Malaysian Journal of Chemistry, 2024, Vol. 26(3), 233-250
(Special Issue: *The International Conference on Advanced Materials & Sustainable Energy Technologies 2023*)

Experimental Investigations on the Impacts of Aluminum Nanoparticles on a Low Heat Rejection Engine Running on a Blend of Soya Biodiesel and Diesel Fuel

Samuelraj Daniel[1]*, M. Amala Justus Selvam[1], Serajul Haque[2] and A. Haiter Lenin[3]*
[1]Department of Automobile Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D
Institute of Science and Technology, Chennai, Tamil Nadu, India
[2]B.S. Abdur Rahman Crescent Institute of Science and Technology, GST Road, Vandalur,
Chennai 600048, Tamil Nadu, India
[3]Department of Mechanical Engineering, WOLLO University, Kombolcha Institute of Technology,
Kombolcha, Post box no: 208, Ethiopia
*Corresponding Author (e-mail: drahlenin@kiot.edu.et; samuelraj1982@gmail.com)

The current study intends to assess how alumina nano-particles (Al_2O_3) at a focus of 25ppm affect a biodiesel blend known as B20 (20% biodiesel with 80% diesel) in a DI-diesel engine with 4.5 kW power output and a compression ratio of 17.5. This engine runs at a constant speed of 1500 rpm. The research focus about the engine's performance, combustion and emission parameters when using B20 with B20 blended with 25 ppm of Alumina (referred to as B20+Al) against a DI-diesel engine. Alumina nanoparticles were mix with biodiesel using a blend of a magnetic stirrer and an ultrasonicator device. At full engine load conditions (100%), cylinder pressure was known to be highest for B20, followed by B20+Al, superior liken to diesel fuel. The outcomes suggest that using Alumina nanoparticle slightly 5.66% drops in BSFC and a significant 12.5% rise in (BTE), which can be added due to the HRR rate. In terms of emissions, the adding of Alumina nanoparticles to the blended biodiesel led to in reduced levels of (HC), (CO), and smoke associated to the DI-diesel engine due to oxygen present in soya bean biodiesel. Still, the emissions of (NOx) and (CO2) increased to a greater extent.

Keywords: Diesel**;** biodiesel; alumina nano additives; engine combustion; performance and emissions

Received: February 2024; Accepted: February 2024

As non-modified substitute energies for current diesel engines, biodiesel and biofuels have both grown in popularity recently. Most of the time, biodiesel doesn't need to be modified for usage in diesel-powered engines. With the exception of NOx emissions, it produces fewer harmful emissions in evaluation to diesel fuel. Renewable fuels possess the capability to offer a workable resolution to the worldwide petroleum fuel predicament. It is thought that vegetable oils made from biomass are a good alternative to conventional fuels [1]. Nevertheless, they result in much higher reduced thermal efficiency, as well as emissions of smoke and exhaust, when it was utilized directly in a diesel engine [2]. To obtain an 88.63% conversion rate in the transesterification of palm oil into biodiesel [3]. Because of the depletion of oil reserves and the detrimental impacts of the effects of motor vehicle emissions on the atmosphere, the environment, public health and researchers have concentrated on their attention on renewable energy sources. Finding alternative energy sources for internal combustion engines is crucial because automobiles are one of the main emitters of greenhouse gasses [4]. The study comes to the conclusion that is a promising design for enhancing the efficiency and exhausts of diesel engines driven by biodiesel. Additionally, the study makes the case that energy and exergy analysis might offer helpful insights for improving engine operation and design [5]. Furthermore, the current global energy system surely contributes to the deficiency of fossil fuels and their toxic emissions by increasing their use. In addition to meeting legal requirements, using premium gasoline with possible additives in diesel engines lowers emissions. The solution to these potentially fatal problems caused by the usage of biodiesel powers the diesel engine and fuel mixes including nano additives [6]. The authors looked into how the compression ratio affected the thermal efficiency of the brakes, the amount of gasoline used specifically for the brakes, and the exhaust emissions of hydrocarbons, nitrogen oxides, smoke opacity, and carbon monoxide. With the exception of nitrogen oxides, they discovered that hovering the compression ratio enhanced engine performance and decreased emissions. Additionally, they examined the characteristics related to combustion parameters [7]. Waste or underutilized agricultural products can be converted into oils made from biodiesel. The oils have naturally occurred fatty acids that aid in lowering emissions during combustion. Furthermore, biodiesel

---

†Paper presented at the International Conference on Advanced Materials & Sustainable Energy Technologies 2023

is regarded as a plentiful, affordable, environmentally beneficial, and biodegradable resource derived from natural resources [8]. In the meantime, a multitude of feedstocks for biodiesel production—a biofuel substitute for fossil fuels—were also found by the researchers. Some of the most popular raw biodiesels are sunflower oil, jatropha, pongamia pinnata, mahua seed oil, soybean oil, and maize seed oil [9].

Second and third generation biodiesels have been put through testing in diesel engines to observe how effectively it will combust, performed and release pollution. There are several advantages to using biodiesel that are advantageous to the environment as well as the economy. Biodiesel is relatively easy to deal with, store, and transport due to its high degree of biodegradability. It has been proposed that the furthermost efficient mixing ratio in usage of diesel in engines is 20% biodiesel to 80% diesel, which is the most used mix. Additionally, the cetane number, enhanced lubrication, and combustion efficiency of biodiesel were assessed [10]. Biodiesel can be made from fish oils, leftover cooking oils and other materials, as well as from edible and inedible seed oils [11].

For the production of biodiesel, a Malabar tamarind "Kodampuli," was used. Alcohol immobilizes lipase to produce biodiesel. 93.88% biodiesel is produced during transesterification. The diesel engine of the Kirloskar TAF1 type was used. The thermal performance of biodiesel was initiated to be 28.32% lower than related to diesel, when a 20% biodiesel mixture was used. Fuel consumption increased as a result of biodiesel's higher density and lower calorific value. The biodiesel samples exhibited reduced in-cylinder pressure and heat release rate (HRR) as a result of inadequate evaporation and a short ignition delay [12]. Emission characteristics are decreased by rapid ignition and complete fuel combustion. For all mixtures, more oxygen in the biodiesel increases NOx emissions. They concluded that a significant fuel substitute may be 20% biodiesel. Using a Soxhlet method, 42% was the greatest yield by using pre-determined amounts of methanol and oxygen, biodiesel was created from the purchased oil.

DI-air-cooled diesel engine (A Lister Petter (TS1), utilizing an engine with 4.5 kW output at 1500 rpm was tested [13]. The B40, showed that and 54.35 bar and 59.60 J/deg for in-cylinder pressure and engine HRR, while the diesel exposed 64.40 bar and 67.24 J/deg. They therefore concluded that a lower watermelon and biodiesel mixture might be used in diesel engines. Soybeans are becoming more well-liked globally as an oil seed crop. Sunflower and soybean oil both have equal iodine contents. The amount of oil it generates per acre is significantly less than other oils. It accomplishes this by restoring the soil's nitrogen content, allowing it to be cultivated in temperate and tropical regions and lowering the need for fertilizer. The following acids composed of glycine max: linoleic acid (52–60%), oleic acid (25–35%), palmitic acid (5%–10%), and linolenic acid (6%–12%) [14].

Researchers Varatharajan et al. (2013), looked into the emission parameters, impact of adding an aromatic amine antioxidant generated from p-phenylenediamine on the NOx, that a base diesel engine produces running on soy-based biodiesel. The greatest decreases in Nox, at 4.06 % and 9.35%, respectively, were attained by silver and zinc nano additives when related to the amount of NOx drop attained through B20 operating at 75% load. Furthermore, they concluded that NO emissions were reduced to a level less than that of a typical diesel engine because of the action of aromatic amine antioxidants [15]. The engine type that contributes to heat conservation is known as an LHR engine. The LHR engine is designed to recover as much heat from the exhaust as feasible and to minimize heat loss via the cooling system. Furthermore, it improves combustion while reducing pollutants at the same time. A diesel engine pairs incredibly well with the LHR idea, it reduces gas consumption, eliminates the need for a cooling system, and speeds up the ignition's response time [16].

A study was conducted by Manickam and Rajan (2015), to evaluate the impact of a partly stabilized zirconia (PSZ)-based thermal barrier-coated piston. They combined methyl ester diesel with soybean oil in a plasma coating method. They discovered that for B20, the BTE grew by 6.2% and as the BSFC dropped by 8.5%. However, when compared to the basic engine, they found that using the B20 blend's mixture quantity while running in a coated engine will drop the emissions of HC, CO, and smoke. It was discovered that it was effective to decrease the ignition delay while concurrently raising the peak pressure, maximum rate of pressure rise, and HRR [17]. By experimenting with various diesel and bio-oil mixes, loads, and compression ratios, the authors were able to maximize engine performance and emissions. They discovered that 12.22% mix, 18 compression ratio, and 6.665 kg load were the ideal parameter [18].

Rajan et al. (2011), studied the engine characteristics of an LHR engine running at complete load in the 1800, 2100, 2400, and 3000 rpm speed range with soybean methyl ester mixes of 20%, 35%, and 100%. According to a few sources, the engine's power can improve by around 8.4% by using diesel and 3.5% by using biodiesel; nevertheless, the specific fuel consumption (SFC) can drop by about 5% by using diesel and by about 8% by using blends of biodiesel. Emissions of smoke and CO fell by 8.2% and almost 24%, respectively. For biodiesel blends, whereas NOx emissions increased by approximately 7.3% [19]. When glycerol is used in the manufacturing of catalysts, it can prevent carbon dioxide and water poisoning of the active species, increasing catalyst efficiency. At the same time, this by-product might be valued. Under inert environment, a refined soybean oil was successfully trans esterified using a catalyst [20].

In an experiment, Krishnamani et al. (2018) used plasma spray coating at 70 m in the cylinder liner and piston with Al_2TiO_5 at 80 m on a diesel engine coated with thermal barrier (TBC). As the TBC engine's test fuels, diesel and sesame oil methyl ester mixes (B10, B20) via means of diesel were utilized in contrast to uncoated diesel. The BTE of uncoated diesel was 28.47%, whereas the BTE of (B10 and B20), coated diesel was 30.25%, 30%, and 29.62%, respectively. The diesels SFC that was coated and uncoated was 0.2619, 0.2759, and 0.283 kg/kWh, correspondingly. They showed that the oxygen content in the blend and the insulation of the combustion chamber, which decreased heat loss, elevated the temperature of combustion, and improved combustion efficiency, were responsible for the increase in BTE and the decrease in SFC. With the thermal coated engine, NOx increased but exhaust contaminants like CO and HC reduced. They discovered that the mixture's high temperature, carried on by the coating, and the quantity of oxygen present in the fuel to oxidize and combustion more quickly [21].

Researcher, Senthur et al. (2017) assessed the effects of diesel fuel and diesel-water on the less heat-generating engine coated with (PSZ). The outcomes displayed that the fuels produced lesser CO and HC, greater maximum pressure, decreased HRR under maximum load conditions, and increased BTE and minimum BSFC. The different nano additives mixed with Garcinia biodiesel 20%. were then evaluated on the diesel engine at different load settings by Janakiraman et al. (2013) [22]. Due to limited ID, better evaporation rate, atomization, and little fuel accumulation, the biodiesel +25 ppm of TiO_2 nano additives mix showed 6.05% improved BTE, low BSEC, peak rate of HRR, and in-cylinder pressure in these test findings. Notable reductions in CO, NOx, and 16.25% smoke emissions were also observed as compared to diesel fuel, along with a decrease in emissions under peak load. The effect of Al_2O_3 nano additions at amounts between 10 and 30 ppm on the fuel efficiency of ethanol mixed with 20 percent jatropha biodiesel was investigated by Dhana Raju et al. (2021) [23].

According to test results, adding Al_2O_3 (200 ppm) to the 20% mango seed methyl ester (MSME) significantly improved its braking thermal performance by 1.39% and significantly minimize its CO and HC emissions at full load by 35.48% and 13%, respectively. On the other hand, under full load, NOx emissions slightly increased [24]. It was discovered that the engine performance of gasoline doped with ethanol outperformed that of pure gasoline, while the engine performance at low loads was somewhat worse when toluene was added. Toluene-doped gasoline performed better in engines at higher loads than pure gasoline, nevertheless. The engine's efficiency with benzene was determined to be subpar for all load values. The short-term trial findings demonstrated that gasoline can be successfully replaced with a 20% toluene and 20% benzene addition without changing the engine's architecture [25]. Numerous benefits are demonstrated by the mixed nanoparticles in the blend of tamarind seed oil, including improved oxidation, increased air-fuel mixing, enlarged brake thermal efficiency due to a larger surface area to volume ratio, and a notable decrease in, hydrocarbon, carbon monoxide and smoke opacity emissions [26]. Since usage of the fuel blends' increased carbon content, the adding of carbon nanoparticles to the water-emulsified fuel blends had a negative impact on incomplete hydrocarbons and CO emissions at complete load circumstances, but it reduced nitrogen oxide emissions [27].

The experimental investigation efforts on how combustion chamber shape, injection timing, and nano additives interact with diesel engine with one cylinder that runs on mixtures of diesel, biodiesel, and ethanol [28] Together with the pure diesel and the blends of biodiesel, these nanoparticles and hydrogen enhanced the performance characteristics. For instance, while the fuel consumption specifically for the brakes was reduced, torque, power and BTE were increased. While the NO emission was somewhat increased, the primary goal of lowering the CO, CO_2, and other UHC emissions was achieved [29]. Brake thermal efficiency and emissions are positively impacted by nanoparticles such as Al_2O_3 and Ce-ZnO. The combustion efficiency of biodiesel boosted with nanoparticles is increased by higher cetane numbers. The combustion dynamics of biodiesel are enhanced by nanoparticle additions. Nanoparticles help biodiesel emit fewer pollutants [30].

Positive effects from the nanoparticles of TiO_2 in the fuel mixture included reduced emissions of CO and HC at low injection pressures. In comparison to diesel and B20, CO_2 emissions improved by 2.5% and 4.4% with B20 with T100. At 240 bar FIP, the extreme drop in smoke opacity and NOx was noted [31]. The outcomes of the experiment revealed that the air-plasma spray method is used to generate the low heat rejection (LHR) engine parts' thermal barrier coat for ceramic composites made of titanium dioxide, partly stabilized zirconia, and nickel chromium aluminium (NiCrAl–120 micron) [32].

The search for novel synthetic pathways to pursue in the production of nanoparticles (NPs) has never stopped researchers. Although NPs can be created via a few different chemical methods. Many attempts have been undertaken to develop biomimetic techniques in in reaction to growing environmental concerns about chemical synthesis procedures. Researchers are driven by green chemistry to create synthetic techniques based on biomaterials. Among these strategies is the use of microbes and plant extracts to synthesize NPs. Hazardous chemicals are not used in the processes of any synthesis that is environmentally safe. A large number of costly chemical processes that utilize unpleasant and hazardous substances are used in the production of metal nanoparticles. Their usage in the field of biology has been severely limited due to their hazardous character. Due to these challenges, scientists are trying to figure out how to make NPs in a less damaging method for the environment.

Considering the outcomes of current studies on LHR, oxygenated additives, nanoparticles and biodiesel. It was discovered that using fuels in an LHR engine might partially replace using more diesel. After then, there will be less usage of fossil fuels and a decline in the emissions of pollutants. As of right now, no research has been done testing the combination of these fuel blends on the LHR coated diesel with PSZ and TiO_2 These blends include soybean biodiesel, oxygenated additives (Al_2O_3) and premium diesel. Thus, testing the LHR engine's performance, combustion, and pollutant emissions with various fuel blends is the primary objective of this study. The fuel mixes filled a recognized research need by providing an innovative fuel substitute for the LHR diesel engine.

EXPERIMENTAL SECTION

Chemicals and Materials

Multiple studies have explored the usage of nano particles (NPs) to diminish emission levels in traditional fuels. However, there's a conspicuous gap in research concerning the potential application of Alumina oxide nanoparticles at very low concentrations. While prior studies have separately examined the effects of soya biodiesel and alumina nano additives, there's a shortage of articles that analyze how Al_2O_3 nano additives at a 25-ppm concentration in soya biodiesel (SBD) impact a diesel engine's characteristics. To fill this void, the current study conducted experiments with three different blends of fuel: diesel, soya biodiesel (SBD), soya biodiesel combined with Al_2O_3 nano additives (referred to as B20+Al). The results of this investigation provided crucial insights, demonstrating that the inclusion of Alumina nano additives notably influenced important fuel properties such as calorific value, flash point, and cetane rating. These experiments were conducted using a single-cylinder direct injection (DI) diesel engine, comprehensively evaluating the engine's performance, combustion behavior, and emission characteristics. The tested fuels in this study included a biodiesel blend with (20%) and diesel with (80%), known as B20, a similar blend together with the inclusion of 25 ppm Alumina oxide nanoparticles (B20+Al), and the standard baseline diesel fuel.

Coating Process

Every step of the coating process was carried out at the facility owned by Ideal Engine Coating Private Limited at the Ambattur industrial estate in Chennai, India.

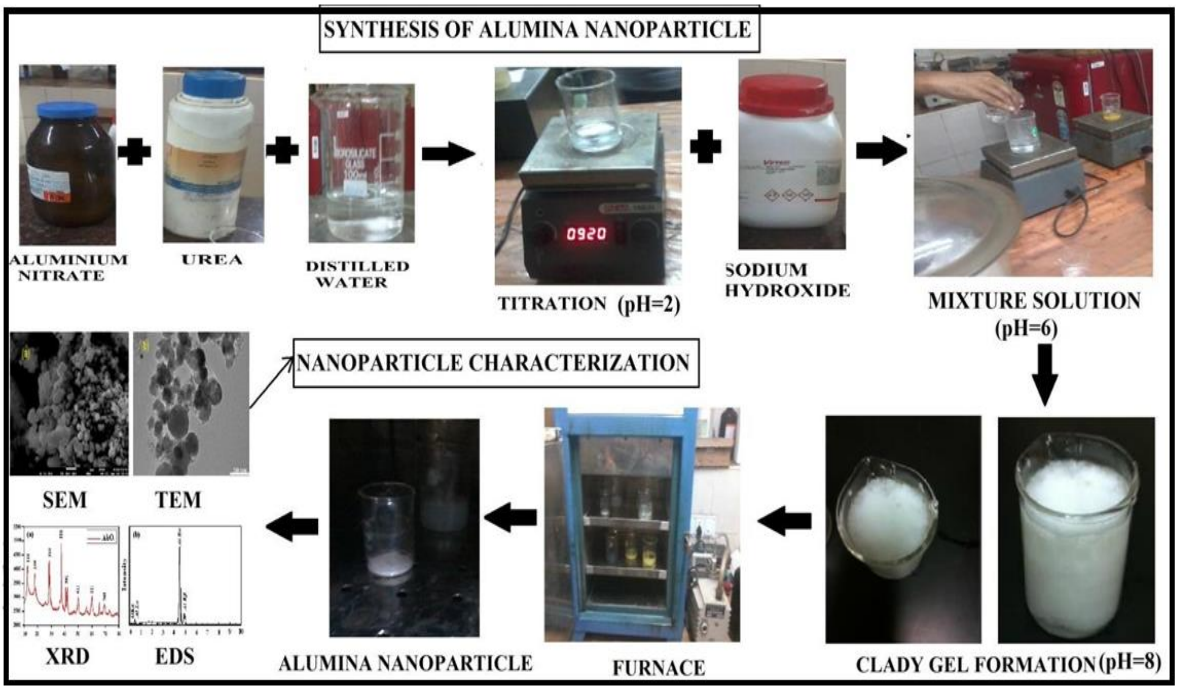

Figure 1. The process flow diagram for creating Al_2O_3 nanoparticles.

CHARACTERIZATIONS

Test Fuels used and Nano Particle Process

Nanoparticle Step-by-step Processes

Alumina nanoparticles and sol-gel chemical-producing method were put together by using an $Al(NO_3)$ solution (0.5M) mixed up in H_2O-50 ml at 22ºC and mixed well with a magnetic mixer. The mixture of urea (0.05M) and aluminium nitrate is then investigated for half an hour till a pH_2 solution is obtained. A Clady gel (pH = 8) and addition of NAOH, titration of H_2O-25 mL, and sodium hydroxide (0.1 M) were carried out until a physical hardness-6 solution was obtained. After that, the sample was dehydrated for 12 hours at 150°C, and nanoparticles (Al_2O_3) were obtained in a vessel and allowed towards dry in the crucible furnace at a heating temperature of 300°C for at least two hours [33] as shown in Figure 1. Synthesised Al_2O_3 nanoparticles with SEM and TEM spectroscopy shown in Figure 2.

Biodiesel-Test Fuel Blend Preparation

From soybean, soy oil will be extracted by the process of transesterification blended with biodiesel. In the process, soy bean oil is intense to a temperature of 52–56°C. With this solution, KOH (5 g) mixed in methanol (250 ml) is extra added and blended for 1 hour. Following the completion of the chemical reaction, the solution is once more run down the drain for a day. The soy bean oil will arrive at the top, and glycerin will reach the lowermost of the container. This esterified soy bean oil (biodiesel) is taken away and cleaned with hot water. The finished goods were taken away and heated for 10 minutes at a temperature of 60°C.

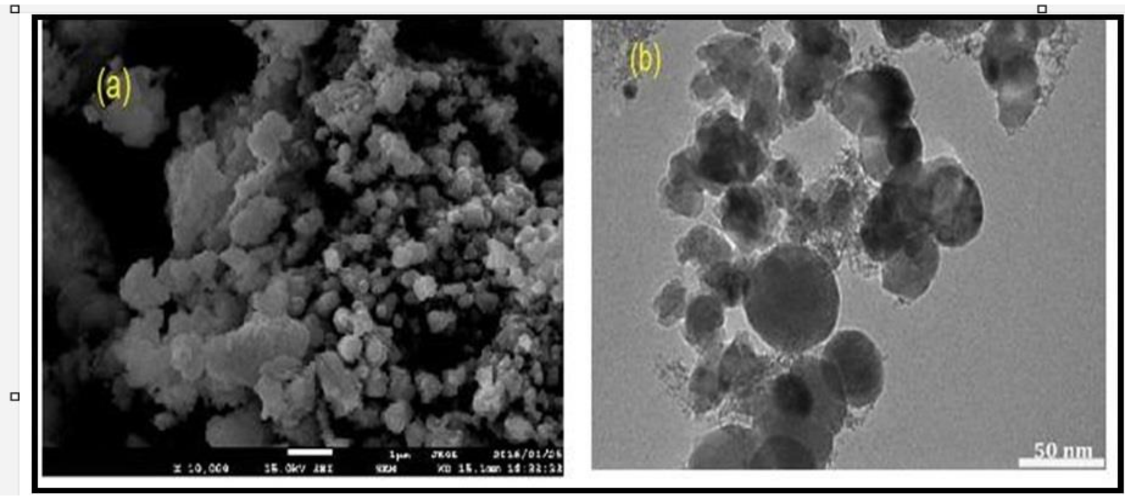

Figure 2. Synthesised Al_2O_3 nanoparticles with SEM and TEM spectroscopy.

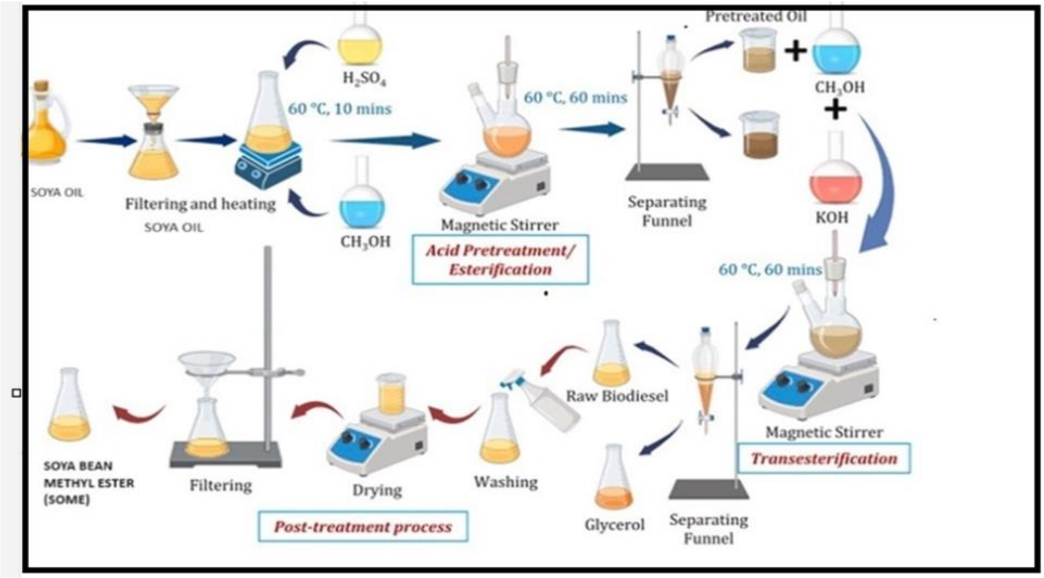

Figure 3. Soya biodiesel preparation.

Figure 3, shows the preparation of biodiesel for biodiesel and the transesterification procedure, the separator funnel for decantation, and the removal of glycerol, respectively. An ultrasonicator running for 20 minutes at 440 kW of power and 60 kHz of operating frequency blends the nanoparticles. The soya biodiesel's nanoparticles were found to be stable for roughly ninety-six hours. 100% soy biodiesel is combined with 25 ppm Al_2O_3 nanoparticles to create biodiesel+25 ppm Al_2O_3.The process of generating biodiesel from soybean oil involves a transesterification method [25]. This encompasses the gentle heating of soybean oil to approximately 50–55°C. Initially, 5 grams of KOH are added to 250 ml of methanol, and the resulting blend is vigorously stirred for 60 minutes. After the completion of the chemical reaction, for a whole day, the solution is allowed to settle.

At this time, glycerin sinks to the bottom. while the soybean oil, now converted into biodiesel, separates at the top. This biodiesel is isolated and subjected to a purification step using hot water. Following this cleansing phase, the finishing output is heated to 60°C for 15 minutes, concluding the biodiesel production. The incorporation of nanoparticles is achieved through the aid of an ultrasonicator running at a vibration frequency at 60 kHz and 440 kW power output for 20 minutes. Interestingly, the nanoparticles remain stable in soy biodiesel for approximately 96 h. The creation of Biodiesel+ 25 ppm Al_2O_3 involves 25 ppm fuel mixing with nano-particles (Al_2O_3) with 100% soy biodiesel. The fuel properties were evaluated following the standards outlined by the American Society for Testing and Materials (ASTM), detailed in Table 1.

Table 1. Fuel properties with various blends.

Property	ASTM standard	DIESEL	B20	B20+25 Al_2O_3
Density, @ 15°C (g/cm^3)	D4052	840	874.4	885
Kinematic viscosity, @ 40°C (mm^2/s)	D445	2.83	4.35	4.82
Calorific value, (kJ/kg)	D240	42700	42673	43568
Cetane number	D613	48	52	54
Flashpoint, (°C)	D976	51	54	55

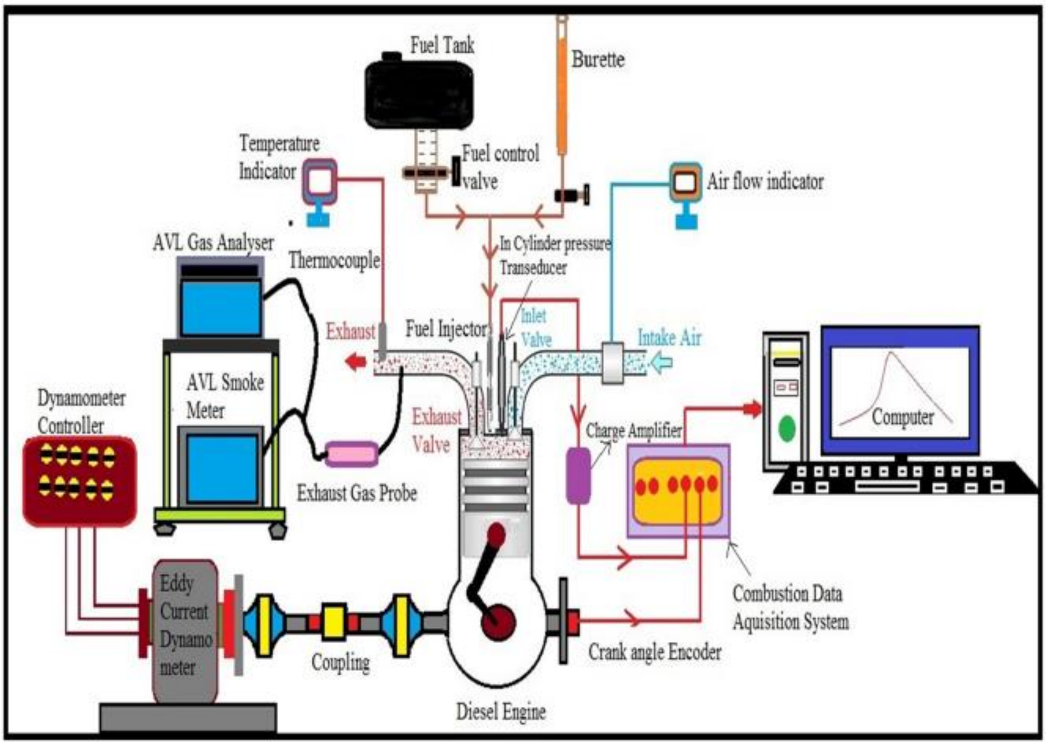

Figure 4. Layout of experimental setup.

Table 2. Specifications of engine.

Type	Kirloskar, four stroke, air cooled, single cylinder DI diesel engine
Bore x Stroke	87.5 mm x 110 mm
Compression ratio	17.5: 1
Injection timing	23^0 bTDC (static)
No. of nozzles	3
Nozzle spray hole diameter	0.3 mm
Angle of fuel spray (cone angle)	120 deg
Piston geometry	Hemispherical
Swept volume	661 cc
Engine Power	4.5 kW
Engine Speed	1500 rpm

Test Engine Specifications

A single-cylinder, four-stroke Kirloskar engine were shown in Figure 4. At 1500 rpm, this engine produces about 4.4 kW of output power. Its specifications include an 87.5 mm bore, a 110 mm stroke, and a compression ratio of 17.5:1. The manufacturer's recommended values for injection timing and pressure stand at 23°bTDC and 200 bar, respectively. The test engine specifications were displayed in Table 2.

LHR Coating

"LHR" engines, short for "Low Heat Rejection", represent a specific engine type engineered to efficiently retain heat. The concept behind these engines focuses on maximizing heat reuse and minimizing heat loss through the cooling system, thereby decreasing emissions and increasing combustion efficiency. The utilization of LHR engines brings particular benefits to diesel powertrains. It eliminates the necessity for a cooling system, reducing vehicle fuel consumption and expediting the ignition process. The process of transforming a diesel engine into a low heat rejection engine involved thermally insulating various engine components using a variety of materials. This study included the initial cleaning and drying of components like valves, piston crowns, cylinder heads, and grit-blasted surfaces using ethyl alcohol. These parts were then coated with a 0.16-mm-thick layer of NiCrAl. Subsequent this, ceramic composites at top layer consisting of partly stabilized zirconia (PSZ) and titanium dioxide (TiO_2), 0.5 mm thick, was applied. Diameters of the particles varying from 8 to 60 µm were used in the coating process. The piston crown's surface underwent machining or cleaning to remove any undesired or coated materials. To enhance the strength of the aluminum alloy, a grit blasting procedure was implemented. The Ideal Engine Coating Private Limited facility, located in Chennai, India's Ambattur industrial estate, handled every stage of the coating process. [34]

Diesel Engine Configuration

The experimental investigation used a hydraulic eddy current dynamometer in conjunction with a Kirloskar TF1-DI diesel engine that produced by power 4.5 kW at speed 1500 rpm. The eddy current dynamometer, which features a fixed rotor surrounded by electro-magnets and a flexible link with the help of crankshaft to measure the power output. When the motor is supplied with sufficient electric current, its spinning motion opposes the magnetic field generated by the electromagnet. Consequently, the engine experiences stress due to the generation of rotor resistance. Therefore, the load can be changed by adjusting the electromagnet's current. The variable reverse force generated on the eddy current dynamometer is measured with the help of a strain gauge instrument. The variable opposing F-force is then multiplied by R-distance to obtain the torque. With the help of engine brake power and engine running speed (constant) of 1500 rpm, torque was obtained. Research experiment with different brake powers while enable to continue steady state injection pressure of 220 bar and an injection time of 23°bTDC. The following phase involved testing and analysing the AVL di-gas analyser (444) for CO, HC and NOx. In addition, the AVL 444 digital di-gas analyser's smoke output was restrained using the AVL 437 smoke meter. With the help of Kistler piezoelectric transducer, the pressure of cylinder and HRR were then monitored, which was involved to the DI single cylinder engine and subsequently attached to the system. The needed coating was sprayed to the engine components, and then the engine was restarted. The test fuel mixes were then tested under different load circumstances. The result outcomes were then compared to those achieved with standard fossil fuel.

1H NMR and FTIR Spectroscopy

Crude oil to methyl ester oil estimates and transforms by using the 1H NMR spectrum analysis (biodiesel). Tetramethyl silane was employed as an internal reference along with $CDCl_3$ as a solvent. The methoxy proton-methyl ester oil(singlet) and methylene proton (triplet), which are seen at 3.68 ppm and 2.32 ppm, are observed, are regarded to be the ratio of the soyabean biodiesel yield (%). The EN14214 quality approach was used to significant the methyl ester ratios in soybean biodiesel. Gas chromatography (Shimadzu) specifies (0.15-30 mm) capillary tube and linked with an ionization detector (using flame) was practically used to assess making of soya biodiesel and the fatty acid content.

The biodiesel and biodiesel blends were examined by FTIR spectroscopy were done using Version- IR prestige’21-used to analyse liquid samples as shown in Figure 5. The penetrating distance of this method to the surface is roughly 2 m. When comparing the spectra of raw soy oil (R1-(COR) = O) with soya biodiesel relates to complex HC chains were extremely obvious variations between biodiesel and raw soya bean oil. Due to process of transesterification, which separates glycerine and methyl esters from triglycerides, there are changes should be visualize by signals. The signal at 1153 cm corresponds to the largest peak in raw soy oil. The disintegration of 1 to 1189.43 cm.1 and 1172.46 cm.1 is a sign that the conversion of triglycerides to methyl esters has returned to normal. Similar comparable deformations are 1449.72 cm.1 and 965 cm.1 respectively. For water and lubricant performance monitoring, Fourier transform-infrared spectroscopy (FT-IR) in the mid region has been utilized [35].

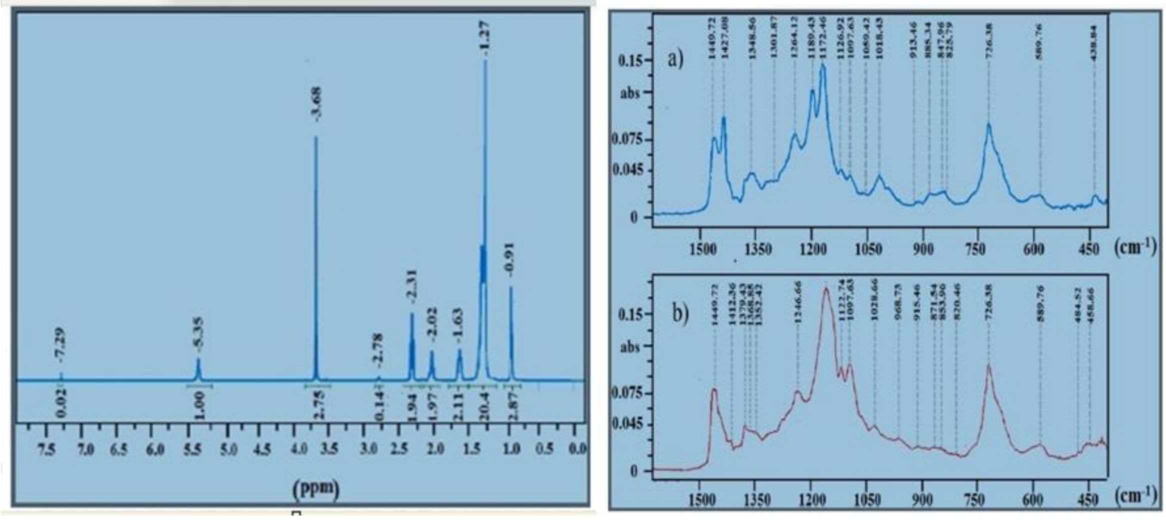

Figure 5. 1H NMR spectroscopy and FTIR spectroscopy.

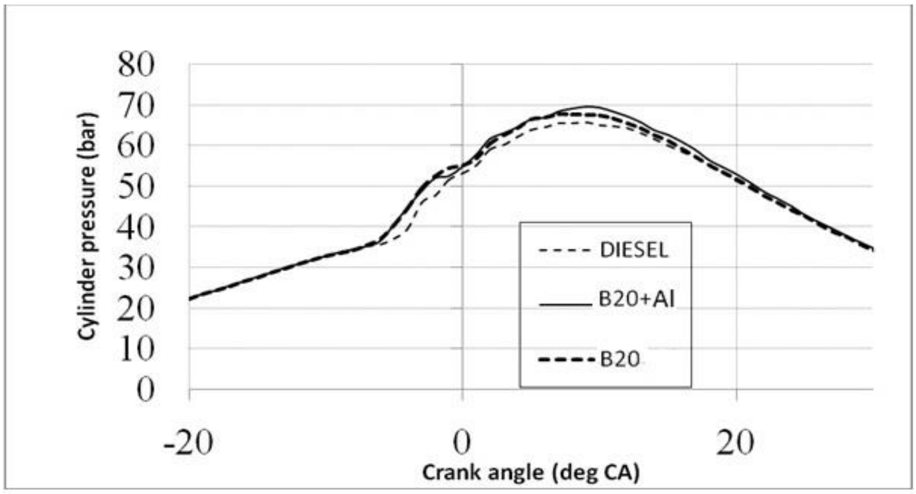

Figure 6. Cylinder pressure variation with engine load.

RESULTS AND DISCUSSION

Cylinder Pressure

The changes in cylinder pressure according p-theta for different fuel mixes, i.e. B20, B20 with Al_2O_3 and standard diesel cylinder pressure were 69.54 bar, 67.24 bar and 65.41 bar as indicated in Figure 6 shows, B20-biodiesel provides elevated cylinder pressure due to enriched O_2 particles existing in it, resulting in improved complete combustion and, hence, better quality cylinder pressure. Despite the fact that nano products provide good improved combustion and in-cylinder pressure is to some extent decreases than B20 owed to closely compacted nanoparticle additives, where enriched oxygen molecules are available is lesser (as in B20). We can note that biodiesel with nano particles fuel has enhanced value of calories for consuming less fuel with a less peak pressure [36]. Peak pressure was increased when Al_2O_3 nano-additives were added to SBD at 25 ppm. This improvement in peak pressure may have been caused by the enhanced heat conductivity of the resultant mixture of nano fuels [37].

Heat Release Rate

The various tested fuels were calculated at each crank angle to found out HRR were intended by using thermodynamics first law. The difference of HRR demonstrates in the Figure 7. To investigate entirely fuel trials as a purpose of pressure and crank angle at complete engine load (100%). It has emerged that the quantity of biodiesel in the nano-mixture has a greater effect of the maximum HRR. The combustion rate increases quickly and the rate of heat release decreases because biodiesel fuel blends have a short ignition delay, a higher cetane index, and a lower calorific value. The diesel shows the results 60.2 J/deg, bio-diesel 62.67 J/deg and both biodiesel and nano particle shows 64.35 J/deg. The equation of cumulative HRR can be calculated [38]. The use of nanoparticles quickens the combustion process and releases the most heat possible. The chemical activity of the fuel is increased by high surface area nanoparticles, which speeds up combustion and shortens the ignition delay. The pace at which fuel mixes and release heat is significantly increased by the use of nano-particles [39].

Brake Thermal Efficiency

The variation of BTE vs BP Brake thermal efficiency shows in the Figure 8, an indicator of the effectiveness in converting fuel into heat and mechanical energy, has been explored by Harish Venu.et al. (2019). The changes in BTE for B20, B20 with Al, and standard diesel fuel in response to variations in engine load. Marked improvements in brake thermal efficiency are noticeable in the nano-blends when combined with B20, primarily due to the increased calorific value. This heightened calorific value suggests enhanced injection spray and fuel atomization processes, leading to an augmented brake thermal efficiency [40]. The BTE of nano additives doped TF was higher than that of TF at doping levels of 10 ppm, 20 ppm, and 30 ppm, respectively, by 2.48%, 7.8%, and 1.42% [41].

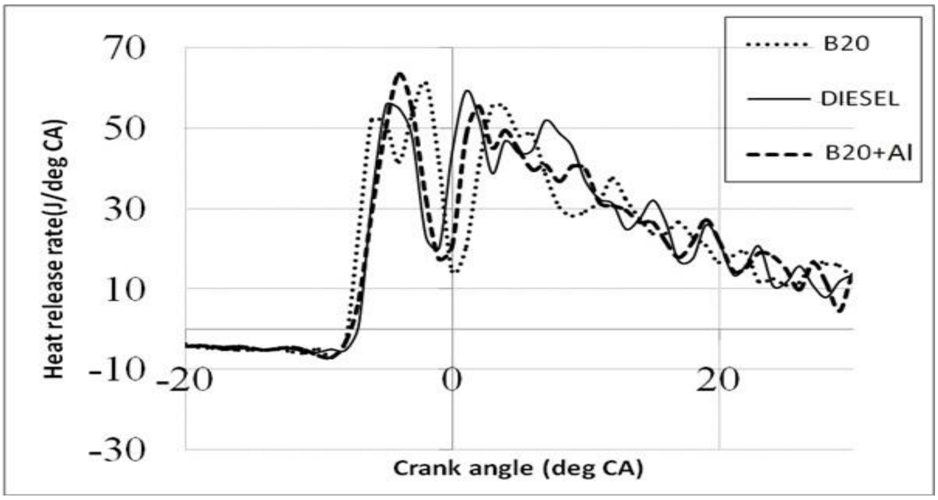

Figure 7. Heat release rate variation at 25% engine load.

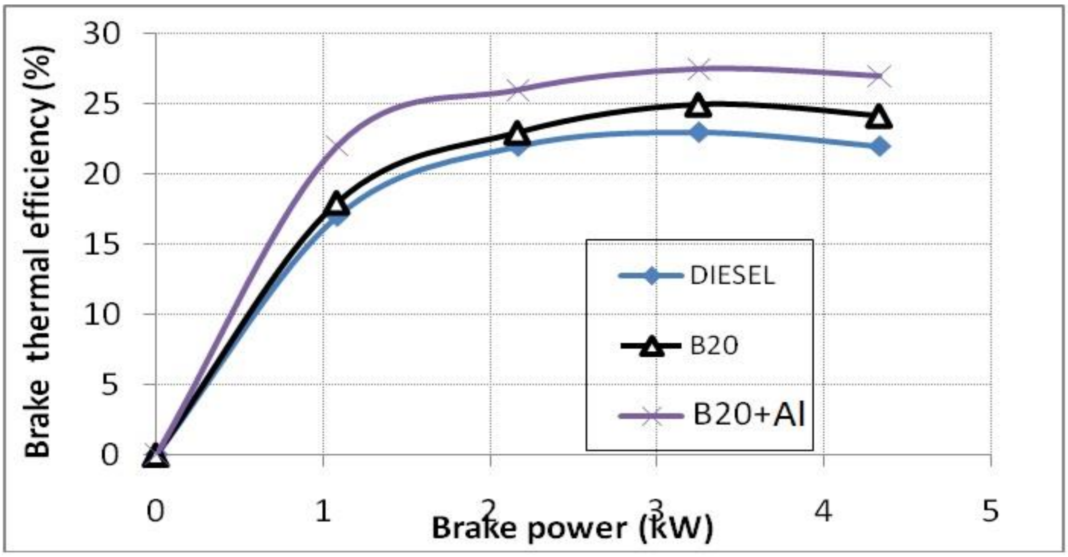

Figure 8. Variation of brake thermal efficiency vs brake power

BSFC and BSEC

BSFC and BSEC are both performance parameters denoted to as “performance analysis”. The assessment of performance often involves analysing (BSFC, BSEC), which provide insights into the energy of fuel intake and the work needed per unit mass of fuel. BSFC specifically measures the fuel required to uphold a constant engine speed (1500 rpm). Typically, BSFC tends to decrease as engine load surges, mainly due to higher peak cylinder temperature and drops ignition delay. Figure 9, illustrates a decline in Specific Fuel Consumption (SFC) as engine load rises, aligning with higher engine temperatures. The diesel fuel at full engine load, records more usage of fuel, followed by B20 and B20 with Al. Diesel exhibits a consumption rate of 0.305 kg/kWh, while B20 shows a rate of 0.254 kg/kWh. The SFC data implies that increased oxygen content enhances combustion efficiency, and the inclusion of B20+Al nano additives significantly impacts combustion due to a greater ratio of exterior area to capacity in the fuel mixtures, ultimately resultant in reduced fuel consumption. Incorporating Al_2O_3 nano additives boosts the oxidation process in biodiesel, contributing to decreased fuel consumption. The oxygen content introduced by Al_2O_3 nano additives quickens the combustion process, enhancing combustion efficiency, thus reducing the BSFC. [42] Numerous studies reported lower BSFC when nanoparticles were added. Additionally, it displays a greater BTE, a lower BSEC, a higher BSFC in diesel, and a higher fuel flow rate [43].

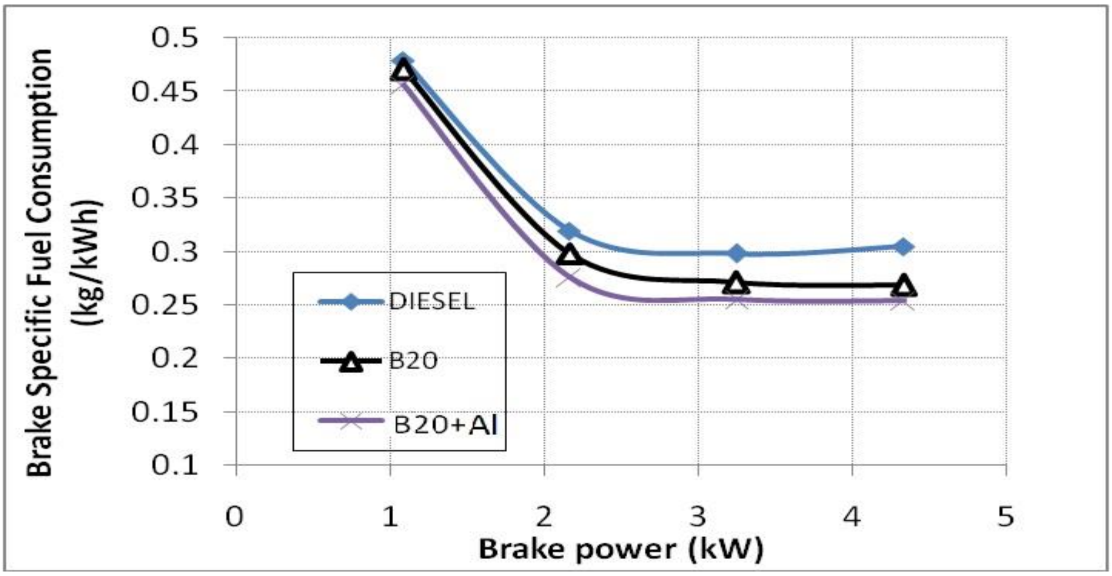

Figure 9. Variation of brake specific fuel consumption vs brake power.

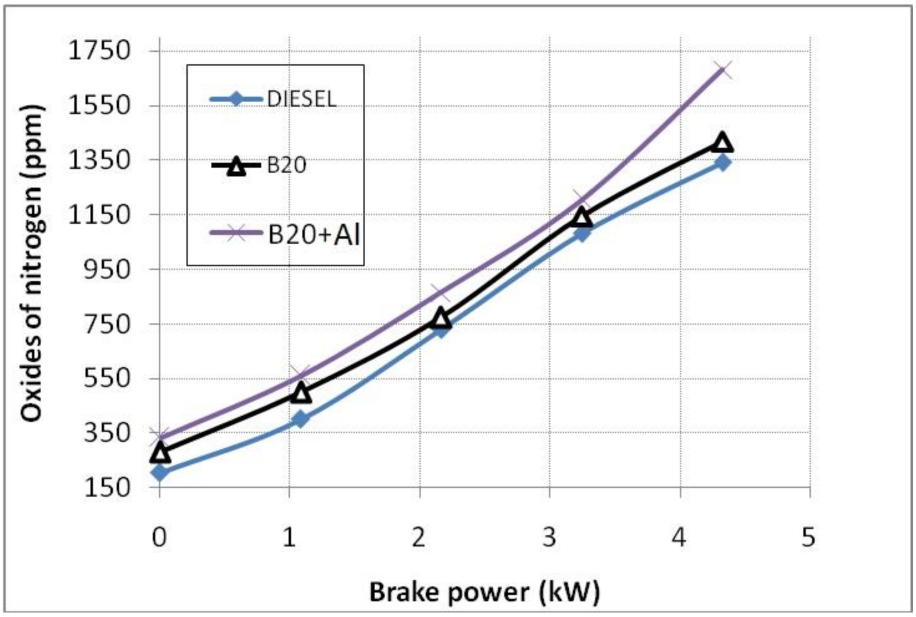

Figure 10. Variation of NOx emissions vs brake power.

Nitrogen Oxide (NOx)

Nitrogen oxide (NOx) emissions in standard Compression Ignition (CI) engines are closely linked to the ignition process occurring within the in-cylinder engine. Various factors such as peak temperature, increased fuel oxidation, and latent heat fuel parameters contribute to the generation of NOx emissions. The correlation between NOx emissions and engine load is depicted in Figure 10. It is evident that at advanced engine loads lead to increased temperatures in the combustion zone, resulting in heightened NOx emissions, aligning with the Zeldovich NO thermal mechanism. [44]. The outcomes demonstrated that NO, soot, unburned hydrocarbon, CO, and CO_2 emissions from diesel engines can be decreased without the use of following-treatment frameworks or fossil fuels, opening the door to prolonging the diesel's lifespan [45]. Compared to other tested fuels, standard diesel fuel displays higher NOx emissions due to elevated exhaust gas temperatures. NOx emissions primarily arise due to the increased O_2 content present at higher engine temperatures.

Higher NOx emissions correspond to greater heat release. In essence, a fuel that produces higher NOx emissions indicates more detailed and fully combustion of diesel fuel. It's detected that NOx levels rise with increasing engine load owing to maximum engine temperatures. The figure distinctly displays that B20+Al demonstrates the highest NOx levels across all loads. Specifically, at 100% engine load, B20+Al records 1680 ppm, whereas B20 and diesel exhibit NOx levels of 1419 ppm and 1340 ppm, respectively. When compared to other fuel additives, the fuels' cetane numbers are greater [46]. This researcher discusses the progress and delaying techniques for examining engine emission characteristics [47].

Carbon Monoxide (CO)

The difference of CO emissions of B20, B20+Al and Diesel fuel. Standard Compression Ignition (CI) engines usually maintain low carbon monoxide (CO) emissions by operating beyond the lean mixture zone, as observed by Kumar and Subudhi in 2019. However, the presence of alcohol and ignition enhancers can influence various characteristics of fuel spray, quantity of oxygen, rate of oxidation, cylinder temperatures, and formation ignition, affecting CO emissions. Additionally, the chemical and physical attributes of the fuel can impact CO formation.

In Figure 11, the changes in CO emissions concerning brake power are shown for diesel (0.050%), B20 (0.038%), and B20+Al (0.018%) fuel blends. Notably, B20+Al exhibits the lowest CO emissions among the fuel blends. Carbon monoxide, a product of incomplete combustion, tends to be more noticeable in lower-load engines with reduced in-cylinder temperatures and pressures due to the similarity ratio and higher dissociation temperatures. The enhanced properties of SBD+25ppm Al_2O_3, combined with the appropriate nano-additives, contribute to an additional 8.28% reduction in CO emissions, lowering it to 2.6 g/kWh with a 25ppm nanoparticle concentration. These research outcomes supported previous studies findings [48], which demonstrated the nanoparticle's helped to reduce carbon-monoxide emissions. In some unique applications, such as removing CO, where more conventional catalysts would be undesirable to remove carbon monoxide through catalyst makes it a very promising material [49].

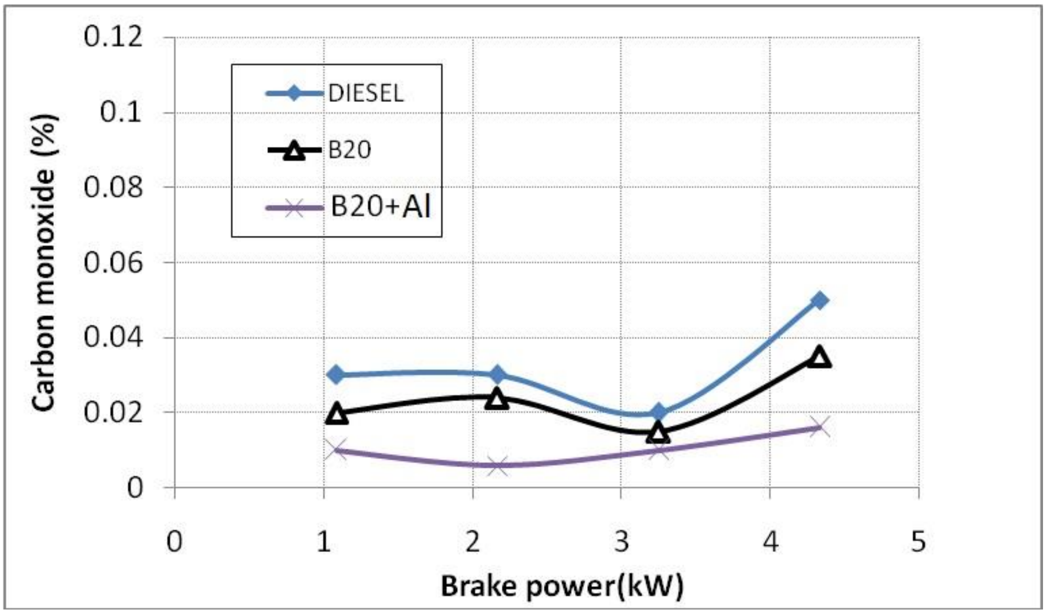

Figure 11. Variation of CO emissions vs brake power.

Carbon Dioxide (CO_2)

Carbon dioxide is a resultant of overall combustion due to oxidized. Owing to nano mixes increased oxygen concentration. Figure 12 shows B20 +Al has a higher CO_2 than diesel. Alumina nano additives have a significant role in enhancing combustion as a result of increasing CO_2 emissions. In order to become CO_2, the available extra oxygen molecule further reunites with CO. The better quality of fuel properties SBD + 25 ppm Al_2O_3 additionally to the presence of nano-additives at a concentration high enough to increase the rate of combustion efficiency may be responsible for the further reduction in CO emissions observed with increasing nanoparticle concentration to 25 ppm. These experimental results agreed well with earlier research findings that the nanoparticle helped to lower CO emissions. The SBD +25 ppm Al_2O_3 enhanced fuel characteristics and the occurrence of enough nano-additives to increase the rate of combustion zone efficiency may be responsible for the additional 8.28% reduction in CO emissions to 2.6 g/kWh with increasing nanoparticle concentration to 25 ppm [50]. The experimental findings supported with previous trials, which, demonstrated that the addition of nanoparticles increased CO_2 emissions. Due to its reduced CO_2 reduction to CO and its ability to transform a hazardous greenhouse gas into a useful chemical, suitable electrochemical reduction of CO_2 is one of the most suitable technologies [51].

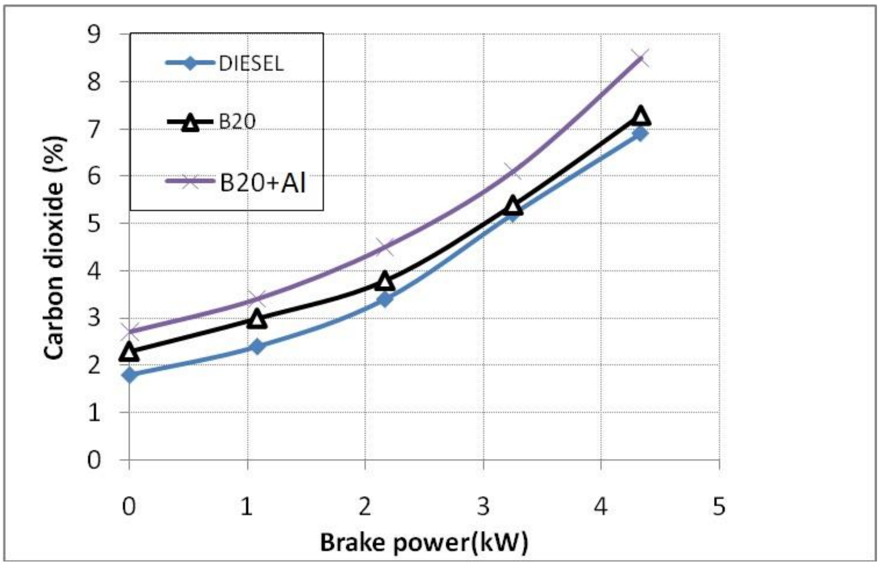

Figure 12. Variation of CO_2 emissions vs brake power.

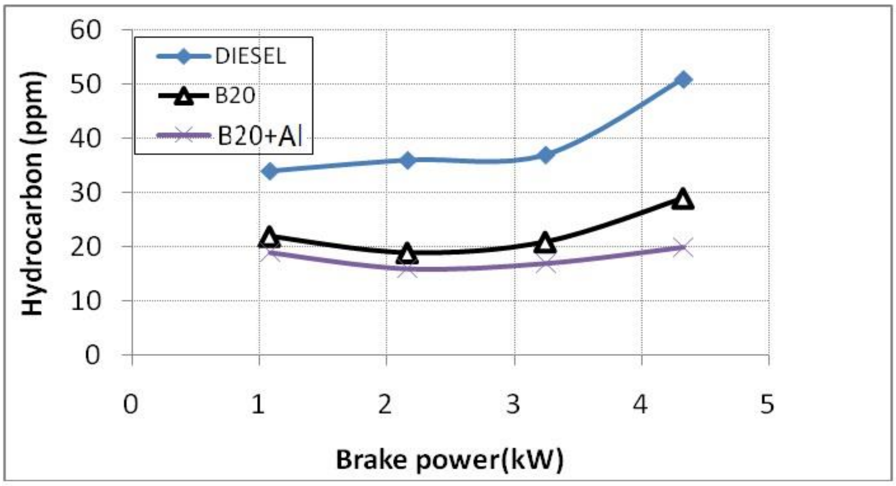

Figure 13. Variation of HC emissions vs brake power.

Hydo Carbon Emissions (HC).

In Compression Ignition (CI) engines, hydrocarbon (HC) emissions have various sources. The primary contributor to HC emissions is fuel trapped in areas such as nozzles, crevices, and cylinder-piston junctions, as highlighted in the research by Mandal and Cho [26]. Figure 13, displays the relationship between brake power and hydrocarbon emissions for diesel (30 ppm), B20 (52 ppm), and B20+Al (20 ppm) fuel blends. It's evident from Figure 13 that biodiesel holds a higher oxygen concentration, which enhances combustion and reduces fuel entrapment in various engine areas. The accumulation of Alumina nano particles in biodiesel significantly diminishes HC emissions. Nano additives with high surface volume-to-area ratios effectively address residual fuel particles within the cylinder chamber, attributed to an appropriate quantity of nanoparticles that expedite combustion and enable oxygen-assisted combustion, leading to reduced Hydro with carbon emissions. These results are in better accordance with the conclusions [52]

Smoke Opacity

Smoke is produced when combustion is incomplete. Overall relationship between smoke and NOx (i.e., smoke drops when NOx increases and vice versa). As compared to B20 and B20+Al, diesel produces more smoke at all load settings, as seen in Figure 14**.** diesel has 22.2 percent at full engine load, trailed by biodiesel(B20) and B20 with Al at 18.1 and 13.1 percent respectively. It shows that B20 with Al produces full burning when compared to the other mixes resulting in lower smoke opacity. In hydrocarbon fuel during combustion, CO_2 and water vapour are liberated. Increased CO_2 levels in engine exhaust imply better fuel oxidation [53]. During combustion, hydro carbon ratio, fuel mixture density, oxygen all play a role in CO_2 production. As seen in Figure 14, As engine load increases, CO_2 emissions increase too. Throughout the load, B20+Al emits more carbon monoxide than biodiesel (B20) and diesel.

During the load circumstances, it can be shown that B20+Al produces more carbon monoxide than biodiesel (B20) and diesel. Under engine full load, B20+Al provides 8.5% respectively. B20 and diesel, on the additional it yields 7.2% and 6.8%, respectively. The occurrence of Al_2O_3 in the B20 mix expands combustion by substitute as a catalyst. As an outcome, there is a greater release of CO_2. Better combustion may also be seen in the smoke characteristics with B20+Al producing the least amount of smoke suggesting better combustion. The reduction in smoke that occurs with a 25ppm increase in nano-particle concentration is due to the existence of a significant quantity of nanoparticles that provides combustion with the help of oxygen, hence reducing synthesis formation of soot and stifling formation of NOx. These results are reliable with individuals of numerous investigators [54], discovered that using nanoparticles decreased the production of smoke gas. According to test results, the thermal performance, THC, CO, and smoke related emissions of a 20% cotton methyl ester (CEME)+80% diesel fuel mixes were equivalent to those of diesel fuel. However, the amounts of CO_2 and NOx emissions were marginally greater with CEME blends [55].

Exhaust Gas Temperature

The generation of heat inside the cylinder during the combustion zone is replicated in the EGT from conventional engines, and EGT has effect on its contaminant formation. The greater combustion temperature of the fuel causes the higher gas temperature i.e EGT, in other words, is related to the high calories inside the fuel. Due to in cylinder peak temperature and increases of engine load, the EGT rises as well [56]. As shown in figure 15d, respectively.

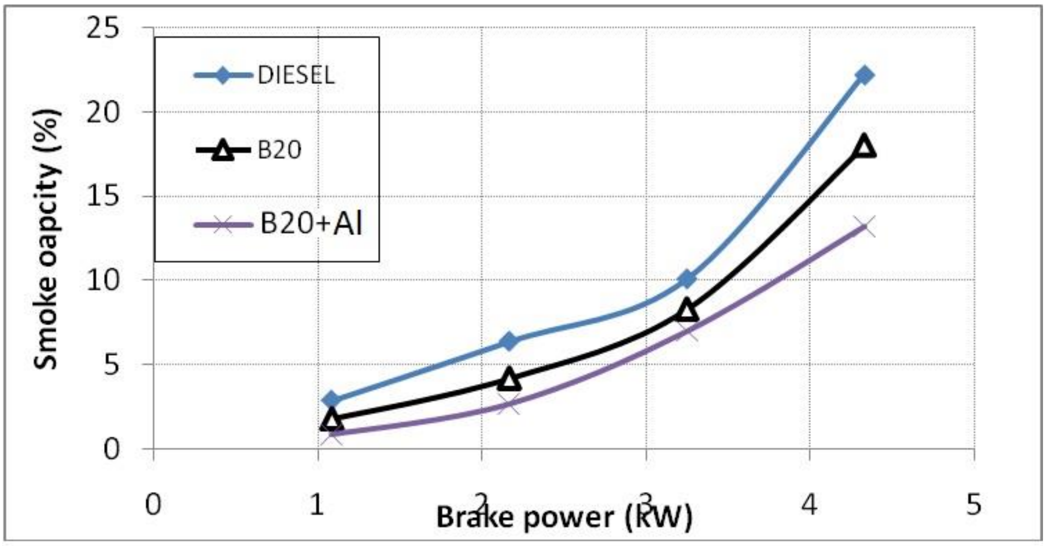

Figure 14. Variation of smoke emissions vs brake power.

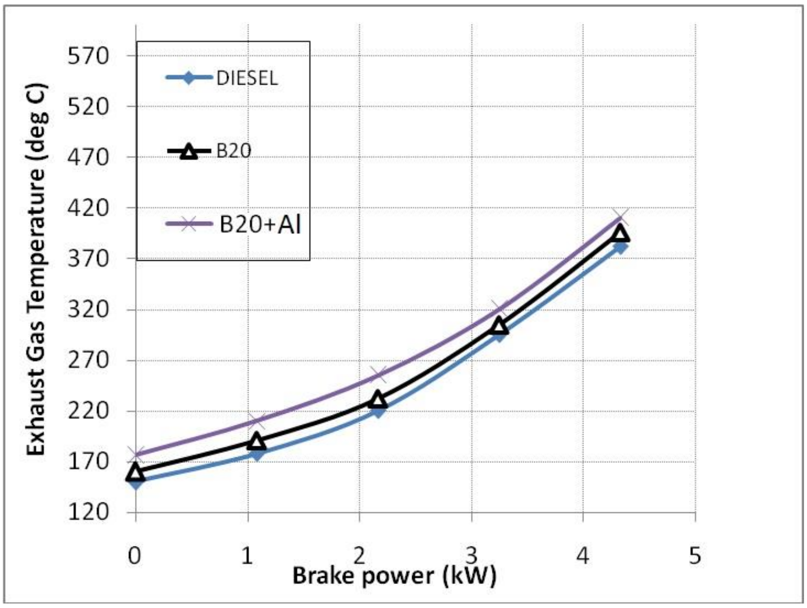

Figure 15. Variation of exhaust temperature vs brake power.

CONCLUSIONS

The present study compares engine characteristics of a 4-stroke single-cylinder CI engine using (diesel, B20 soya bean biodiesel-diesel blend fuel and B20+ Al_2O_3 nano particles. The experiment draws several conclusions: B20 shows the maximum cylinder pressure at full engine load, followed by B20+Al and diesel. The main key findings are concise as follows:

HRR: The diesel shows the results 60.2 J/deg, biodiesel 62.67 J/deg and both biodiesel and nano particle shows 64.35 J/deg-quickens combustion process and releases more heat.

Cylinder Pressure: B20, B20 with Al_2O_3 and standard diesel cylinder pressure were 69.54 bar, 67.24 bar and 65.41 bar; resulting in improved complete combustion; better quality cylinder pressure; enhanced heat conductivity.

BSFC: Diesel exhibits a consumption rate of 0.305 kg/kWh, while B20 shows a rate of 0.254 kg/kWh and the inclusion of B20+Al nano additives significantly impacts combustion due to a greater ratio of exterior area to capacity in the fuel mixtures- resultant in reduced fuel consumption. Numerous studies reported lower BSFC when nanoparticles were added.

BTE: Marked improvements in brake thermal efficiency -7.8% are higher, are noticeable in the nano-blends when combined with B20, primarily due to the increased calorific value. Enhanced injection spray and fuel atomization processes.

HC: Hydrocarbon emissions for diesel (30 ppm), B20 (52 ppm), and B20+Al (20 ppm) fuel blends, which enhances combustion and reduces fuel entrapment in various engine areas significantly diminishes HC emissions.

CO_2: B20 +Al has a higher CO_2 than diesel, the nanoparticle helped to lower CO emissions observed with increasing nanoparticle concentration to 25 ppm.

CO: With the appropriate nano-additives, contribute to an additional 8.28% reduction in CO emissions.

NOx: B20+Al demonstrates the highest NOx levels of 1650ppm, compare whereas B20 and diesel exhibit NOx levels of 1419 ppm and 1340 ppm, respectively.

Exhaust Gas Temperature: B20+Al has a temperature of 420ºC, followed by 396ºC and 382ºC for biodiesel (20) and standard fuel due to the generation of heat inside the cylinder during the combustion zone.

Smoke Opacity: Diesel has 22.2 percent at full engine load, trailed by biodiesel(B20) and B20 with Al at 18.1 and 13.1 percent respectively- B20 with Al produces full burning when compared to the other mixes resulting in lower smoke opacity.

At complete engine load, B20 generates the most heat, followed by diesel and B20+Al. B20+Al exhibits lower BSFC related to B20 and base fuel. The introduction of nanoparticles has reduced CO_2 and HC emissions related to B20 and diesel. CO_2 and nitrogen levels increase due to alumina nanoparticles, promoting more efficient combustion compared to diesel and B20.

Despite Soya bean biodiesel's (SBD) lower Brake thermal efficiency (BTE) compare to diesel across all load conditions of engine. The introduction of Alumina nanoparticles at a 25-ppm concentration enhances BTE (36.94%) and decreases BSFC (30%).

The improved energy density of the fuel mix is attributed to the improved calorific value, requiring less fuel to sustained at an engine speed (1500 rpm). However, this fuel blend emits higher NOx levels due to inherent O_2 content.

Nonetheless, the addition of Alumina nanoparticles serves as a potential catalyst for NOx reduction (Compared w0 fuel, the nano fuel increases the NOx emission from 53 to 60 ppm)

Future work:1. Modified in piston geometry with nano-biodiesel.2.Optimizing the injector nozzle geometry with nano-biodiesel can be done in future for further investigations.3.Experimental study is required on CI engine design parameters such as pilot injection, nozzle geometry, spray pattern and swirl ratio when nano additives blended fuels are used.

ACKNOWLEDGEMENTS

We would like to thank to Department of Automobile Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, Chennai- 600062, India for supporting this research for finding fuel properties. We would also like to thank our colleagues from various engineering colleges, who gave insight and knowledge that considerably aided the research.

REFERENCES

1. Prabu, A. & Anand, R. B. (2016) Emission control strategy by adding alumina and cerium oxide nano particle in biodiesel. *Journal of the Energy Institute*, **89(3)**, 366–372.
2. Chandrasekaran, V., Arthanarisamy, M., Nachiappan, P., Dhanakotti, S. & Moorthy, B. (2016) The role of nano additives for biodiesel and diesel blended transportation fuels. *Transportation Research Part D: Transport and Environment*, **46**, 145–156.
3. Selvakumar, P. & Sivashanmugam, P. (2017) Optimization of lipase production from organic solid waste by anaerobic digestion and its application in biodiesel production. *Fuel Processing Technology*, **165**, 1–8.
4. Sharma, A., Singh, Y., Ansari, N. A., Pal, A. & Lalhriatpuia, S. (2020) Experimental investigation of the behaviour of a DI diesel engine fuelled with biodiesel/diesel blends having effect of raw biogas at different operating responses. *Fuel*, **279**, 118460.
5. Karthickeyan, V. (2019) Effect of combustion chamber bowl geometry modification on engine performance, combustion and emission characteristics of biodiesel fuelled diesel engine with its energy and exergy analysis. *Energy*, **176**, 830–852.
6. Perumal, V. & Ilangkumaran, M. (2017) Experimental analysis of engine performance, combustion and emission using pongamia biodiesel as fuel in CI engine. *Energy*, **129**, 228–236.
7. Patel, H., Rajai, V., Das, P., Charola, S., Mudgal, A. & Maiti, S. (2018) Study of Jatropha curcas shell bio-oil-diesel blend in VCR CI engine using RSM. *Renewable energy*, **122**, 310–322.
8. Subramani, L., Parthasarathy, M., Balasubramanian, D. & Ramalingam, K. (2018) Novel Garcinia gummi-gutta methyl ester (GGME) as a potential alternative feedstock for existing unmodified DI diesel engine. *Renewable energy*, **125**, 568–577.

9. Vellaiyan, S., Subbiah, A. & Chockalingam, P. (2021) Effect of Titanium dioxide nanoparticle as an additive on the working characteristics of biodiesel-water emulsion fuel blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **43(9)**, 1087–1099.

10. Amini, Z., Ilham, Z., Ong, H. C., Mazaheri, H. & Chen, W. H. (2017) State of the art and prospective of lipase-catalyzed transesterification reaction for biodiesel production. *Energy Conversion and Management*, **141**, 339–353.

11. Patel, P. D., Lakdawala, A., Chourasia, S. & Patel, R. N. (2016) Bio fuels for compression ignition engine: A review on engine performance, emission and life cycle analysis. *Renewable and Sustainable Energy Reviews*, **65**, 24–43.

12. Warkhade, G. S. & Babu, A. V. (2018) Impact of supercharging and compression ratio on performance characteristics in a single cylinder DICI engine. *Journal homepage*, **36(3)**, 955–961. http://iieta. org/Journals/IJHT.

13. Janakiraman, S., Lakshmanan, T., Chandran, V. & Subramani, L. (2020) Comparative behavior of various nano additives in a DIESEL engine powered by novel Garcinia gummi-gutta biodiesel. *Journal of Cleaner Production*, **245**, 118940.

14. Karthikeyan, S., Elango, A. & Prathima, A. (2014) An environmental effect of GSO methyl ester with ZnO additive fuelled marine engine. *Indian J Geo-Mar Sci.*, **43(4)**, 564–570.

15. Varatharajan, K. & Cheralathan, M. (2013) Effect of aromatic amine antioxidants on NOx emissions from a soybean biodiesel powered DI diesel engine. *Fuel processing technology*, **106**, 526–532.

16. Jagtap, S. P., Pawar, A. N. & Lahane, S. (2020) Improving the usability of biodiesel blend in low heat rejection diesel engine through combustion, performance and emission analysis. *Renewable Energy*, **155**, 628–644.

17. Manickam, A. R., Rajan, K., Senthil Kumar, K. R. & Manoharan, N. (2015) Performance, emission and combustion characteristics of a diesel engine with the effect of thermal barrier coating on the piston crown using biodiesel. *International Journal of ChemTech Research*, **8(7)**, 397–405.

18. Vedharaj, S., Vallinayagam, R., Yang, W. M., Saravanan, C. G., Chou, S. K., Chua, K. J. E. & Lee, P. S. (2014) Reduction of harmful emissions from a diesel engine fueled by kapok methyl ester using combined coating and SNCR technology. *Energy Conversion and management*, **79**, 581–589.

19. Rajan, K. & Kumar, K. S. (2011) Combustion and emission characteristics of a biodiesel fuelled diesel engine with the effect of thermal barrier coated internal jet piston. *IET*, 184–189.

20. Ferrero, G. O., Almeida, M. F., Alvim-Ferraz, M. C. & Dias, J. M. (2015) Glycerol-enriched heterogeneous catalyst for biodiesel production from soybean oil and waste frying oil. *Energy Conversion and Management*, **89**, 665–671.

21. Krishnamani, S., Harish, V., Harishankar, V. & Raj, T. M. (2018) The experimental investigation on performance and emission characteristics of ceramic coated diesel engine using diesel and biodiesel. *Materials Today: Proceedings*, **5(8)**, 16327–16337.

22. Prabu, S. S., Asokan, M. A., Roy, R., Francis, S. & Sreelekh, M. K. (2017) Performance, combustion and emission characteristics of diesel engine fuelled with waste cooking oil bio-diesel/diesel blends with additives. *Energy*, **122**, 638–648.

23. Raju, V. D., Reddy, S. R., Venu, H., Subramani, L. & Soudagar, M. E. M. (2021) Effect of nanoparticles in bio-oil on the performance, combustion and emission characteristics of a diesel engine. *Liquid Biofuels: Fundamentals, Characterization, and Applications*, 613–637.

24. Srinivas Rao, T., Jakeer Hussain, S., Dhana Raju, V., Venu, H. & Subramani, L. (2022) Experimental assessment of various fuel additives on the performance and emission characteristics of the spark ignition engine. *International Journal of Ambient Energy*, **43(1)**, 1333–1338.

25. Raju, V. D., Venu, H., Subramani, L. & Reddy, S. R. (2020) Comparative assessment of various nanoadditives on the characteristic diesel engine powered by novel tamarind seed-methyl ester blend. In *Recent Technologies for Enhancing Performance and Reducing Emissions in Diesel Engines*, 138–158.

26. Hosseinzadeh-Bandbafha, H., Khalife, E., Tabatabaei, M., Aghbashlo, M., Khanali, M., Mohammadi, P., & Soltanian, S. (2019) Effects of aqueous carbon nanoparticles as a novel nano-additive in water-emulsified diesel/biodiesel blends on performance and emissions parameters of a diesel engine. *Energy Conversion and Management*, **196**, 1153–1166.

27. Allasi, H. L., Rajalingam, A. A., Jani, S. P. & Uppalapati, S. (2023) Influence of synthesized (green) cerium oxide nanoparticle with neem (Azadirachta indica) oil biofuel. *Bulletin of the Chemical Society of Ethiopia*, **37(2)**, 477–490.

28. Zhang, X., Yang, R., Anburajan, P., Van Le, Q., Alsehli, M., Xia, C. & Brindhadevi, K. (2022) Assessment of hydrogen and nanoparticles blended biodiesel on the diesel engine performance and emission characteristics. *Fuel*, **307**, 121780.

29. Mofijur, M., Ahmed, S. F., Ahmed, B., Mehnaz, T., Mehejabin, F., Shome, S. & Kamangar, S. (2023) Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics. *Energy Conversion and Management: X*, 100515.

30. Simhadri, K., Rao, P. S. & Paswan, M. (2024) Improving the combustion and emission performance of a diesel engine with TiO2 nano-particle blended Mahua biodiesel at different injection pressures. *International Journal of Thermofluids*, **21**, 100563.

31. Samuelraj, D., Harish, V. & Jaichandar, S. (2023) The influence of thermal barrier coating on an LHR engine fueled by soybean biodiesel blended with various additive spectrums: Performance, combustion, and emission analysis. *Heat Transfer*, **52(5)**, 3839–3868.

32. Guimarey, M. J., Comunas, M. J., Lopez, E. R., Amigo, A. & Fernandez, J. (2019) Thermo-physical properties of polyalphaolefin oil modified with nanoadditives. *The Journal of Chemical Thermodynamics*, **131**, 192–205.

33. Manickam, A. R., Rajan, K., Senthil Kumar, K. R. & Manoharan, N. (2015) Performance, emission and combustion characteristics of a diesel engine with the effect of thermal barrier coating on the piston crown using biodiesel. *International Journal of ChemTech Research*, **8(7)**, 397–405.

34. Borin, A. & Poppi, R. J. (2005) Application of mid infrared spectroscopy and iPLS for the quantification of contaminants in lubricating oil. *Vibrational Spectroscopy*, **37(1)**, 27–32.

35. Perumal Venkatesan, E., Kandhasamy, A., Subramani, L., Sivalingam, A. & Senthil Kumar, A. (2019) Experimental investigation on lemon-grass oil water emulsion in low heat rejection direct ignition diesel engine. *Journal of Testing and Evaluation*, **47(1)**, 238–255.

36. Venu, H., Raju, V. D. & Subramani, L. (2019) Influence of injection timing on torroidal re-entrant chamber design in a single cylinder DI engine fuelled with ternary blends. *Heat and Mass Transfer*, **55**, 2931–2948.

37. Venu, H., Raju, V. D. & Subramani, L. (2019) Combined effect of influence of nano additives, combustion chamber geometry and injection timing in a DI diesel engine fuelled with ternary (diesel-biodiesel-ethanol) blends. *Energy*, **174**, 386–406.

38. Kumar, M. V., Babu, A. V. & Kumar, P. R. (2018) Experimental investigation on the effects of diesel and mahua biodiesel blended fuel in direct injection diesel engine modified by nozzle orifice diameters. *Renewable energy*, **119**, 388–399.

39. Radhakrishnan, S., Munuswamy, D. B., Devarajan, Y. & Mahalingam, A. (2018) Effect of nanoparticle on emission and performance characteristics of a diesel engine fueled with cashew nut shell biodiesel. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **40(20)**, 2485–2493.

40. Venu, H., Raju, V. D., Lingesan, S. & Soudagar, M. E. M. (2021) Influence of Al2O3nano additives in ternary fuel (diesel-biodiesel-ethanol) blends operated in a single cylinder diesel engine: Performance, Combustion and Emission Characteristics. *Energy*, **215**, 119091.

41. Venu, H., Raju, V. D., Lingesan, S. & Soudagar, M. E. M. (2021) Influence of Al2O3nano additives in ternary fuel (diesel-biodiesel-ethanol) blends operated in a single cylinder diesel engine: Performance, Combustion and Emission Characteristics. *Energy*, **215**, 119091.

42. Venu, H., Veza, I., Selvam, L., Appavu, P., Raju, V. D., Subramani, L. & Nair, J. N. (2022) Analysis of particle size diameter (PSD), mass fraction burnt (MFB) and particulate number (PN) emissions in a diesel engine powered by diesel/biodiesel/n-amyl alcohol blends. *Energy*, **250**, 123806.

43. Karin, P., Tripatara, A., Wai, P., Oh, B. S., Charoenphonphanich, C., Chollacoop, N. & Kosaka, H. (2022) Influence of ethanol-biodiesel blends on diesel engines combustion behavior and particulate matter physicochemical characteristics. *Case Studies in Chemical and Environmental Engineering*, **6**, 100249.

44. Subramani, L., Parthasarathy, M., Balasubramanian, D. & Ramalingam, K. (2018) Novel Garcinia gummi-gutta methyl ester (GGME) as a potential alternative feedstock for existing unmodified DI diesel engine. *Renewable energy*, **125**, 568–577.

45. Duraisamy, G., Rangasamy, M. & Hossain, A. K. (2022) A study on flexible dual-fuel and flexi combustion mode engine to mitigate NO, soot and unburned emissions. *Fuel*, **322**, 124276.

46. Al-lwayzy, S. H. & Yusaf, T. (2017) Diesel engine performance and exhaust gas emissions using

Microalgae Chlorella protothecoides biodiesel. *Renewable Energy*, **101**, 690–701.

47. Shameer, P. M., Ramesh, K., Sakthivel, R. & Purnachandran, R. (2017) Effects of fuel injection parameters on emission characteristics of diesel engines operating on various biodiesel: a review. *Renewable and Sustainable Energy Reviews*, **67**, 1267–1281.

48. Raju, V. D., Venu, H., Subramani, L., Kishore, P. S., Prasanna, P. L. & Kumar, D. V. (2020) An experimental assessment of prospective oxygenated additives on the diverse characteristics of diesel engine powered with waste tamarind biodiesel. *Energy*, **203**, 117821.

49. Li, P., Miser, D. E., Rabiei, S., Yadav, R. T. & Hajaligol, M. R. (2003) The removal of carbon monoxide by iron oxide nanoparticles. *Applied Catalysis B: Environmental*, **43(2)**, 151–162.

50. Ahmed, M. M., Pali, H. S. & Khan, M. M. (2023) Experimental analysis of diesel/biodiesel blends with a nano additive for the performance and emission characteristics of CI Engine. *International Journal of Engine Research*, **24(11)**, 4500–4508.

51. Kim, C., Jeon, H. S., Eom, T., Jee, M. S., Kim, H., Friend, C. M. & Hwang, Y. J. (2015) Achieving selective and efficient electrocatalytic activity for CO2 reduction using immobilized silver nanoparticles. *Journal of the American Chemical Society*, **137(43)**, 13844–13850.

52. Seela, C. R., Alagumalai, A. & Pugazhendhi, A. (2020) Evaluating the feasibility of diethyl ether and isobutanol added Jatropha Curcas biodiesel as environmentally friendly fuel blends. *Sustainable Chemistry and Pharmacy*, **18**, 100340.

53. Bala Prasad, K., Meduri, O., Dhana Raju, V., Azmeera, A. K., Venu, H., Subramani, L. & Soudagar, M. E. M. (2020) Effect of split fuel injection strategies on the diverse characteristics of CRDI diesel engine operated with tamarind biodiesel. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–19.

54. Hosseinzadeh-Bandbafha, H., Khalife, E., Tabatabaei, M., Aghbashlo, M., Khanali, M., Mohammadi, P. & Soltanian, S. (2019) Effects of aqueous carbon nanoparticles as a novel nano-additive in water-emulsified diesel/biodiesel blends on performance and emissions parameters of a diesel engine. *Energy Conversion and Management*, **196**, 1153–1166.

55. Venu, H., Raju, V. D., Subramani, L. & Appavu, P. (2020) Experimental assessment on the regulated and unregulated emissions of DI diesel engine fuelled with Chlorella emersonii methyl ester (CEME). *Renewable Energy*, **151**, 88–102.

56. Sarma, C. J., Sharma, P., Bora, B. J., Bora, D. K., Senthilkumar, N., Balakrishnan, D. & Ayesh, A. I. (2023) Improving the combustion and emission performance of a diesel engine powered with mahua biodiesel and TiO2 nanoparticles additive. *Alexandria Engineering Journal*, **72**, 387–398.