and cost-effective mode of disposal for hazardous wastes (Radhakrishnan *et al*. 2023). A much better way would be to produce fuel from polymers of similar calorific content to conventional fuel. Samples were pyrolyzed to evaluate whether catalytic pyrolysis could indeed be an avenue in which recyclable waste plastics are converted into fuels (Damodharan *et al.* 2019; Kabeyi and Olanrewaju, 2023). Recently, research has shown that plastic waste can be converted into a viable energy source. This involves utilizing various types of polymer wastes, such as polypropylene, polyethylene, polystyrene, and polyvinyl chloride. These waste polymers were assessed for their potential in energy conversion. Waste polymer pyrolysis oil has been recognized as a possible substitute for fossil fuels. The engine test trials used these fuels in direct injection. The results obtained from the engine test included a fall in performance and an increase in fuel consumption. The low volumetric rating caused a significant downturn in performance (Mangesh *et al.* 2017).

Recent studies have been conducted on varying nano additives that will improve the diesel blends of WPO (Waste Plastic Oil). These additives aim to enhance an engine's performance while simultaneously reducing emissions. Ulagarjun's work investigated the effect of adding cerium oxide (CeO_2) on the combustion and emission characteristics of diesel-WPO blends. The study's results revealed that adding 50 ppm CeO_2 resulted in a significant reduction in CO, HC, and NOx emissions. The results of the study revealed that the addition of 50 ppm CeO_2 resulted in a significant reduction in CO, HC, and NOx emissions. There was also an improvement in brake thermal efficiency of about 3% points. The most efficient blend was B50 + 50 ppm, with the least fuel consumption (Ulagarjun *et al.* 2024). Sachuthananthan also investigated to examine the potential application of rice-husk-based non-metallic nano-additives in a WPO-diesel blend W20. The addition of nano at 75 ppm increased Brake Thermal Efficiency (BTE) by 2.5% and fuel consumption decreased by 3% compared to W20. The decline in emission was seen as HC emission decreased by 15%, CO decreased by 7%, smoke opacity decreased by 20%, but NOx increased by 14.1%. Both studies describe the opportunity for nano additives—primarily cerium oxide and rice husk nanoparticles—to improve fuel efficiency and reduce emissions in WPO-diesel blends (Sachuthananthan *et al*. 2021).

Although WPO has nearly equal calorific value and viscosity to diesel, the low volatility of WPO necessitates modifications to get a better combustion quality. The present article examines the doped concentration effects on titanium dioxide nanoparticles 50 ppm, 100 ppm, and 150 ppm in WPO in a single-cylinder diesel engine at the variance of fuel injection pressures. The results revealed that with the addition of 150 ppm TiO_2 to WPO and operating the engine at 230 bar, significantly improved combustion quality was attained due to enhanced spray penetration (Sundar *et al*. 2023). Similar research was carried out by Sachithananthan by blending WPO, diesel and cerium oxide at various concentrations. In all the blend studies, a 75 ppm CeO_2 admixture has been found to increase 4.5% NOx, significantly lowering the CO, HC, and smoke emissions, with a 1.7% increase in brake thermal efficiency and reduction in brake-specific fuel consumption. The studies highlight the promising role of nanoparticle additives in optimizing WPO as a sustainable alternative fuel (Sachuthananthan *et al*. 2021). Nanographene in 50, 70 and 100 ppm concentrations by mass added to 20 % WPOB blended diesel without any engine modification. The brake thermal efficiency of the 20% plastic oil blended 100 ppm graphene dispersed diesel fuel was increased by 1.16% at a compression ratio of 17:1 compared to diesel. CO, HC, and NOx emissions also declined considerably by adding 100 ppm nanographene to WPO compared to the other combinations of fuels (Das and Panda, 2021).

The continued adoption of plastic products, coupled with poor waste disposal methods, constitutes one of the grave environmental threats, as plastics are poorly biodegradable. One environmentally friendly solution to this situation would be chemical treatment of wastes to recover oil that could then be mixed with fuels. However, pyrolytic oils generally have lower viscosity and lubricity than conventional diesel. To fulfill that, Devan and Balasubramanian (2024) has researched the percentage of ricinoleic fatty acid ester and graphene quantum dots that should be incorporated in pyrolytic blends to improve fuel lubricity. The experiment found that 10% Castor oil methyl ester, 20% pyrolytic oil, and 30 ppm GQD nanoparticles resulted in enhanced combustion characteristics and a marked reduction in emissivity. The performance of the PCD10 blend was better than that of a conventional pyro-diesel blend and not affected by an increase in NOx and smoke emission, so it is to be considered as a viable alternative fuel option (Devan and Balasubramanian, 2024). Ultrasonication processes have been utilized to disperse aluminium oxide and manganese oxide nanofluids into EWPO blends. The results showed that nanofluids in the fuel enhanced thermal efficiency, reducing specific fuel consumption and decreasing CO and HC emissions but increasing NOx emissions. Hence, the results from these studies present a great promise for improving the performance and emissions of diesel engines by using plastic oil blends enriched with nanotechnology (Deepankumar and Senthil, 2022).

Nano additives, particularly metal oxide nanoparticles, hold a wide range of unique properties and features that prove valuable in the use of engines. The size range is micro/nanoscale, and it has a much higher surface-area-to-volume ratio than traditional additives, enabling it to interact effectively with fuel molecules during combustion. They show greater improvement in combustion by atomizing fuel and enhancing the fuel-air mixture. It brings better combustion, meaning the reduction of harmful emissions such as carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter. Nano additives can serve as lubricants or anti-wear agents, forming protective films on metal surfaces within the engine. They distribute uniformly in the fuel, meaning that metal components will experience less friction, reducing wear rates and extending the engine life. In addition, they achieve thermal stability, enabling the engines to work better at higher temperatures without excessive wear; thus, the general durability and performance of engines improve (Modi *et al*. 2024).

The inclusion of MgO nanoparticles, especially at 30 ppm, has considerably increased combustion efficiency and emission performance. Average CO emission was reduced to 10.3%, while HC emission decreased by 17.2%. Such evidence shows that MgO nanoparticles assist with complete combustion, a condition of minimizing the formation of unburned hydrocarbons and carbon monoxide during combustion. SFC increased by 28% for B100W30A, 9.5% for B20W30A, and 2.5% for B10W30A over their corresponding non-nanoparticle blends. Although the nanoparticle blends have higher SFC, the outcome generally indicates the potential of the nanoparticles to enhance the combustion process while reducing harmful pollutants such as CO and HC but at the expense of increased fuel consumption (Ranjan *et al*. 2018). The study concentrated on the tribological properties of the Linseed-based biodiesel. The impact of magnesium oxide nanoparticles as an additive to biodiesel was also studied and compared with biodiesel and base oil diesel. The friction coefficient is higher in all applied conditions, with unsteady behavior occurring for the diesel fuel. From all the blend of biodiesel, B10 was showing good output in terms of coefficient of friction and wear of surface. Of all the biodiesel blends, B10 showed good output in terms of coefficient of friction and surface wear. All the blends benefit from the inclusion of up to 0.5% nanoparticles. However, after increasing their concentration, B30 blends show a higher coefficient of friction and wear of parts (Singh *et al*. 2023).

This study focuses on recovering polycarbonate plastic waste into a fuel source as a potential alternative to fossil fuels. The recovered fuel, blended with MgO nano-additives, was tested in a single-cylinder diesel engine to evaluate its performance and emissions. The research involved blending conventional diesel with 20% and 100% polycarbonate plastic waste fuel. The primary aim was to assess the performance of a 20% blend with 50 ppm and 100 ppm of MgO nanoparticles to enhance engine performance and determine its viability as an alternative fuel. Additionally, the study examined the effects of engine load and nanoparticle concentration on emissions, particularly hydrocarbons and carbon monoxide, using contour plots to evaluate environmental sustainability.

2. MATERIALS AND METHODS

2.1. Polycarbonate Plastic Waste

Polycarbonate is one of those strong, clear polymers that fall in the category of thermoplastic polymers. The molecule is characterized by carbonate linkage between aromatic rings, which impart exceptional strength, impact resistance, and thermal stability. Polycarbonates' rigid structure at high temperatures makes them flexible enough for all manufacturing processes involving injection molding and extrusion. It is a very popular material for many products; it is used for optical discs, automotive parts, eyeglass lenses, greenhouses, and even bulletproof glass. Polycarbonate has high optical clarity and ultraviolet-blocking ability, thereby making it suitable for outdoor and glazing applications (Wang *et al*. 2021).

Polycarbonate is strong, with an impact strength of approximately 600-900 J/m, much higher than glass and acrylics. Tensile strength is often between 55 to 75 MPa and stable at temperatures up to 135 °C without substantial degradation. It is also very resistant to chemical attacks but sensitive to specific solvents such as acetone. The water absorption rate is only at 0.2–0.4%; it works well in more humid surroundings. In addition, polycarbonate has flame-retardant properties that make it excellent for electrical and electronic housings. However, these advantages come with a disadvantage; its scratch-susceptibility and yellowing after some time when exposed to sunlight are disadvantages, although coating with UV can alleviate this situation. Its versatile properties make polycarbonate an asset across various industries. PC is a polymer composed of repeating units of carbonate groups, (-O-C(=O)-O-), linked by aromatic rings derived from Bisphenol A. Its basic structures consist of H, C, and O atoms with alternating C-O bonds in addition to aromatic rings that provide strength and stability to the polymer. Chemically, the repeating unit for the polymer is [-$C_{15}H_{16}O_2$-], which makes it rigid and resistant to heat. It can also be further thermally cracked into oil and other products by pyrolysis of polycarbonate.

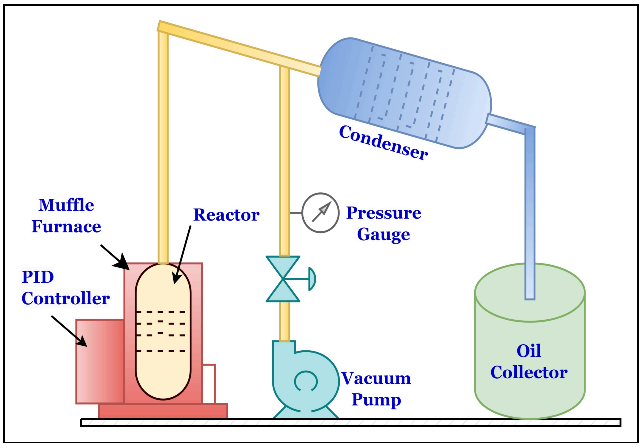

Fig. 1: Layout of pyrolysis setup

Pyrolysis of polycarbonate waste consists of heating plastic scrap in a reactor at varying temperatures between 300°C and 800°C, depending on the desired end product and type of plastic. This process happens without any oxygen, through the utilization of a gas or electricity-powered heating element to provide the right thermal degradation temperature. The effective heat transfer is usually done in a fixed-bed reactor configuration for a longer residence time of materials. Figure 1 represents the layout of pyrolysis setup. A muffle furnace with a variable range of up to 600°C, with a digital controller and thermometer, is considered for accurate temperature control. Low pressure is maintained by using a vacuum pump. The breakdown of polymer using catalysts such as zeolite, magnesium oxide, and silica enhances the reaction rate. Zeolite is used at a weight ratio of 1:4. Operation conditions are between 350°C and 550°C for about an hour. Yields are approximately 65% pyrolysis oil, 25% wax and char, and 10% gas. The processes allow the condensation and cooling of the pyrolysis products for further refinement for energy recovery or use as raw material (Zhang *et al*. 2023).

2.2. Magnesium Oxide Nanoparticle

Magnesium oxide nanoparticles can be added as a metal oxide nanomaterial with unique physical and chemical properties. This would greatly increase its value for various applications, such as fuel and combustion technologies. Typically cubic, MgO nanoparticles have an extremely high surface area of 50 to 150 m^2/g, and demonstrating strong thermal stability up to the temperature above 1000 °C. Their high melting point in the range of 2852 °C and excellent chemical stability, combined with outstanding thermal conductivity around about 60 W/mK, renders them suitable for use under elevated temperature conditions. MgO nanoparticles are also reported to be catalytically active in providing combustion-supporting activity and their capability for impurity adsorption, such as sulfur and carbon residues, that could benefit fuel-based applications (Farouk *et al*. 2024). For this research, the MgO nanoparticles was purchased from Nano Research Lab, Jharkhand, India.

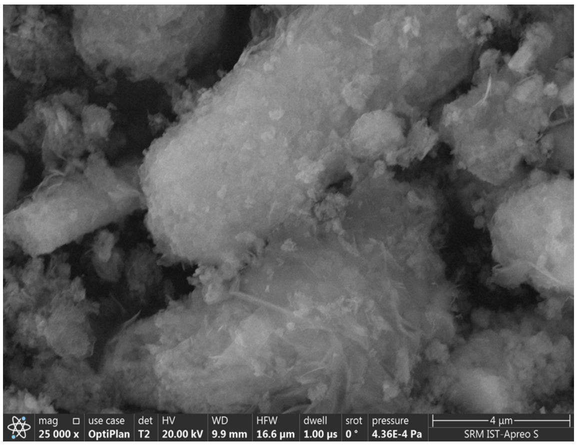

Fig. 2: SEM image of MgO

The SEM image of MgO (Fig. 2) showed clear morphological characters that exhibit the material's surface structure and particle distribution. Edge detection analysis yielded well-defined boundaries of each particle, plus a granular texture that suggested a uniform morphology with probable agglomeration. It indicates that the crystalline aspects are substantial for acting as a catalyst, and adsorption properties in the MgO sample were observed. The average particle size in equivalent diameter is 11.62 µm, and the median is 5.17 µm. The distribution suggests a range of particle size, with a significant contribution of smaller particles causing further reduction of the median size. In the combustion of fuels in engines, MgO nanoparticles play a major role. In the form of very small concentrations smaller than 0.1% and larger than 0.02% by weight added to fuel, MgO nanoparticles improve the combustion process by favoring more complete oxidation of hydrocarbons. Fuel-air mixing occurs better when the speed and efficiency of combustion increase. However, the results from the engine test, on the other hand, showed 5–10% greater brake thermal efficiency and up to 7% decreased fuel consumption during the use of MgO nanoparticles. These also decrease pollutants' harmful emissions, such as CO, HC, and NOx by 10–20%, which implies a more complete combustion process, thus making MgO nanoparticles a very important additive towards achieving cleaner and more efficient engine performance (Vinayagam *et al*. 2021).

2.3. Experimental Details

The experiment was conducted with a single-cylinder direct injection water-cooled diesel engine, which exhibited a maximum power output of 4.4 kW. The engine was coupled to the eddy current dynamometer to ensure it could be loaded from zero to maximum under four loading scenarios. In the test run with normal diesel, the test engine was allowed to run for such a period as it would take it to stabilize at 210 bar of pressure. The emission gas analyzers were used to measure the parameters of exhaust emissions. Hence, the data collected by the engine data collection system will be based on the parameters of the engines and the gas analyzer to determine their performance. This paper discusses the performance and emission characteristics of a diesel engine running on fuel recovered from polycarbonate (PC) plastic waste. The key properties of the recovered fuel are tabulated in Table 1.

Table 1. Properties of polycarbonate and diesel fuel

Property	PC100	Diesel
Calorific Value (MJ/kg)	40-42	42-45
Density (g/cm^3)	0.80-0.85	0.83-0.87
Viscosity (cSt at 40°C)	2.5-3.5	2.0-4.5
Cetane Number	45-50	47-55
Flash Point (°C)	50-60	52-96
Carbon (C)	75–80%	84–87%
Hydrogen (H)	5–7%	13–16%
Oxygen (O)	15–20%	-

This investigation aims to convert polycarbonate waste plastics into a Polycarbonate Plastic Fuel (PC) fuel through catalytic pyrolysis. The two test fuels formulated include PC20, a blending of 20% PC and 80% diesel on volume fraction, and PC 100%, which is 100% polycarbonate plastic fuel. To enhance the performance of the PC20 blend, the blend was incorporated with MgO nano-additives at concentrations of 50 ppm and 100 ppm. The testing fuel blends were formed as PC20nP50 (80% diesel, 20% PC, and 50 ppm

MgO) and PC20nP100 (80% diesel, 20% PC, and 100 ppm MgO). The fuel blend preparation was made through an ultrasonication process, assuring a homogeneous nano blend. In the process, surfactant sodium dodecyl sulfate (SDS) was added to stabilize the fuel blends. The ultrasonication bath was operated at 60 minutes to develop an essential blend of 20% PC and 80% diesel. Finally, further homogenization was achieved with an ultrasonication device of 20 Hz for 30 minutes. In the case of fuel PC20nP50, the addition of graphite nano-additives was done maintaining concentrations of 50 ppm (100 mg/l), with coupled surfactant SDS of 0.5% by weight, and it was stirred at 60°C for 30 minutes to remove residual water. The other fuel blend, PC20nP100 formulation, was made by dispersing 100 ppm of the nano-agent graphite into the essential blend using the same ultrasonication and stirring procedures.

The experiments were conducted on a single-cylinder diesel engine at various loads. Parameters investigated include brake thermal efficiency (BTE), specific fuel consumption (SFC), and exhaust emissions by carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). The present investigation is an endeavor to show the viability of cleaner energy solutions as a contribution to the diverse goals of sustainable development targeting the problems of plastic waste and establishing green fuel alternatives.

3. RESULTS AND DISCUSSION

3.1. Brake Thermal Efficiency

Fig. 3 presents brake thermal efficiency (BTE) comparing diesel with blends of plastic fuel enhanced with magnesium oxide nanoparticles. The blends of PC20 and PC100 showed a high rate of reduction of BTE with increased engine load. PC20 reduces BTE at a modest rate of 3% to 4.5%, while PC100 drops BTE dramatically in the 10-15% range. This decrease in BTE is probably due to the poor combustion characteristics of plastic waste oil compared to diesel fuel. Plastic waste oil generally has poor calorific values and higher viscosities, which may result in incomplete combustion and lower BTE. On the contrary, BTE improved when MgO nanoparticles were incorporated into the PC20nP50 and PC20nP100 formulations. For lower loads, BTE increased dramatically by up to 2.5% for PC20nP50 and less for the PC20nP100 formulation to as much as 0.42%. These effects are greatly alleviated by adding MgO nanoparticles to the fuel. These improve the ignition characteristics and enhance overall combustion efficiency, particularly in the engine's lower loads. The surface area of the nanoparticles is huge; therefore, increased fuel atomization enhances the combustion process. The MgO nanoparticles facilitate combustion and act as a catalyst by improving the overall characterization, reducing activation energy for combustion, and promoting complete combustion at a lower temperature (Ulagarjun *et al.* 2024).

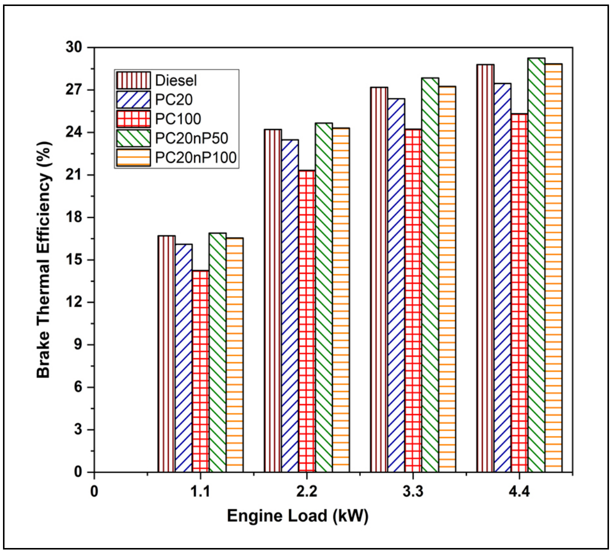

Fig. 3: Effect of MgO on of thermal efficiency

3.2. Specific Fuel Consumption

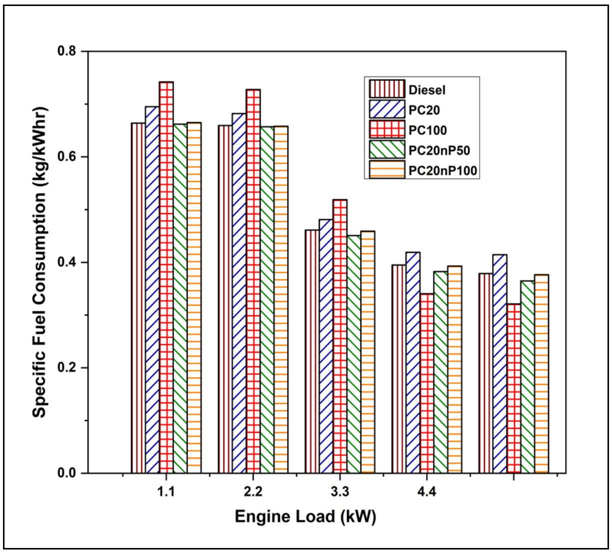

Fig. 4: Effect of MgO on of fuel consumption

Fig. 4 shows SFC data for fuel blends containing diesel and enhanced with MgO nanoparticles. For both the PC20 and PC100 blends, the SFC increases at all engine loads, while the PC100 blends' SFC has a significantly higher value. One should expect it because plastic waste oil has a lower calorific value and poorer combustion characteristics than the selected diesel fuel. PC20 has a relatively flat curve increasing SFC from 3.5% to 9.5%, whereas PC100 has much higher load with maximum SFC values reaching up to 15.5%. The higher values of SFC for PC100 mean that a greater quantity of fuel must be supplied to yield the same power output as is required for diesel, and this increases the magnitude of the destructive effects of using plastic waste oil solely on the efficiency of combustion. For PC20nP50 and PC20nP100 blends, adding MgO nanoparticles lowers SFC values since their values are less than those of PC20. Although both nanoparticle-enhanced blends remain with reduced SFC, PC20nP50 shows a more significant reduction in SFC values as low as 3.8%. On the other hand, PC20nP100 lowers SFC but with much lower efficacies ranging between 0.6%. The reduction of SFC in nanoparticle-reinforced blends suggests that for the same power output, fuel consumption is reduced because combustion efficiency is increased. Nano-enhanced fuels have stronger ignition properties that lead to a better atomization, faster combustion, and less fuel consumption (Yaqoob *et al.* 2024).

3.3 Hydrocarbon Emissions

Higher hydrocarbon emissions are another indication of partially combustion, and thus the higher levels, the more inefficient the combustion as well as the venting of unburned fuel. In the PC20 blend, HC emissions are steadily higher than diesel emissions of 5 to 6.7%, as shown in Fig. 5.

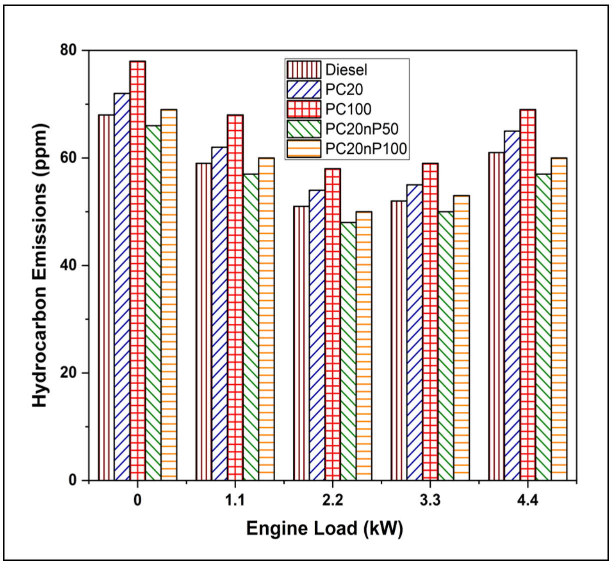

Fig. 5: Effect of MgO on of hydrocarbon emissions

This increase suggests that plastic fuel blends cannot burn completely and for other reasons as well, such as lower volatility and higher viscosity than diesel. HC emissions are enhanced even more by PC100. Results may increase to 15.5%, showing serious combustion inefficiencies when pure plastic waste oil is used as fuel. However, the inclusion of MgO nanoparticles prominently reduces HC emissions in the PC20nP50 and PC20nP100 blends. Therefore, PC20nP50 significantly shows reductions in HCs at increased engine loads, which can reach a maximum of 6.6%. This decrease indicates that the MgO nanoparticles enhance higher burn efficiency, possibly because the nanoparticles act as catalysts for hydrocarbon chain fragmentation and thus enhance overall combustion. PC20nP100 also has reduced HC emissions, although its values vary erratically between positive and negative depending on the engine load. The emissions of HC have increased by a small percentage at lower loads of the engine, up to 1.9%, while at higher loads, it decreased by 1.6%. Whereas plastic fuel increases HC emissions due to incomplete combustion, adding MgO nanoparticles reduces these emissions. Thus, it portrays the role played by nanoparticles in enhancing the combustion process and reducing the production of unburned hydrocarbon in alternative fuel mixtures (Ganesan *et al.* 2017).

3.4 Carbon Monoxide Emissions

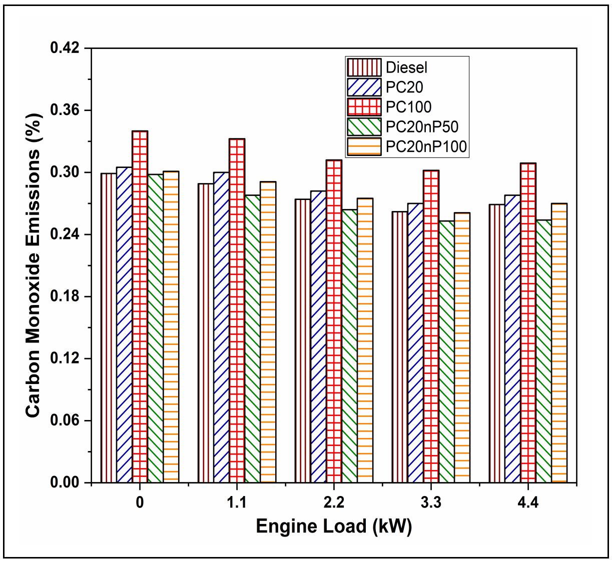

Fig. 6: Effect of MgO on of carbon monoxide emissions

Incorporating MgO nanoparticles tends to decrease CO emissions in the PC20nP50 and PC20nP100 blends. CO emissions in PC20nP50 significantly decrease, especially at higher engine loads, with the reduction going as high as 5.6%, as shown in Fig. 6. MgO nanoparticles have a high surface area with strong thermal stability, thereby enabling them to speed up the breakdown of hydrocarbons in the fuel at lower temperatures. This improved oxidation process ensures that most of the carbon in the fuel is oxidized into carbon dioxide (CO_2) rather than becoming carbon monoxide, a by-product produced from incomplete combustion. By improving fuel combustion efficiency and ensuring the complete oxidation of carbon-containing compounds, MgO nanoparticles inhibit the formation of CO, thus producing cleaner emission gases and furthering efforts to attain strict emission standards. CO emissions in the PC20 blend are steadily higher than diesel emissions of 3.8%. That elevation indicates that plastic fuel blends cannot be burned completely and certainly for other reasons as well, such as lower volatility and higher viscosity than diesel. CO emissions were considerably elevated by PC100. On average, results could go up to 14%, showing serious combustion inefficiencies when pure plastic waste oil was used as fuel (Chinnasamy *et al.* 2019).

3.5 Oxides of Nitrogen Emissions

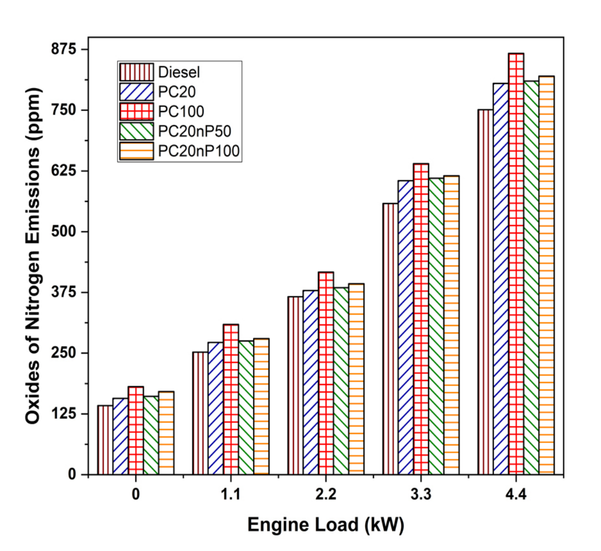

Fig. 7: Effect of MgO on of nitrogen oxides emissions

The NOx emissions for PC20 are augmented above the diesel emissions, with the highest increases happening at low engine loads. This increase should be ascribed to the combustion characteristics related to plastic waste oil, which cause higher peak combustion temperatures. These have been identified as a major source of NOx. PC100 has exacerbated the NOx emissions by augmenting them to a value of 27%, as shown in Fig. 7. Such a steep increase indicates that combustion temperatures are remarkably high when pure plastic waste oil is used, and hence NOx emissions show a considerable increase. NOx Emissions When the MgO nanoparticles are incorporated into PC20nP50 and PC20nP100, NOx emissions are more complicated. NOx of PC20nP50 is higher than that of PC20 by 5% to 14%. This NOx increase could be caused by better combustion efficiency that raises peak temperatures, which can increase NOx formation. PC20nP100, although continues to increase NOx emissions, has somewhat more controlled values that extend between 7% and 21%. Although higher than in PC20, such values indicate that combustion may stabilize the nanoparticles to some extent, reduce the peak temperatures, and control the formation of NOx. Adding these nanoparticles contributes to higher NOx emissions from higher temperature flames (Mustayen *et al.* 2023).

4. STUDY OF CO AND HC EMISSIONS

The design-of-experiments approach was followed to analyze the contour plot for engine load in kW and concentration of nP (MgO nanoparticles). The three levels considered for engine load were 0, 2.2, and 4.4 kW, while three concentrations of nP-MgO nanoparticles were 0, 50, and 100 ppm. Experimental blends were prepared in all three cases by using PC20 as a base material. This approach allows one to evaluate the interactions between load and nanoparticle concentration with HC and CO emissions in great detail and of significant value in achieving optimized fuel formulations for reduced emissions. With increasing engine load, carbon monoxide emissions reduce, as signified by the shift in the color gradient from yellow-green at lower loads to blue at higher loads, as shown in Fig. 8 (a & b).

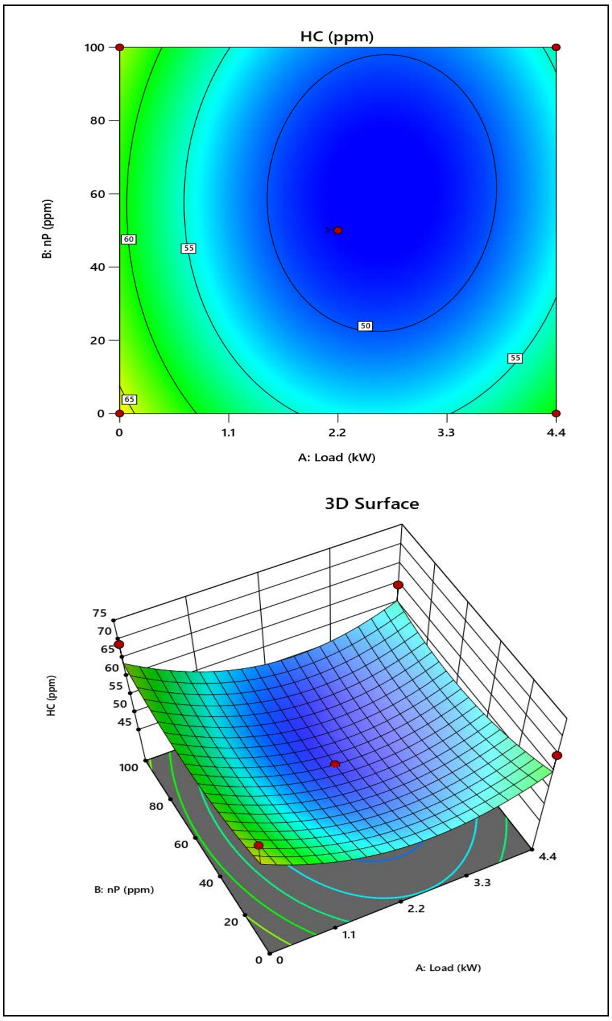

Fig. 8: Influence of MgO and Load on HC emissions

Higher loads enhance air and fuel mixing and combustion efficiency, consequently decreasing CO production, a product of incomplete combustion. Due to their catalytic properties, the addition of nano-additives nP-MgO reduces CO even further at 100 ppm. These nanoparticles are oxygen carriers, improve oxidation, and ensure the complete oxidation of carbon-based intermediates to CO_2 rather than CO. Moreover, the high surface area allows a more effective interaction with combustible reactants, thereby stabilizing the flame and reducing localized oxygen deficiency, a prime cause of CO formation. The curves indicate a gradual fall in the values of CO emissions obtained while the load is raised from 0 to 4.4 kW, with the lowest values realized at higher loads and higher nano-additive concentrations. This trend is further emphasized by the 3D surface plot that demonstrates a constant declining curve in the value of CO emissions with increasing load and nano-additive concentration. The downward slope in the surface plot suggests that the nanoparticles improved the catalytic effect for fuel oxidation, increased the transfer of heat, and increased flame propagation, making combustion more efficient and thus resulting in less harmful emissions such as CO. Using nP-MgO nano-additives consequently significantly enhances combustion efficiency and lowers CO emissions, proving their possible application in alternative fuel blend engines.

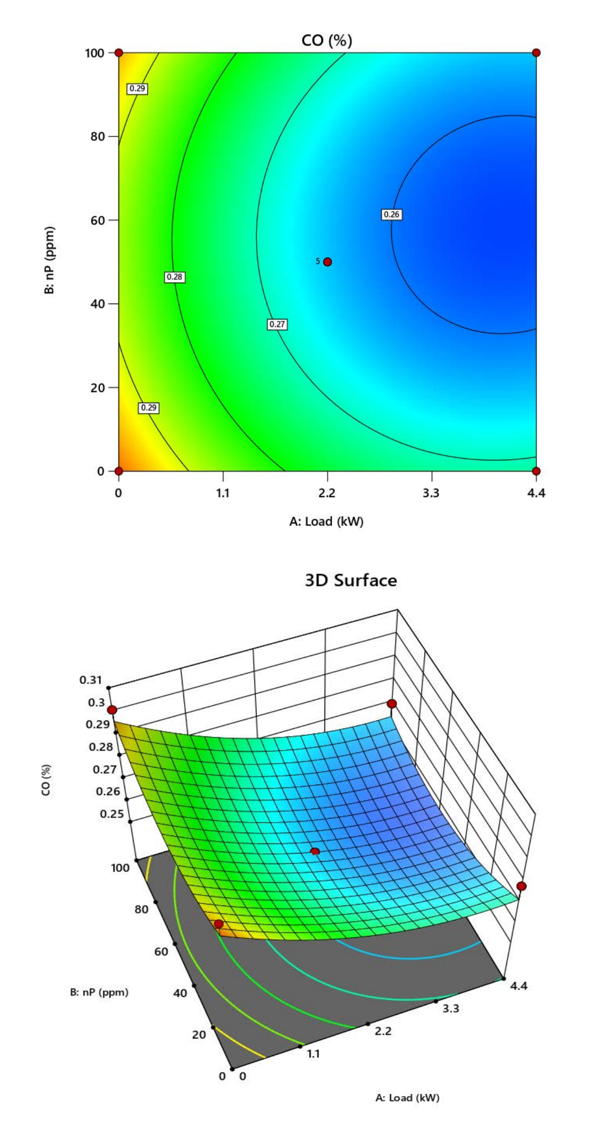

Fig. 9: Influence of MgO and Load on CO emissions

The contour plots, as shown in Fig. 9 (a & b), indicate a reasonable reduction in HC emissions with an increase in engine load from 0 to 4.4 kW. Loads lower than this, especially at 0 kW, are observed peaking at around 65 ppm through the yellow area of the plot. It also appears reasonable that combustion is less efficient and that some fuel will burn incompletely in low-load conditions. In the range of moderate and heavy loads of 2.2 to 4.4 kW, the HC emissions sharply decrease toward an average value at the center of the plot near 50 ppm. A sharp decrease might indicate improved combustion chamber conditions, reflecting a higher extent of hydrocarbon oxidation. Additionally, the effect of nP-MgO nano-additives can be revealed in the plot. HC emission at higher concentrations of nanoparticles (100 ppm) is significantly reduced. Nano-additives enhance combustion by acting as oxygen carriers and by enhancing fuel-air mixing. The catalytic activity of nP-MgO facilitates the more extensive propagation of flames, allowing for more complete combustion with fewer hydrocarbons leaking out through exhaust. The plot demonstrates that the increase in the engine's load and the concentration of the nP-MgO nano-additives significantly reduces the HC release. A decrease in emissions will be an affirmative response to improvements in combustion efficiency, as emissions are released due to the oxidation process and catalytic properties of the nano-additives, which reduce the products of incomplete combustion of hydrocarbons.

5. SUSTAINABILITY IMPROVEMENT

One promising pathway to environmental sustainability, eliminating plastic waste and reducing dependence on fossil-based fuels, is converting PCs into alternative fuels. Polycarbonate is used primarily in packaging, electronics, automotive components, and construction elements. It contributes significantly to a large share of landfill wastes, which would take many centuries to decompose. Pyrolysis resolves this problem, as this waste is decomposed into valuable hydrocarbons for use as fuels or chemical feedstock, thus reducing plastic pollution and producing useful energy. Catalytic pyrolysis, using materials such as zeolite, enriches fuel quality and yield, making the process much more efficient and lowering energy input. It complies with the principles of a circular economy, in which materials are recycled instead of being thrown away. As the fuel is derived from polycarbonate, there are sustainability opportunities in which this fuel leads to reduced emissions of greenhouse gases, especially when compared to fossil fuels. The pyrolysis-derived fuel is relatively cleaner and has less sulfur content, which lowers the emission levels of harmful pollutants such as sulfur and nitrogen oxides. However, its general sustainability is critically tied to optimizing energy requirements and emissions during the process. Further integration with renewable energy sources would uplift its environmental appeal as a feasible waste management and alternative fuel solution (Faisal *et al.* 2023; Vlasopoulos *et al.* 2023).

In this regard, adding MgO nanoparticles to fuels has become essential to reducing harmful emissions in combustion engines. In addition to the above-mentioned effects as combustion catalysts, MgO nanoparticles increase fuel oxidation, thus enforcing complete combustion and achieving a considerable reduction in hydrocarbons and carbon monoxide emissions. During its engine tests, the respective HC and CO emissions reductions were noted between 3% and 7%. These reductions translate to achieving global sustainability targets under the Paris Agreement. Incorporation of MgO nanoparticles into fuel systems supports cleaner combustion, meets stricter emission standards, and reduces the environmental impact associated with transportation and industrial processes while contributing to sustainability goals envisioned for the use of polycarbonate-derived fuels (Modi *et al*. 2024; Pullagura *et al*. 2023). This research investigated the performance and emission characteristics of polycarbonate fuel blends added with MgO nanoparticles in a stationary single-cylinder diesel engine. At low loads, the engine efficiency for the PC20nP50 blend was 2.5% greater than diesel's, indicating improved combustion efficiency. The SFC was determined to be lower by 3.8% for diesel fuel in PC20nP50 evaluation, thus indicating good fuel economy. It can be considered safe as it enhances fuel utilization without compromising engine performance. Emission results showed a 6.6% reduction in hydrocarbons and a 5.6% reduction in carbon monoxide compared to diesel emissions; both fall well within the safe limit and signify more complete combustion. However, with a 5%–14% increase in NOx emissions, that can be optimized in future studies using advanced after-treatment technologies. The study confirms the safe use of the proposed blend for stationary engines, and real vehicle applications can be extended for future work.

6. CONCLUSION

Millions of tons of plastic waste are now being disposed of, posing an ever-increasing and serious environmental threat. Traditional waste handling, landfilling, and incineration methods proved inadequate and, sometimes, led to more pollution. The possibility of using pyrolysis to convert plastic into alternative fuels offers a solution to this plastic pollution and reduces dependence on fossil fuels. In this study, the feasibility of polycarbonate plastic waste as a potential alternative fuel source would help address the increase in plastic waste while overcoming dependence on fossil fuels. The MgO nano-additives added to the recovered fuel resulted in significant performance and emissions improvement for the engine. In general, the blends, especially PC20nP50 and PC20nP100, showed improvements in thermal efficiency of up to 2.5% at lower engine loads and significant decreases in SFC values down to about 3.8%. The PC20nP50 shows remarkable decreases in hydrocarbon emissions to 6.6% at higher engine loads and carbon monoxide emissions that decreased as much as 5.6% at elevated loads. In addition to the general sustainability goals of the Paris Agreement, such improvements also lead to cleaner combustion and tighter emission standards or, in a broader context, a reduced environmental footprint for transportation and industrial processes. Overall, the results suggest the potential of fuels derived from polycarbonate with MgO nanoparticles toward sustainable solutions for waste plastic and enhanced energy security.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest regarding the research, authorship and/or publication of this article.

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