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Performance, Emission, and Combustion of an HCCI Engine Fueled with Tire Pyrolysis Oil–methanol–diesel Nano-blends

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ABSTRACT

The elements of old tire piles have caused environmental pollution, and fossil fuels are decreasing rapidly, which makes it a necessity to find a sustainable alternative fuel for internal combustion engines. The current study experimentally investigated the performance, emissions and combustion behavior of a hybrid nano additive blended tire pyrolysis oil (TPO)–methanol–diesel fueled HCCI engine. Mixtures of fuel blends (20% TPO, 20% methanol, and 60% diesel) were prepared and were added with cerium oxide (CeO_2), copper oxide (CuO), and nickel oxide (NiO) nanoparticles as 5, 10, and 15 ppm concentrations. To keep the nanoparticles in a well dispersed suspension, they were sonicated using an ultrasonic liquid processor. The experimental data show a significant improvement in the combustion and engine performance by the addition of the nanoparticles. The optimum brake thermal efficiency recorded for the blend with 15 ppm CeO_2 was nearly 36% at full load. This improved approximately 9% on neat diesel and 12.5% on pure TPO. Reduction in brake specific fuel consumption (in comparison to diesel operation) was nearly 17% The nano additives improved the air-fuel mixing and oxidation, as emission analysis showed big reductions in unburned hydrocarbons, carbon monoxide and smoke opacity. Combustion analysis indicated that nano-enhanced blends exhibited higher peak cylinder pressure and heat release rates close to top dead center, thereby validating that they had a faster and more complete combustion process. However, with a relatively higher dosage of the nano additives, nitrogen oxide emissions increased marginally as a result of higher combustion temperature. This systematic analysis indicates that TPO–methanol–diesel nano-blends can enhance the efficiency and reduce principal emission in HCCI engine. This indicates that they could be a sustainable substitute for conventional diesel fuel from waste.

Keywords: Tire Pyrolysis Oil (TPO); CeO_2 nanoparticles; HCCI engine; Alcohol blends; CuO nanoparticles, NiO nanoparticles.

1. INTRODUCTION

The search for eco-friendly and long-lasting alternatives in the transportation industry is even more crucial now that the world's need for energy is expanding and fossil fuel resources are running out. One of the current ideas that has gained attention is making energy from waste. Waste tire pyrolysis oil (TPO) is a smart alternative since it might help with difficulties that come up when tires are thrown away and it could also help cut down on the consumption of fossil fuels (Ramalingam *et al.* 2020; Janaki, *et al.* 2025)

As a result of the requirement for internal combustion engines to be more efficient and produce less pollution, Homogeneous Charge Compression Ignition (HCCI) technology has attracted a lot of attention. The HCCI engines are different from other types of engines because they use both spark ignition and compression ignition systems to get the best of both. Consequently, they work better with less NO_x and particulate emissions. Ethanol and methanol count as low-viscosity alcohol fuels that help combustion and a lower level of emissions. However, they perform very poorly in engines and bring about a sequence of problems for fuels to coexist together (Kale and Krishnasamy, 2024a)

The critical challenge lies in regulating the onset of auto-ignition and the subsequent termination of combustion. Owing to the inherent operating principle of HCCI engines, these processes are governed predominantly by fuel chemistry and chemical kinetics. Consequently, modifications in fuel properties and combustion strategies directly influence ignition timing, combustion duration, and overall combustion behavior. Homogeneous Charge Compression Ignition engines also tend to offer more thermal efficiency than conventional spark ignition (SI) ones, as they can operate on low-mix fuels instead of relying on high-octane gasoline. (Kale and Krishnasamy, 2024b; Kale and Krishnasamy, 2024c)

In HCCI engines, a well-premixed and homogeneous air–fuel mixture is formed throughout the

combustion chamber, and ignition occurs via compression-induced auto-ignition rather than spark or direct fuel injection. The near-simultaneous combustion at multiple locations within the cylinder results in lower peak in-cylinder temperatures, thereby significantly reducing NO_x emissions and suppressing particulate matter (PM) formation. These engines have higher thermal efficiency, i.e., they can burn at more high compression ratios with a lighter fuel-air mixture density. Also, they are able to use different types of fuels such as gasoline, diesel, alcohol and so on. However, the practical application of HCCI engines remains limited due to the inherent difficulty in precisely controlling auto-ignition timing and heat release rates, despite their demonstrated advantages. The way HCCI burns is determined by fuel composition and thermodynamic conditions rather than by direct mechanical control. Recent research contributions overcome these limitations with intelligent fuel strategies, variable valve timing, intake charge management, and fuel additives loaded with nanoparticles to promote combustion stability. Compared to diesel, some of the fuel produces less thermal efficiency but nano additives such as CeO_2, MgO, and Al_2O_3 are always an effective improvement (Janaki, *et al.* 2025; Ansari *et al.* 2024). Blending low-carbon fuels with nanoparticles can not only improve brake thermal efficiency and reduce the carbon footprint, but other unexpected benefits may also result based on distribution ratio of it. These parameters represent direct measurements of combustion-related pollutants in the exhaust gas, where carbon monoxide is quantified as CO, unburnt hydrocarbons are reported as HC, and particulate emissions are expressed as PM. (Venu *et al.* 2024)

Injecting nano-additives, particularly carbon nanoparticles (e.g. graphene oxide, carbon nanotubes), into internal combustion engines has been found to improve combustion efficiency and lower the emissions. Additives in the fuel increase its reactivity and make it atomize better; as a result, peak cylinder pressure rises, heat release during combustion speeds up, and ignition lag decreases. CO, unburnt HC and smoke opacity will decline drastically. The incorporation of graphene oxide as an engine additive not only reduces friction arising from surface asperity interactions under boundary and mixed lubrication regimes, but also improves fuel economy while simultaneously lowering exhaust emissions. However, the effectiveness of such nano-additives is strongly dependent on optimal dosage, as excessive concentrations do not yield proportional benefits and may adversely affect performance. However, further research is needed in order to determine what effect these materials might have on engine parts and the environment over time. (Eslami *et al.* 2023).

CeO_2 nanoparticles have such remarkable catalytic activity that they are highly effective in controlling combustion and emissions. Their ability to store oxygen in a very efficient manner, their unique redox nature, and their ability to create oxygen vacancies all facilitate them to sustain fast oxygen exchange, which is essential for catalytic reaction. The nanoparticles could donate and deliver oxygen very effectively, especially when they are optimized in terms of doping, particle size and surface shape. They can be doped with certain elements in a way that enhances their ability to catalyze reactions, especially CO oxidation. (Anjanidevi *et al.* 2025).

For instance, CeO_2 nanoparticles are of great utility in soot combustion since smaller particles are more active due to having greater contact points. The nature of the specific crystallographic planes that exist on particle surfaces also determines how efficiently catalysis occurs. While their performance is promising, there remain challenges in optimizing CeO_2 nanoparticles for practical industrial application, with respect to their stability and scalability in real-world applications. (Singh *et al.* 2024)

Alcohol-TPO blends with carbon and silver nanoparticles have exhibited significant improvement in engine performance and emission control of exhaust. Incorporation of nanoparticles improves combustion properties, which results in perceptible improvement in brake thermal efficiency and decrease in brake-specific fuel consumption (BSFC). Particularly, silver nanoparticles are responsible for an acute increase in BTE, whereas carbon and TiO_2 nanoparticles have been observed to be beneficial regarding the efficiency of combustion as well as fuel consumption (Kale and Krishnasamy, 2024a). From the emission standpoint, the application of the nanoparticle-doped blends reduces the emissions of CO and HC lower than the standard fuels. But while overall emissions are reduced, in certain cases, there has also been a reduction in nitrogen oxides (NO_x) (Munimathan *et al.* 2025. This makes the importance of having the right fuel mix and engine calibration to provide the best compromise between enhanced performance and lowest emissions even more critical (Fu *et al.* 2023).

The innovation of this research is the blending of waste-derived tire pyrolysis oil with low-viscous alcohol fuels in an HCCI engine, boosted by CeO_2 nanoparticles, CuO, and NiO nanoparticles, presenting a novel strategy that blends waste-to-fuel conversion, nano-catalytic combustion control, and green fuel utilization to promote brake thermal efficiency while concurrently minimizing CO, HC, and particulate emissions.

The research measures the magnitude of nanoparticle addition in influencing combustion timing, efficiency, and characteristics of emission while the working conditions are varied. The study was conducted under a systematic experimental framework comprising fuel formulation, fuel characterization, and experimentation on the engine. The results will open the

way for TPO-type nano fuels as the environmentally friendly alternative solution for cleaner efficient combustion in the future automobile market. The study further compares the combustion-enhancing effects of CeO_2, CuO, and NiO nanoparticles to identify the most effective nano-catalyst for TPO-based HCCI operation.

2. MATERIALS AND METHODS

2.1 Fuel Preparation

2.1.1 Tire Pyrolysis Oil Extraction and Purification Steps

Tire pyrolysis oil, or TPO, results from the pyrolysis of used tires and plastic. It can substitute industrial diesel and furnace oil as fuel in heavy industries such as steel, cement, and boiler industries. TPO has a calorific value of 10592.48 kcal/kg, which is higher compared to that of coal. It is comparable to grade 6 fuel oil. Tables 1 and 2 show the differences between HCCI-1-BD and HCCI-1-biofuel + alcohol fuels. Table 3 lists the parts that make up TPO. Cutting the car tire was the initial process. The chips of the tire were washed and dried and placed on the pyrolysis reactor unit for mild metal pyrolysis. The pyrolysis reactor produces a vacuum and then 1.5 kW heaters warm up the exterior of the reactor. The process was conducted in the reactor for two and a half hours at temperatures ranging from 450 to 650 °C. Approximately 2.09 kg of scrap tire feedstock, containing 40–45 wt.% oil, was required to produce 1 kg of tire pyrolysis oil, with an estimated heat input of about 7.8 MJ kg^{-1} for the conversion of waste tires into usable products. The obtained TPO was subsequently charged into the reactor of the TPO refining unit. Heating was carried out under oxygen-deficient conditions, during which the TPO progressively vaporized as the temperature increased. Fractional separation was achieved based on the different boiling ranges of the hydrocarbon components. Lower-molecular-weight hydrocarbons remained in the gaseous phase, while condensed oil vapors passed through the cooling system, where diesel-range fractions liquefied. Non-condensable gases remained in the gaseous state, and the condensed diesel fraction was collected separately. Fig. 1 illustrates the process of pyrolysis (Anjanidevi *et al.* 2025). Table 1 shows the composition of TPO blends, Table 2 shows the property of base fuels and Table 3 shows the fuel nomenclature.

2.1.2 Preparation of Fuel Blends

The underlying drawbacks of neat TPO under HCCI operation was addressed by blending methanol and diesel with tire pyrolysis oil. Methanol is a low viscosity, oxygenated fuel that enhances fuel–air uniformity and facilitates complete oxidation during combustion, ultimately leading to lower soot and unburnt hydrocarbons. But the cetane number of methanol is very low and its auto–ignition temperature is quite high, which makes a poor combustion stability when used by itself. Hence, diesel remained in the blend to improve ignition quality, ensure reliable auto-ignition and stabilize combustion phasing in HCCI mode. This means methanol and diesel mixture complementary together with TPO representing a rational fuel formulation bettering mixture preparation, combustion stability, and comprehensive engine performance.

Table 1. Composition of TPO

Compound	Percentage (%)	Compound	Percentage (%)
Carbon	85.6	Sulphur	1.4
Hydrogen	10	Ash	NA
Nitrogen	0.4	Oxygen	2.5

Table 2. Properties of base fuels

Property	Diesel	TPO	Methanol
Density (kg/m³)	820	910	791
Cetane Number	48.5	<45	5–8
Lower Heating Value (MJ/kg)	42.3	38.15	19.9
Viscosity (cSt at 40 °C)	2.87	3.35	0.59
Flash Point (°C)	78	49	11
Pour Point (°C)	-6	–	–97
Sulphur (% wt.)	0.45	0.95	0
Hydrogen (% wt.)	12.95	10.47	12.6
Nitrogen (% wt.)	0.65	–	0
Oxygen Content (% wt.)	~0	~0–2	49.9
Auto-Ignition Temp (°C)	210	~250–300	470
Stoichiometric A/F Ratio	14.5:1	~14.7:1	6.4:1

2.1.2.1 Ultrasonication of Nanoparticle Additives

To achieve effective mixing, the fuel and nanoparticles were ultrasonicated together (Fig. 2). This is a technique typically applied in nano fuel preparation as it is effective in disintegrating Van der Waals force-aggregated nanoparticles, thereby forestalling agglomeration and providing a uniform suspension. Achieving a good suspension is important as the additives should be well distributed in the fuel in response to achieving sustained catalytic activity during combustion.

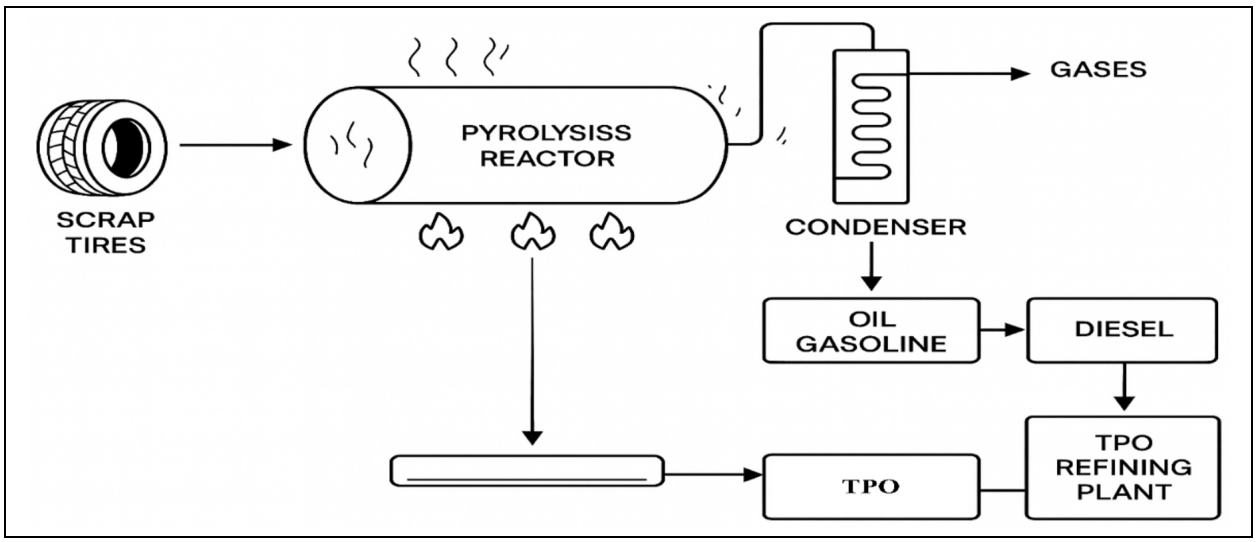


Fig. 1: Pyrolysis process

Table 3. Fuel nomenclature

Fuel Code	Blend (by vol. %)	Description
D100	Diesel 100%	Neat diesel (baseline)
TPO100	Tire Pyrolysis Oil 100%	Neat TPO (waste-derived pyrolysis oil)
TPO20M20D60	TPO 20% + Methanol 20% + Diesel 60%	Base ternary blend (no additive)
TPO20M20D60-C5	TPO 20% + M 20% + D 60% + 5 ppm CeO_2	Ternary blend + 5 ppm CeO_2 nanoparticle additive
TPO20M20D60-C10	TPO 20% + M 20% + D 60% + 10 ppm CeO_2	Ternary blend + 10 ppm CeO_2 nanoparticle additive
TPO20M20D60-C15	TPO 20% + M 20% + D 60% + 15 ppm CeO_2	Ternary blend + 15 ppm CeO_2 nanoparticle additive

In the current study, nanoparticles (CeO_2, CuO, and NiO) were added into TPO–alcohol–diesel fuel mixtures with 5, 10, and 15 ppm by weight. These mixtures were sonicated in a probe-type ultrasonication system at a frequency of around 20 kHz, for 30 to 60 minutes. The higher frequency ultrasonic waves generate cavitation bubbles in the medium, and, during collapse, the bubbles generate steep turbulence and shear forces. These forces distribute the nanoparticles in groups and lead to equal distribution into the fuel.

During extended ultrasonication, the temperature of the fuel was continuously monitored to prevent overheating, as excessive thermal input could alter fuel properties and compromise suspension stability. When appropriately controlled, ultrasonication yielded a uniform and stable nanofuel dispersion with no observable sedimentation. The resulting stability permitted immediate and reliable evaluation of engine performance under consistent operating conditions. Table 4 shows the calculated properties of the fuel blends used in the experiment. (Anjanidevi *et al.* 2025).

Table 4. Calculated fuel properties

Property	Diesel	TPO	Methanol	TPO20 M20D60 (base)
Density	820	910	791	832.2
Cetane number	48.5	<45 (≈44)	5–8 (≈6.5)	39.5
Lower Heating Value (LHV)	42.3	38.15	19.9	37.13
Viscosity (@40 °C)	2.87	3.35	0.59	2.54
Flash point	78	49	11	58.9
Pour point	-6	NA	-97	NA
Sulphur (% wt.)	0.45	0.95	0	0.47
Hydrogen (% wt.)	12.95	10.47	12.6	12.34
Nitrogen (% wt.)	0.65	NA	0	0.38
Oxygen (% wt.)	~0	~0–2 (≈1.0)	49.9	9.7
Auto-ignition temperature (°C)	210	~250–300 (≈275)	470	273.6
Stoichiometric A/F ratio	14.5:1	~14.7:1	6.4:1	NA

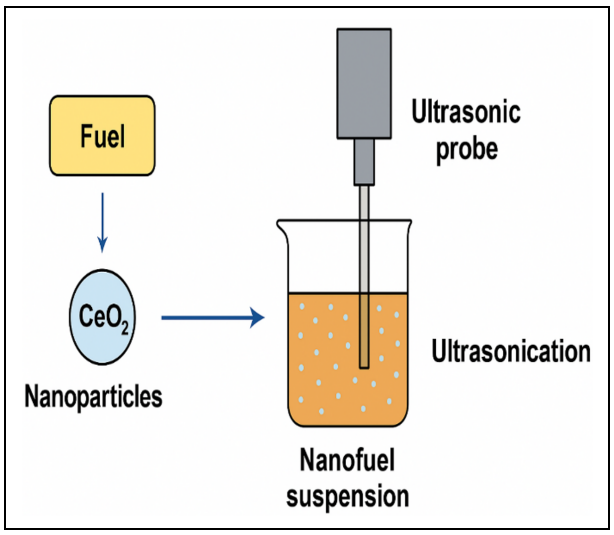


Fig. 2: Ultrasonication of the nanoparticles in the fuel

2.1.2.2 Calculated Properties of Fuel Blends

2.2 Engine Specification and Nomenclature

2.2.1 Schematic Layout of the Engine Set Up

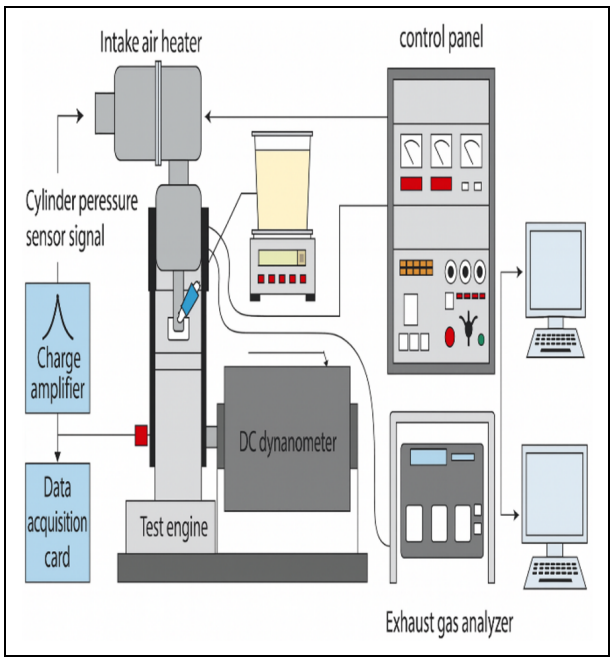


Fig. 3: Schematic layout of the engine

The test setup was a four-stroke, direct-injection, single-cylinder diesel engine powered through an eddy current type dynamometer to generate different loading conditions. The CI engine was driven in the HCCI mode and was equipped with all the sensors needed in this investigation, referring to in-cylinder pressure and crank-angle position measurement. The overall experimental test bed arrangement was schematically provided in Fig. 3.

The engine was in a dual fuel mode. The primary fuel was delivered by a dedicated primary fuel tank by a high-pressure fuel injection system, and the secondary fuel (pentanol) was supplied separately into the intake manifold. The gas injector was controlled by a digital control unit, and injector opening was synchronized using an infrared indicator, connected through an electronic control unit. This provided strict control and precise fueling over the secondary fuel fraction. The quantity of pentanol inducted into the intake manifold was systematically varied to investigate its influence on HCCI combustion characteristics.

The system employed a data acquisition card and a charge amplifier to measure combustion and monitor engine performance and acquire cylinder pressure traces in real time. The HC, NO_x, CO, and CO_2 exhaust emissions were observed by a multi-gas analyzer via the exhaust manifold. The exhaust gas soot concentration or opacity was obtained by a smoke meter.

Table 5. Specifications of the engine

Parameter	Specification
Rated power	5.2 kW
Cylinder bore (diameter)	87.5 mm
Stroke length	110 mm
Compression ratio	17.5:1
Orifice diameter	20 mm
Dynamometer arm length	185 mm

The engine specifications are summarized in Table 5. During measurement, a few instruments were used in obtaining physical quantities, thus introducing sources of random error by virtue of instruments' limitation, changes in the environment, and human operation. To account for it, uncertainty analysis was performed. The method involved taking 4 or 5 readings in every measurement, from which a reliable average was calculated, and the range in precision was obtained through procedures in established analysis. This ensured experimental results obtained had specified confidence limits and high accuracy.

2.3 Synthesis of Nano Particles (Sol Gel Method)

In this study, CeO_2, CuO and nickel oxide NiO nanoparticles were chosen because these metal oxides have different but complementary catalytic characteristics that affect combustion. The high oxygen storage capacity and oxygen release property characteristics of CeO_2 nanoparticles through the reversible Ce^{3+}/Ce^{4+} redox cycle facilitates oxidation of carbon monoxide and unburned hydrocarbons. With an excellent catalytic effect of the CuO nanoparticles towards oxidation and considering the high thermal conductivity characteristics of the CuO nanoparticles, it

can be concluded that CuO nanoparticles facilitate the improvement of the heat conduction and accelerate the combustion kinetics of the propellant. NiO nanoparticles promote fuel decomposition reactions and promote flame propagation by rapidly facilitating oxidation processes. This study, in conjunction with recent work, provides a comparison of catalytic mechanisms of different metal oxide nanoparticles on HCCI combustion performance and emissions.

Sol–gel nanoparticle synthesis was carried out through controlled manipulation of chemical parameters to obtain homogeneous and fine nanomaterials. Appropriate chemical precursors, such as metal alkoxides or metal salts, were dissolved in a suitable solvent (water or alcohol) to form a homogeneous solution. The solution was then subjected to hydrolysis and condensation reactions, with or without catalysts, under controlled pH and temperature conditions to generate a colloidal sol. Continued aging of the sol facilitated nucleation and growth of nanoparticles within the developing gel network. The resulting gel was processed to separate the nanoparticles by centrifugation or filtration, followed by repeated washing to remove residual impurities. The isolated nanoparticles were subsequently dried and, when required, calcined at elevated temperatures to enhance crystallinity and phase purity. Fig. 4 illustrates the overall nanoparticle synthesis process.

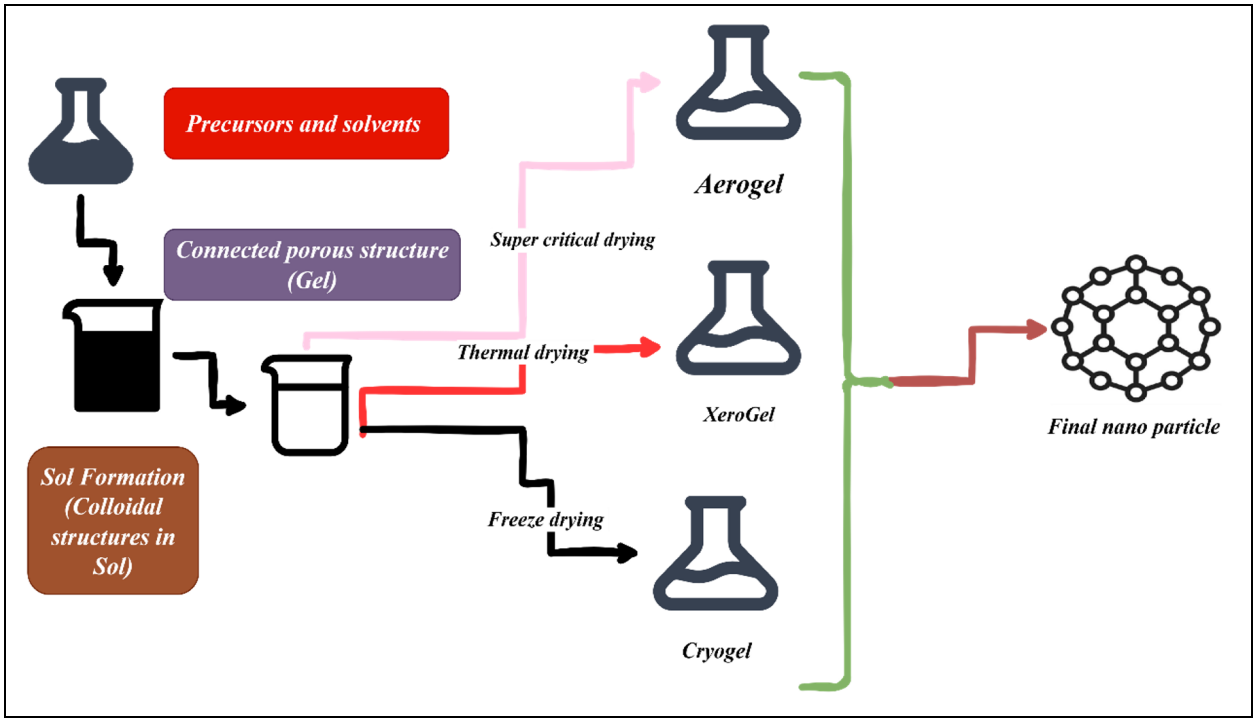


Fig. 4: Nano particle synthesis process

3. RESULTS AND DISCUSSION

3.1 Performance Parameters

Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) are the two most significant factors that influence the extent to which an engine operates well. Diesel engines usually have higher BTE and lower BSFC because they have more calorific value. On the other hand, biodiesel and its blends usually have slightly lower BTE and higher BSFC because they have lower heating values and higher viscosity. Plant-based alternative biofuels inherently contain oxygen, which enhances combustion efficiency and helps compensate for thermal losses within the engine. The addition of hydrogen or nano-additives further promotes improved combustion characteristics, resulting in higher BTE and lower BSFC. Consequently, BTE and BSFC exhibit a strong inverse relationship, as enhanced combustion generally leads to improved fuel economy and increased overall engine efficiency.

3.1.1 Brake Thermal Efficiency (BTE)

Fig. 5 shows that BTE is the lowest for 100% diesel (D100) and 100% tire pyrolysis oil (TPO100), but it increases when TPO blends with methanol and diesel fuels (TPO20M20D60) suggesting more favorable energy conversion. The addition of nano additives enhances BTE significantly, and the increments are higher upon further increase in the additive concentration and load. At full load, a BTE of 36% was achieved for the 15ppm nano-additive blend (CeO_2, CuO, NiO), representing an improvement of approximately 9%

compared to neat diesel and 12.5% relative to TPO100. The improvements were most pronounced at maximum load, where BTE increased by approximately 2–4% with each incremental rise in nano-additive concentration. This trend indicates enhanced combustion efficiency in the presence of nano-additives, with the 15ppm blend exhibiting the most favorable performance. Consequently, these blends demonstrated more effective utilization of fuel energy compared with neat diesel or TPO alone. Based on this observed trend, TPO–methanol–diesel blends supplemented with nano-additives appear to be a promising option for engine operation. (Hariharan, *et al.* 2013; Ramalingam *et al.* 2020).

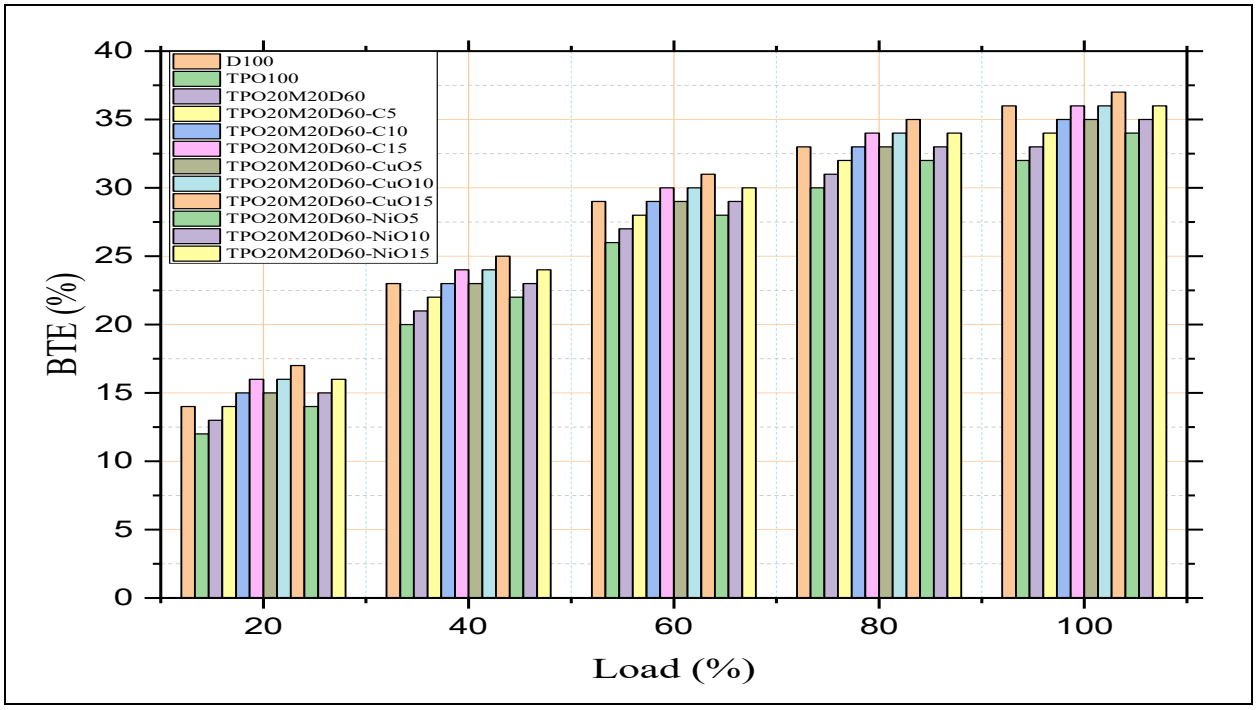


Fig. 5: Load vs brake thermal efficiency

3.1.2 Brake Specific Fuel Consumption (BSFC)

The brake specific fuel consumption (BSFC) is the highest for pure diesel (D100) and TPO100 meaning both need a higher amount of fuel for the same power output (Fig. 6). Brake specific fuel consumption decreases with TPO blends with methanol and diesel (TPO20M20D60), however, demonstrates greater efficiency. Minimum BSFC values reduce consistently further with the addition of nano additives at increasing concentrations (5, 10, and 15 ppm) at especially higher loads. At full load, the 15ppm nano-additive blend exhibited the lowest brake-specific fuel consumption (BSFC), with reductions of approximately 27% compared to neat diesel and about 34% relative to TPO100. The largest reductions also happen with increasing load and additive levels, with the difference between adding each new additive decreasing 10–20 g/kWh per additive step at higher loads. The results conclude that with increasing nano additive concentrations, TPO-methanol-diesel blends have lower fuel consumption for the same power compared to pure diesel or TPO thus using less fuel during combustion makes combustion more economical. As a result, such optimized blends provide the highest engine performance and fuel economy (Auti *et al.* 2021).

3.2 Emission Parameters

In HCCI engines, the notable emission characteristics that are of interest include unburnt HC, CO, NO_x, and smoke (particulate matter). The HC emissions are usually more in HCCI combustion compared with conventional diesel engines because of the presence of lower combustion temperatures as well as incomplete oxidation in the quenching zones. The same low-temperature combustion similarly causes the HCCI's CO emission levels to be high because it is also difficult to oxidize CO totally to its final product, CO_2. Nevertheless, NO_x formation is highly reduced in HCCI mode because the overall combustion temperature remains low compared with conventional standard premixed or diffusion-controlled combustion, which inhibits the formation of the thermal NO_x. Formation of smoke is similarly reduced because the HCCI combustion promotes more uniform fuel–air mixing, limiting the rich zones as well as the formation of soot precursors. Therefore, even though HCCI engines offer the advantage of zero NO_x and smoke formation, they usually suffer from the problem of high HC and CO formation, which needs mitigation through fuel modification, use of additives, or after-treatment systems.

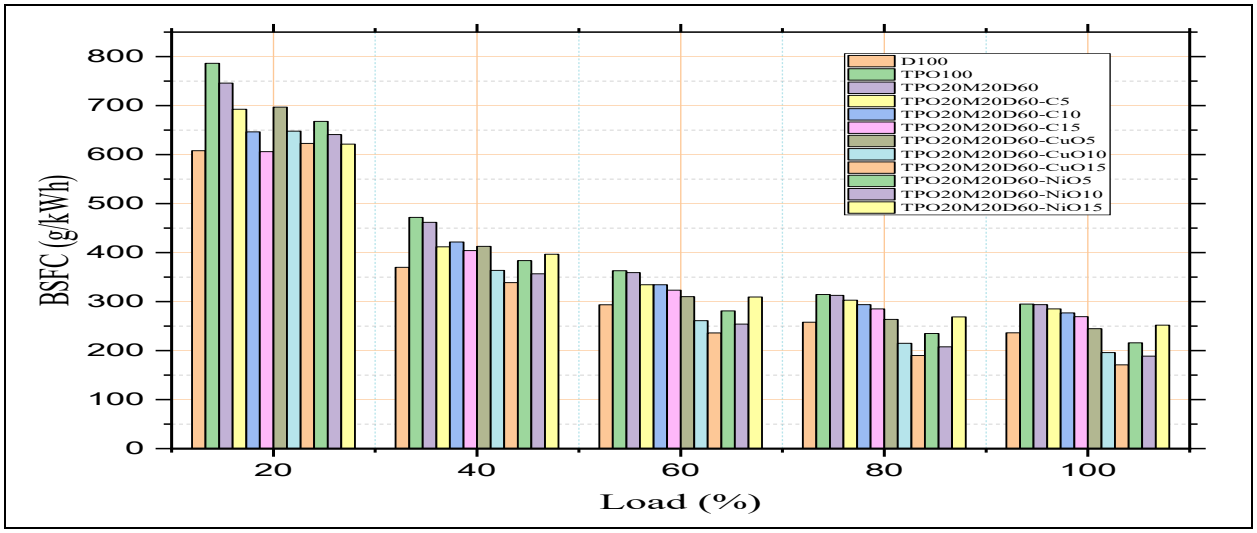


Fig. 6: Load vs brake specific fuel consumption(g/kWh)

3.2.1 Hydrocarbon (HC)

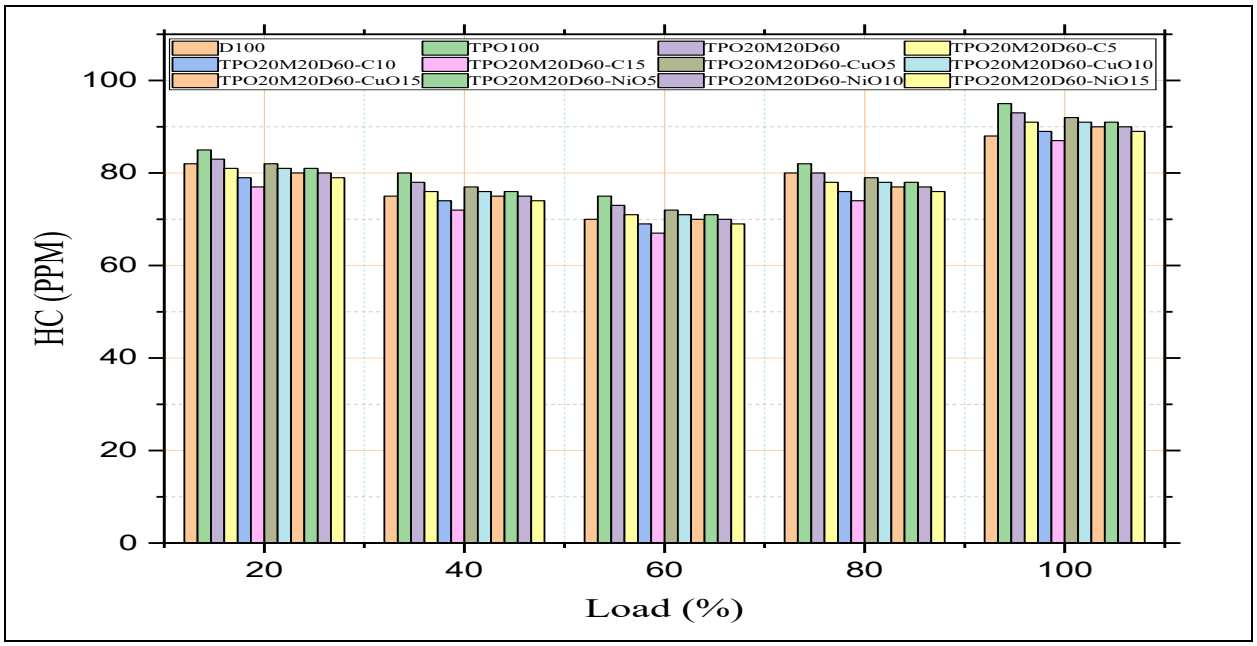


Fig. 7: Load vs hydrocarbon(ppm)

Fig. 7 illustrates that HC emissions were significantly higher for neat tire pyrolysis oil (TPO100) compared with conventional diesel fuel (D100). When TPO was blended with methanol and diesel (TPO20M20D60), HC emissions decreased consistently across all load conditions. The addition of nano-additives further reduced HC emissions, with NiO (15 ppm) and CuO (15 ppm) showing noticeable improvements, particularly at higher engine loads. Among the individual additives, CeO_2 at 15 ppm exhibited the most pronounced reduction in HC emissions, followed by CuO and NiO. Compared with the base TPO20M20D60 blend, HC emissions were reduced by approximately 5.5% with 15 ppm CeO_2, 4.4% with 15 ppm CuO, and 2.2% with 15 ppm NiO. At higher loads, blends containing nano-additives (≤15 ppm) achieved HC reductions ranging from about 3% to over 6%. The observed reductions are attributed to enhanced combustion efficiency promoted by the catalytic activity and oxygen-buffering capability of the nano-additives, leading to more complete oxidation of hydrocarbons. Consequently, TPO–methanol–diesel blends supplemented with nano-additives produced cleaner exhaust emissions compared with neat diesel or TPO alone. (Saravanan, *et al.* 2020)

3.2.2 Carbon monoxide (CO)

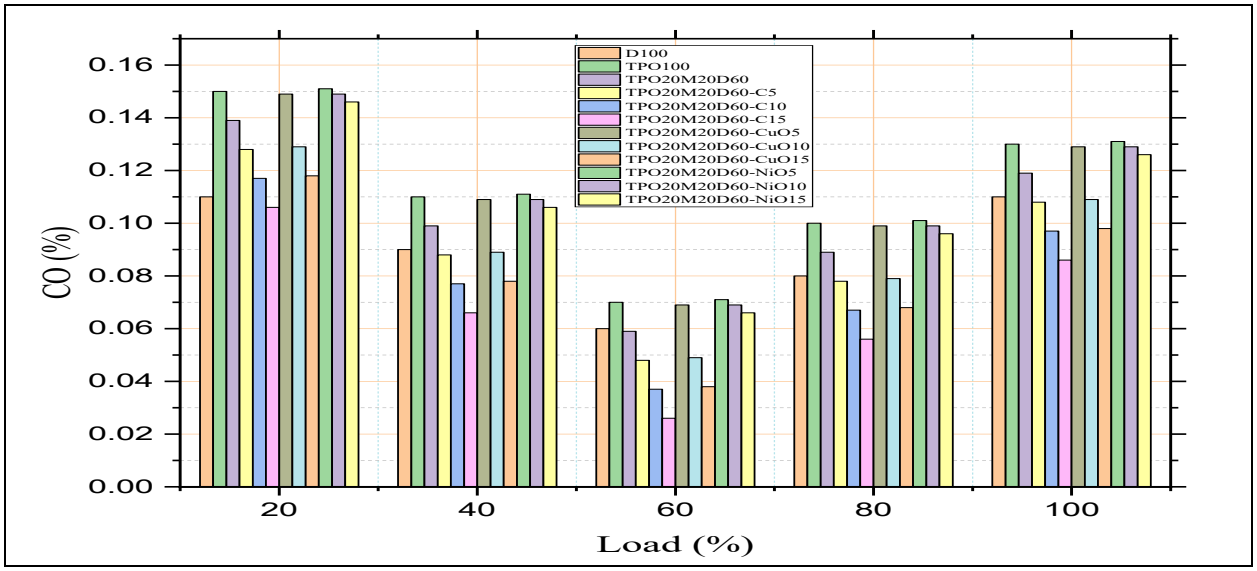


Fig. 8: Load vs carbon monoxide(ppm)

Fig. 8 presents the variation of CO emissions with engine load. Among the baseline fuels, neat TPO100 exhibited the highest CO emissions, whereas conventional diesel (D100) showed the lowest. Blending TPO with methanol and diesel (TPO20M20D60) resulted in lower CO emissions than TPO100 across all load conditions and, in several cases, lower than those of D100. The incorporation of nano-additives led to further reductions in CO emissions, particularly at higher additive concentrations and elevated engine loads. At full load, the addition of 15 ppm CeO_2 to the TPO20M20D60 blend achieved an approximate 9% reduction in CO emissions, while corresponding reductions of about 7% and 6% were observed for CuO and NiO, respectively. At higher loads, increasing the nano-additive concentration from 5 to 15 ppm resulted in substantial CO reductions in the range of 10–20%. These trends indicate that nano-additive-enhanced TPO–methanol–diesel blends promote more complete combustion, thereby outperforming neat diesel and non-additive TPO–methanol blends in mitigating CO emissions and improving environmental performance. (Pradeep *et al.* 2022).

3.2.3 Oxides of Nitrogen (NO_x)

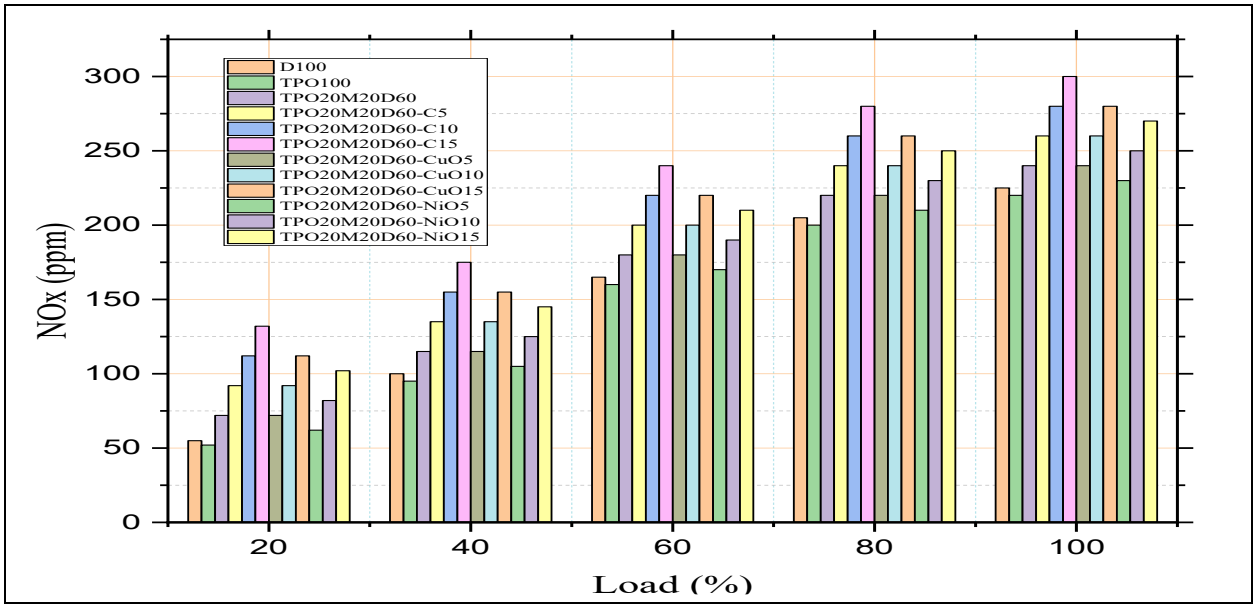


Fig. 9: Load vs NOx(ppm)

Fig. 9 illustrates the variation of NO_x emissions with engine load. Neat diesel (D100) and TPO100 exhibited relatively lower NO_x emissions, whereas blending TPO with methanol and diesel (TPO20M20D60) resulted in elevated NO_x formation. The addition of nano-additives at concentrations of 5, 10, and 15 ppm led to a further increase in NO_x emissions compared with the baseline blend, particularly under high-load operating conditions. At full load, the TPO20M20D60–CeO_2 (15 ppm) blend showed an approximate 30% increase in NO_x emissions relative to D100, while the CuO15 and NiO15 blends exhibited even higher increases of about 33% and 35%, respectively. These increases were more pronounced at elevated loads, corresponding to higher in-cylinder temperatures and enhanced oxidation rates promoted by the catalytic activity of the nano-additives. Although nano-additive-enriched TPO–methanol–diesel blends improve combustion efficiency and overall engine performance, the associated rise in NOx emissions underscores the need for effective emission control strategies when deploying these fuels. (Cengiz *et al.* 2023)

3.2.4 SMOKE

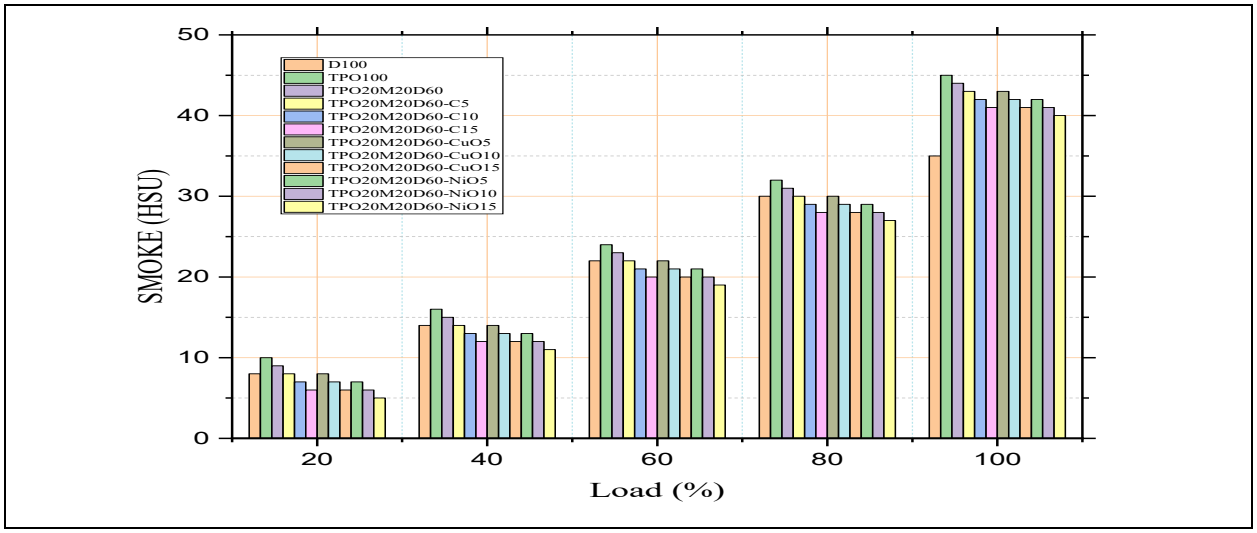


Fig. 10 Load vs smoke (HSU)

Fig. 10 shows the variation of smoke emissions, expressed in Hartridge Smoke Units (HSU). Neat TPO100 exhibited higher smoke emissions than conventional diesel (D100). However, blending TPO with methanol and diesel (TPO20M20D60) resulted in reduced smoke emissions across all engine load conditions. Use of nano additives CeO_2, CuO, and NiO irrespective of type and dosage significantly reduced smoke emissions at all loads with 15 ppm of each additives giving the maximum percentage of reduction at high loads. At full load, the TPO20M20D60–CeO_2 (15 ppm) blend recorded a smoke opacity of 38 HSU, representing a reduction of approximately 13% relative to the base TPO20M20D60 blend and about 16% compared with TPO100. Similarly, the CuO15 and NiO15 blends exhibited reduced smoke levels of 41 and 40 HSU, respectively. The magnitude of smoke reduction increased with both engine load and nano-additive concentration. These reductions indicate that the presence of nano-additives enhances the combustion process, leading to lower smoke formation compared with neat diesel, TPO alone, or non-additivated blends. Consequently, the optimized nano-additive blends demonstrate improved environmental compatibility (Ramalingam, *et al.* 2019; Kale *et al.* 2024b)

3.3 Combustion Parameters

3.3.1 In Cylinder Pressure

The in-cylinder pressure intensity against crank angle (°CA) for diesel and B100 along with the tyre pyrolysis oil (TPO), methanol (M) and CeO_2 (C), CuO and NiO additives (Figs 11 (a) and 10(b)). The same kind of phenomenon is observed for diesel as shown 10(a) where the pressure builds smoothly and peaks shortly after TDC, which suggests relatively stable premixed and diffusion combustion for diesel. Under B100, the characteristic pressure trace shows a higher peak pressure than diesel, but the increase can be attributed to the oxygen content and the higher inherent reactivity of biodiesel, which tends to improve combustion quality. But, if TPO is blended with methanol (TPO20M20D60), the in-cylinder pressure rise becomes sharper and the peak pressure increases further, which reflects the characteristics of enhanced premixed combustion. The increase is predominantly attributed to the oxygenated characteristic of methanol, which facilitates the mixing of fuel and air and allows for efficient combustion near

TDC, however, due to methanol's low cetane number, the ignition delay can be lengthened in neat cases of operation without additives. The enhancement of pressure characteristics by addition of some combustion-promoting additives is very clear from Figure 11(b). The higher cylinder pressure peak together with the more rapid pressure rise yielded from the higher dosage of CeO2 (C15) as compared to C10 is attributed to CeO2 being an oxygen buffer and catalytic agent which can facilitate oxidation reactions and enhanced flame propagation. Opacity, together with the overall combustion behavior, indicate that the maximum and more stable peak pressures with a peak better tuned towards TDC (maximum indicated power), and therefore confirming better combustion phasing, are primarily observed in the blends containing CuO and NiO additives. This is because CuO and NiO are catalytic to oxidize the heavier hydrocarbons included in TPO, resulting in a shorter ignition delay and reinforced premixed combustion. In general, part (a) and (b) of Figure 11 verify the combined effect of TPO and methanol on the combustion intensity, and the inclusion of CeO_2, CuO, and NiO can also promote the in-cylinder pressure evolution due to the enhanced ignition quality, catalytic oxidation and combustion completeness (Swamy, *et al.* 2023; Bala *et al.* 2020).

Fig. 12(a) and 12(b) show the heat release rate (HRR) profiles at crank angles demonstrate the impact of different fuel blends or nanoadditives on combustion. Those of pure diesel (D100) and TPO100 give lower HRR values and shorter release durations. Once diesel vehicle was blended in this manner (TPO20M20D60), the maximum HRR increased. This indicates that with improved combustion as well as fuel oxidation beyond pure diesel fuel mode and unblended TPO blends Nucleating Diesel Model Vaporizers are always in perfect operation. A 15-ppm concentration of CeO_2, CuO, and NiO Nano additives increases the peak HRR further still around TDC. This peak represents 15–20% more rapid energy liberation per degree of crank angle and means better engine performance with smaller emissions. Improved HRR at the optimal crank angles directly offsets this with better brake thermal efficiency and lower brake specific fuel consumption. From -10 to +10 ° crank angle, the blend of nano additives (especially at 15 ppm) makes for a faster combustion kinetic than diesel, TPO100, or any base TPO blend. CeO_2, CuO, and NiO are accountable for early intense HRR peaks. These are supported by enhanced cylinder pressure curves under the same condition, and complete mean brake power. Such nano optimized blends deliver more power as a result, have better fuel economy, and eliminate more than pure diesel Objects. To sum up, blends of TPO-methanol-diesel with 15 ppm CeO_2, CuO or NiO additives produce superior HRR profiles (Venu, *et al.* 2022; Sanyasi *et al.* 2024; Ali *et al.* 2024).

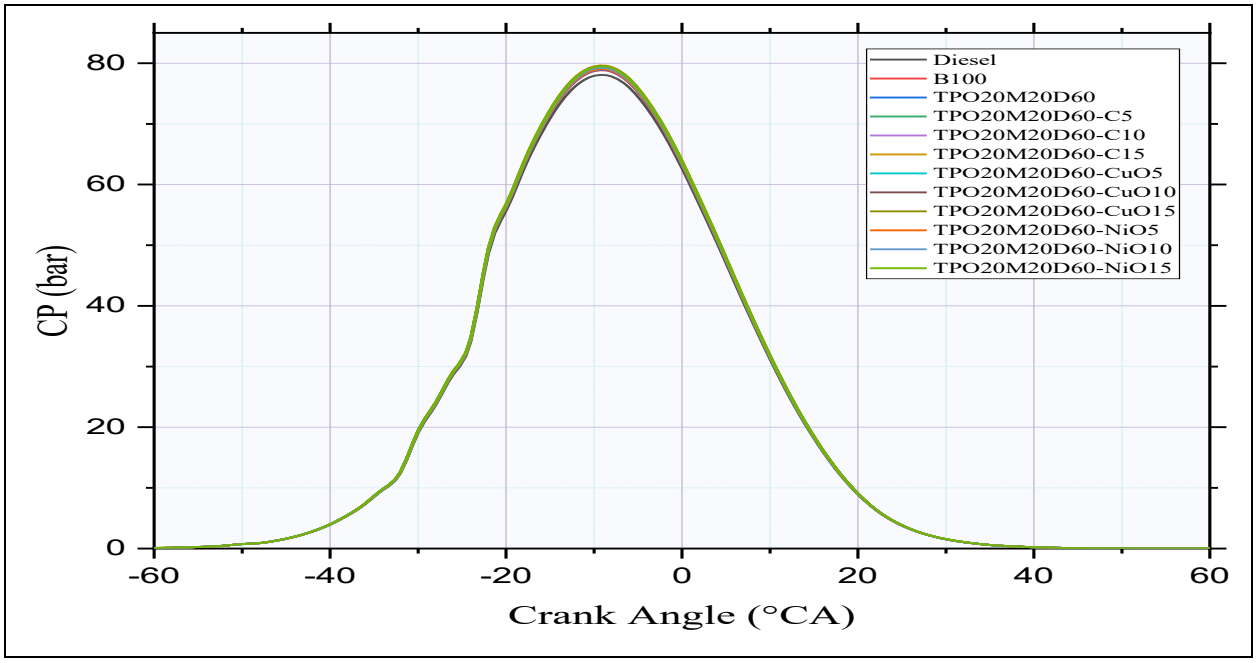


Fig. 11(a): Crank angle vs in cylinder pressure(bar)

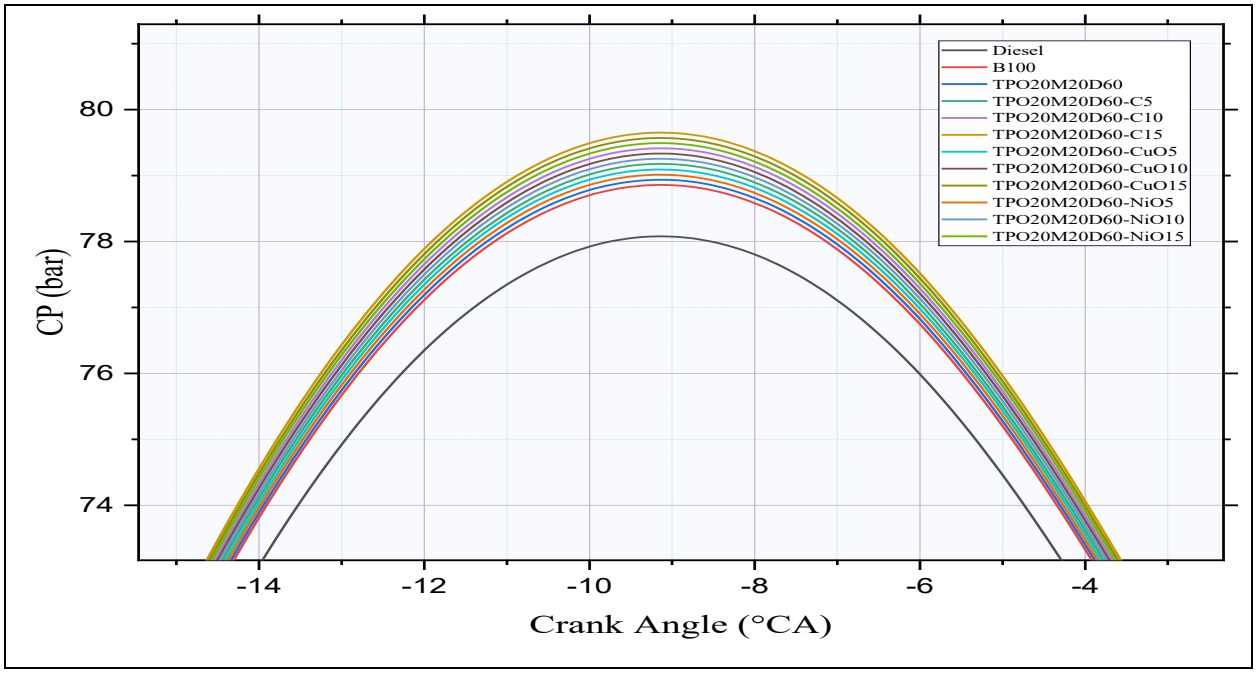


Fig. 11(b): Crank angle vs in cylinder pressure(bar)

3.3.2 Heat Release Rate

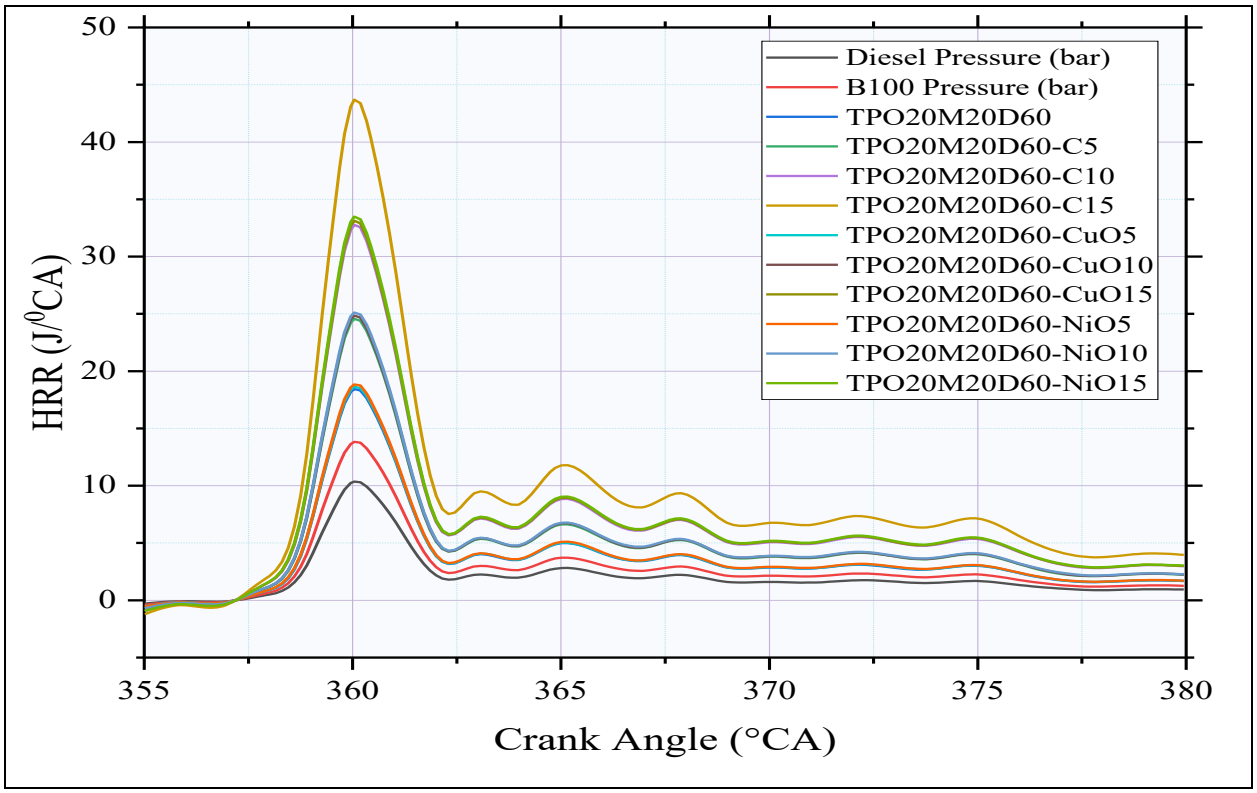


Fig. 12(a): Crank angle vs heat release rate(J/OCA)

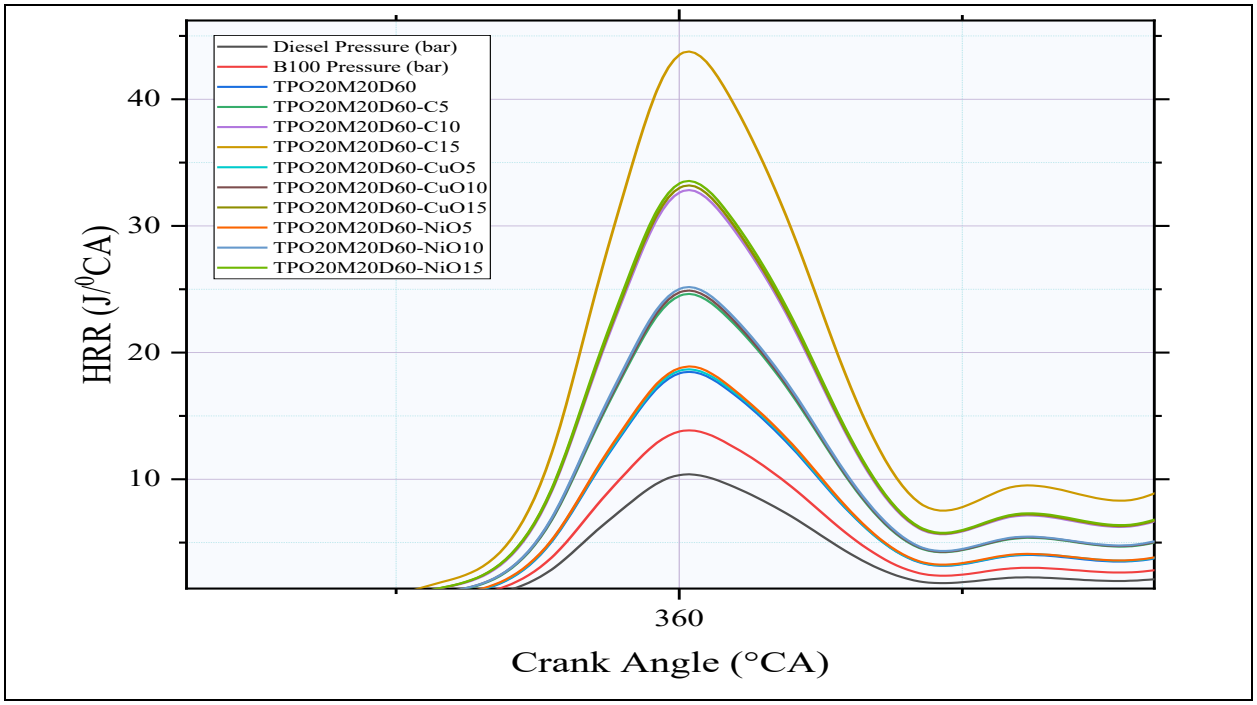


Fig. 12(b): Crank angle vs heat release rate(J/OCA)

The improved combustion performance achieved with CeO_2-doped fuels, can be primarily ascribed to the oxygen buffer capacity and redox properties of ceria nanoparticles. CeO_2 can store active oxygen during combustion due to a reversible Ce^{4+}/Ce^{3+} redox cycle. CeO_2 releases lattice oxygen under fuel-rich condition to facilitate oxidation of carbon monoxide and unburned hydrocarbons, whereas it has a great tendency of refilling its oxygen vacancies under oxygen-rich condition. This persistent buffering action of oxygen promotes kinetics of oxidizing the fuel, enables a rapid heat release close to top dead center, and provides a peak cylinder pressure and brake thermal efficiency. Thus, CeO_2 nanoparticles enable more thorough and stable combustion in HCCI mode than that with the blend without nano additives.

4. CONCLUSION

Feasible fuel blends for use in HCCI engines were fabricated from TPO, a waste-derived tire pyrolysis oil, by adding methanol and diesel, then using nano CeO_2, CuO or NiO powders as auxiliaries. These nano additives, when added to TPO at the same rates as any of them, or 15 ppm, all had excellent results. Tire pyrolysis oil has a great potential as a substitute for diesel fuel, driven by its good chemistry and high energy content. TPO primarily contains carbon and hydrogen and has a lower heating value of around 38.15MJ/kg, like that of diesel fuel. Neat TPO shows some drawbacks such as higher viscosity and lower Cetane number, but these limitations are overcome through blending with methanol and diesel. This ternary blend enhances ignition quality and fuel–air blending and stabilizes combustion during HCCI operation. Thus, TPO could be a waste-derived diesel substitute when correctly formulated and combustion-improved from the viewpoint of both composition and energetic principles.

Brake thermal efficiency initially decreased but gradually stabilized with CeO_2 treatment, achieving values comparable to pure diesel and TPO at full load. Nano-optimized blends exhibited the lowest BSFC, with reductions in HC, CO, and smoke emissions, although NO_x increased at higher additive concentrations, highlighting the need for effective aftertreatment strategies. Combustion analysis showed elevated peak cylinder pressures, higher heat release rates, and improved energy efficiency due to nano-additive incorporation. Ultrasonic treatment of the fuel suspensions ensured uniform, stable, and repeatable nanofuel blends. These optimized TPO–methanol–diesel–nano additive blends enhance both engine performance and environmental sustainability, supporting circular economy principles by valorizing waste tires and reducing landfill burden. Overall, 15 ppm nano additives proved most effective, and future studies should focus on optimizing dosages and evaluating long-term engine performance for next-generation high-efficiency fuels.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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