

Clean energy technology: Hydro-processing of waste tyre pyrolysis oil (WTPO) to diesel fuel in a continuous reactor using Co/SBA-15 catalyst

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ABSTRACT

The need for sustainable fuel sources and efficient waste management has led researchers to explore innovative methods for converting waste into fuel. One promising avenue is the utilization of 100 % tyre oil (TO), which could offer a profitable and environmentally friendly solution for disposing of waste tyres. With rising fossil fuel costs, environmental concerns, and the challenges of waste tyre landfilling, there is increased interest in waste tyre pyrolysis oils (WTPO) as an alternative energy source. This study examines the hydro processed WTPO (HWTPO) was analysed using a metallic catalyst, specifically Co/SBA-15. This method involves hydrolysing WTPO with the metallic catalyst, assessing the physical-chemical properties, formulation efficiency compared to petroleum products, and diesel engine performance like the impact on fuel consumption, combustion, and emissions. The synthetic HWTPO's chemical and physical properties were found to be comparable to European diesel specifications (European standard 590). Under hydroprocessing conditions (80 bar and 375 °C), the Co/SBA-15 catalyst produced isoalkanes, n-alkanes, and aromatics in quantities nearly equivalent to 100 % diesel. HWTPO demonstrated the potential to maximize greenhouse gas emissions reduction and enhance the performance of diesel-powered engines. The favourable properties of HWTPO suggest that waste tyre pyrolysis oil could be a viable transportation fuel.

1. Introduction

The number of cars used in the transportation sector has grown, which has raised the demand for fuel [1]. The world's reserves of petroleum are depleting at the same time, which is causing concerns about environmental degradation and driving the need for research into alternative sources of energy [2]. Biofuels present a number of benefits over conventional petrol derived from petroleum, such as sustainability

for the environment and renewability [3]. This has to do with the fact that harmful pollutants including the greenhouse gases hydrocarbons (HC), carbon dioxide (CO₂), carbon monoxide (CO), and soot among others are reduced during the mixture from burning [4]. Fortunately employing sustenance-based biodiesel as a substitute for gasoline, such as those created from palm, the seeds of rap and oil from soybeans has drawn criticism from every corner of the world concerning reforestation and the possible conflict between the production of food and fuel [5].

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The following resulted in worries about the possibility creating a world food crisis [6,7]. As a result, the enormous possibility of turning garbage into fuel is a substitute that reduces the amount of waste in the world is becoming increasingly apparent. Solid waste is a big issue which brings about problems for the environment and the economy as a whole [8]. Tyre trash ought not to be disposed of in landfills or stockpiles as this presents a serious risk towards the environment along with exacerbates problems with the environment. A number of automakers and producers of diesel fuel injection equipment have updated their warranty policies to address these issues, permitting mixes with up to 20 % (by volume) of alternative fuels [9].

Tyre oil (TO), which is obtained from used tyres, possesses multiple advantages over conventional diesel fuel. The process of pyrolysis, which entails oxygen-deprived thermal breakdown, provides the additional advantage of reusing used rubber and lowering reliance on natural resources [10]. In this process, the naturally occurring component, rubber, breaks down at about 500 °C to produce petrol, oil and char whilst permitting steel to be recovered [11]. The recovered tyre oil can be stored in petroleum refineries, processed using catalysts to produce high-quality fuel, or used to create hydrogen [12]. Without significantly to the global waste load, TO provides a sustainable solution to the growing volume of discarded tyres and rubber material produced by automobile manufacturers [13]. Approximately 1.5 billion tyres are discarded annually in the world, which is a serious problem because of their potential environmental impact and lack of biodegradability [14]. Tyre composition normally comprises stainless steel (16–26 wt%), black rubber (46–66 wt%), carbon (22.5–36.5 wt%), and different additives like zinc and sulphur [15]. The tyre's composition modifications depending upon its intended usage; industrial tyres have a greater proportion of natural rubber, whereas car tyres include synthetic rubber (consisting of 28 %). Tyres' rubber component is made up of the hydrocarbons and fibrous materials, and its non-rubber components are made of metal, fillers, plasticizers in order additives, and chemicals like sulphur [16,17]. Rubber's high calorific value (over 36 MJ/kg) and carbon content make it a desirable feedstock for fuel production. Waste tyre oil (TO) have been investigated as an eventual diesel substitute in a number of experimental investigations [18]. Compared to diesel fuel, tyre oil has a higher oxygen content (0.12–3.99 %), which affects the fuel's calorific value, engine performance, kinematic viscosity, and level of unsaturation that exists [19].

Plenty of research into the energy and exergy-economic analysis of energy systems particularly those involving internal combustion engines, have been carried out by a single-cylinder, 4-stroke compression ignition engine to study the environmental, exergo-economic, and environmentally sound aspects of fuel made from diesel and tyre oil (TO) blended fuel at various torque ranges [20,21]. The results of the investigation demonstrated that the mixture containing TPO10D90 mix outperformed the clean diesel at 26.11 % and 25.31 %, respectively, in terms of conservation of energy (28.35 %) and energy efficiency (26.40 %) [22]. Additionally, TPO10D90's sustainability index score at 12 Nm torque had been 1.358, while the diesels were 1.337. Another investigation was carried out by Mori and the researchers Caliskan with varying weights at a constant speed of 1800 rpm. The study concentrated on both pure diesel as well as biodiesel-diesel blends [23].

In the final analysis, it was determined that blended diesel and biodiesel fuel was more energy and energy efficient than diesel alone. Moreover, this efficiency had been further improved by the higher proportion of biodiesel in the entire mixture [24]. Yaqoo also conducted a study of the same type of data using mixtures of diesel fuel, biodiesel, and tyre oil (TO) in a four-cylinder supercharged diesel engine [25]. The research findings showed that the combination of the TO10 blend (10 % TO, 90 % Diesel) outperformed the biodiesel-diesel blended fuel. The highest energy efficiency (37.12 %) and (39.6 %) have been identified in TO10 [26]. Furthermore, when compared to the biodiesel-diesel mixed fuel, TO10 was the most environmentally friendly and sustainable fuel as determined by its sustainability index parameter. Dogan investigated

the incorporation of a combination of titanium dioxide (TiO₂) and silver oxide (Ag₂O) nanoparticles to cottonseed oil-based biodiesel fuel [27]. The combination of nanoparticles in biodiesel fuel resulting with improved thermal and energy efficiency [28]. Nanotechnology-based fuel mixes have reduced the overall energy inefficiencies. The test fuels C100, CAg-75 (100 % cottonseed oil-based biodiesel with 75 parts per million silver dioxide), and CTi-75 (100 % the seeds of cotton oil biodiesel with 80 components per million titanium oxide) all experienced total electricity losses of 14.51 kW, 13.81 kW, and 12.20 kW, respectively, when 40 Nm of engine torque was applied [29,30]. Under the same circumstances, the total electrical energy loss in D100 petrol was calculated to be 12.04 kW. At 45 Nm of engine torque, the environmental sustainable development indexes for the D100 and CTi-80 fuels were 1.712 and 1.626, respectively. Balli assessed the J69 military turbojet engine, which uses an entirely renewable biofuel and jet fuel mixture to power the Cessna T-38 B/C. The J69 turbojet engine's environmental effect factor goes from 5.324 to 5.301 and the engine's energy efficiency rises from 17.16 to 17.56 % when biofuel is used. Although biofuel has somewhat higher fuel prices and uses less energy than jet fuel, it can still be used as a renewable aviation fuel source [31, 32].

The operational methods of different types of plastic derived oil hydroprocessing and catalysts pyrolysis possess the capability to convert plastic waste into valuable products, mitigating its detrimental environmental impact and fostering the circular economy [ref]. Producing waste tyre pyrolysis oil (WTPO) is of significant interest due to its potential to address both waste management and energy production issues. The process of pyrolysis involves the thermal decomposition of materials at high temperatures in an inert atmosphere, resulting in the production of oil, gas, and char from waste tyres. Waste tyres are a significant environmental problem due to their non-biodegradability and the space they occupy in landfills. Pyrolysis offers an effective method to reduce the volume of waste tyres and convert them into useful products. Traditional disposal methods, such as landfilling and incineration, lead to pollution and greenhouse gas emissions. Pyrolysis is a cleaner alternative, reducing harmful emissions and preventing leachate formation in landfills [33]. WTPO can be utilized in industrial furnaces, power plants, and diesel engines, contributing to energy diversification. The oil can be refined and used as a substitute for conventional fuels [34]. Converting waste tyres into pyrolysis oil adds economic value to otherwise worthless waste. The oil, gas, and char produced can be sold, providing a source of revenue. Utilizing WTPO as a fuel can reduce costs for industries dependent on conventional fuels, contributing to economic efficiency [35]. The production of WTPO supports the principles of a circular economy by recycling waste materials and reducing the demand for virgin fossil fuels [36]. Research has focused on optimizing the pyrolysis process parameters to maximize oil yield and improve the quality of the produced oil. The production of WTPO is a promising solution that addresses multiple environmental and economic challenges [37]. It represents a sustainable approach to waste management and energy production, with significant potential for future development and implementation.

Continuous flow processes offer higher operational efficiency compared to batch processes. They allow for steady-state operation, which can be more easily controlled and optimized, leading to higher throughput and consistent product quality [38]. Continuous flow systems often provide better catalyst performance due to improved mass and heat transfer. The constant flow of reactants and products helps maintain optimal reaction conditions and prolongs catalyst life. The design of continuous reactors allows for more efficient use of catalysts, ensuring that the entire surface area of the catalyst is utilized effectively [39,40]. This methodology of catalytic hydro processing can achieve higher yields and selectivity for desired products, enhancing the economic viability of the process [41]. The continuous flow catalytic hydro processing of WTPO presents significant advantages in terms of efficiency, product quality, economic viability, and environmental

sustainability. It is a promising technology for the effective conversion of waste materials into high-value fuels and chemicals [42].

The environmentally friendly assessment analyses a system's sustainability by taking into account both current requirements and potential future advantages. Many research projects that combine sustainability and energy analysis throughout a range of disciplines and processes are available in the literature [43]. Exergy is primarily described as the level of energy which represents the maximum work output generated by a system that interacts with its environment or the least amount of effort required achieving a given state within a given environment [44]. In comparison with energy analysis alone, energy analysis takes irreversibility into account and provides a more comprehensive comprehension of a system's thermal characteristics [45].

The purpose of this study was to create waste tyre pyrolysis oils (WTPO), mix it with regular diesel and examine how well it burned and produced emissions in a diesel engine. ZSM-5 was used as the catalyst in catalytic pyrolysis, which was carried out utilising post-consumer waste tyre pyrolysis oils (WTPO) as the starting material. Utilising Co/SBA-15 as the catalyst, the oil produced from hydro processing waste tyre pyrolysis oils (HWTPO) were hydro processed at 80 bar hydrogen pressure and 375 °C. In order to examine and contrast the physicochemical properties and composition of WTPO and HWTPO with diesel, GCMS and physicochemical experiments were conducted. Diesel was blended with HWTPO at weight percentages of 20 %, 40 %, and 60 %. In order to ascertain the combustion, performance, and emissions, performance of engines trials were carried out for the HWTPO blend.

2. Experimental section

The prerequisite for the hydro processing of WTPO involves the following steps:

- * Pyrolysis of waste tyre oil by ZSM-5 catalyst.
- * Synthesis of catalyst (Co/SBA-15) for hydro processing
- * Continuous flow catalytic reactor.

2.1. Pyrolysis of waste tyre oil by ZSM-5 catalyst

The amount of garbage waste tyre pyrolysis oils (WTPO) from post-consumer tyres were shred to a 3 mm size. In a specifically designed semi-batch reactor, waste tyre pyrolysis oils (WTPO) granules had been the catalytic process paralysed using the ZSM-5 catalyst. The reactor and furnace of the pyrolysis apparatus are simplified in Figure. S1. With a 2.5 KW rating, the furnace can operate at temperatures as high as 900 °C with the heating rate of 10 °C/min. The tube length to diameter ratio of the stainless steel reactor is 5:2. The reactor's inert environment was kept in place through the utilisation of vacuum.

2.2. Synthesis of Co/SBA-15 catalyst for hydroprocessing

The n-butanol was employed as a co-surfactant and as a template, accordingly, using Pluronic P123 (EO20PO70EO20, Poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol)). The 3.5 g of Pluronic F123 triblock copolymer (Sigma-Aldrich) was roughly disintegrated using 180 ml of 0.3 M Hydrochloric acid at 45 °C. The aforementioned mixture was constantly stirred while 12 mL of n-butanol was added. 17.1 g of Tetraethyl orthosilicate (TEOS-98 %, ACROS Organics) and the needful amount of Sodium tungstate were added to the above mixture. Then, the resulting mixture was stirred thoroughly for about 20 hrs. After that, the complete mixture was intermittently heated for 24 hrs in a polypropylene bottle at 98 °C. Subsequently, the precipitate was filtered off in hot condition (without washing) and dried for a whole night at 100 °C. The resultant substance was calcined for 5 hrs at 550 °C for the elimination of the template with the air movement. The

metal catalyst on the support was synthesized by a wet-impregnation method by using 5 wt.% Co on the SBA-15, then, the resultant slurry was dried at 120 °C for 8 h followed by calcination at 550 °C for 5 h. Finally, the end product was obtained and represented as Co/SBA-15 [46].

2.3. Set-up of continuous flow catalytic reactor for hydro processing

The study experiment was carried out in a down flow mode employing a stainless steel fixed bed reactor with a 6 mm diameter that was intended to function under high pressure. The 4.2 g pure catalyst with a 1–2 mm size was used. Figure S2 shows a schematic illustration of the high-pressure fixed-bed micro reactor that was utilised in the present investigation. There are three sections to the flow diagram. The feed line and input lines are located in the first section (right side of the picture), the reaction chamber and eight-port valve are located in the second part (middle), and the vent and condenser to collect the finished product are located in the last part. Feed line filters and valves with checks in the mass flow control systems govern the initial part's gas flow control components. An additional input port next to the reactor's gas pipelines is used to feed the liquid reactant via an eight-port valve and a pump into the reactor chamber. Then, using a hot oven in the middle, the feed mixture is poured into the reactor via an eight-port valve. Utilising this procedure, vaporised input mixtures or output can be added to an online gas chromatograph. A temperature metre and controller are used to monitor and control the reactor furnace's temperature. A mass flow controller electronically controls and measures the oven's temperature, which is typically kept at about 375 °C. Waste plastic oil indicates the pressure inside the reactor. The drain gate, liquid condenser, high-pressure barrier, and back-pressure controller make up the last part.

2.4. Hydro-processing of waste tyre pyrolysis oils(wtpo)

A continuous flow, high-pressure stainless steel reactor was used to hydrogenate liquid phase waste tyre pyrolysis oils. On an hourly basis on average, an HPLC pump was used to circulate 8 millilitres of waste tyre pyrolysis oils (reactant), along with 4.2 gs of Co/SBA-15 catalyst. The combination indicated above was heated to 375 °C for one hour while being stirred and subjected to 80 bar of pressure (with a hydrogen flow rate of 15 mL/min). Afterwards, it was cooled to room temperature. The hydro processed components were separated by centrifugation resulting in the final step of the catalytic reaction. The final components were identified using a gas chromatography apparatus with a flame ionization detector where nitrogen is used as a carrier gas. The SGE BPX70 (70 % cyanopropylpolysilphenylene-siloxane) capillary column in the reactor has dimensions of 60 m × 0.53 mm in ID and 0.50 µm in film thickness.

2.5. Diesel engine performance and test for physicochemical properties

The physical and chemical properties of premium WTPO, HWTPO, and commercial diesel were investigated in accordance with IS specifications. The physicochemical results facilitate the comparison and analysis of the properties of HWTPO with WTPO, commercial diesel, and EN590 standards. On a turbocharged Eicher E484, diesel engine tests have been conducted at a constant pace. Figure S3 depicts the schematic structure of the test engine establishment Table 1 lists the test engine's technical characteristics.

2.6. Samples characterization

Fourier transform infrared (FT-IR, Thermo Nicolet 380) spectra of ILs and samples were measured at room temperature with a spectral range from 4000 to 500 cm⁻¹, and anhydrous KBr was employed as the reference criterion. The crystal structures of the samples were recorded by X-ray diffractometer (XRD, Rigaku, Saudi) using Cu Kα (λ = 0.1541

Table 1

Diesel engine specifications.

Engine Brand	Renault Kangoo K9 K 700 model engine
Diesel Engine	Type 4 cylinder in-line T/C, DI
Compression ratio	18.25: 1
Fuel injection system	Common-rail direct injection system
Displacement	3298 cm ³
Max. power	48 kW @ 4000 rpm
Turbocharger	Boost pressure
No. of cylinders	4
Strokes	4
Valves/cylinder	2
Injector: hole _ dia	5 _ 0.209 mm
Injection timing	12 °CA bt dc
Nozzle opening pr	23 MPa
Bore × Stroke	76.0 × 80.5 mm
Total cylinder volume	1.461 L
Emission certification	India 4

nm) radiation with a diffraction range of $2\theta = 1^\circ$ to 5° & 10° to 80° transmission electron microscopy (TEM, JEM-2100 F) images of the sample surface were obtained for the analysis of the morphology and size. Surface areas of samples were measured through the BET tests with a Micromeritics porosimeter (ASAP-2020 HD88). N_2 adsorption-desorption and porosity results were obtained using a Micromeritics Tristar II 3020 surface area analyzer. 0.2–0.3 g of catalyst was degassed, and all samples were degassed before analysis using the Barrett, Joyner & Halenda (BJH) method. Temperature-programmed desorption (NH_3 -TPD) measurements were performed on a chemisorption device (Micromeritics Auto Chem II) by using a thermal conductivity detector over a 70 mg catalyst sample, respectively. In H_2 -TPD, NH_3 absorption is monitored up to $1000^\circ C$ under 10 % H_2/He gas, whereas in NH_3 -TPD, CO_2 desorption is monitored upon raising the temperature to $800^\circ C$ under 10 % CO_2/He gas. The products analyzed were acquired with a Quadrupole Mass Spectroscopy Gas Chromatography (GC-MS).

3. Results and explanation

3.1. Establishment of the structure and phase

The Co/SBA-15 samples' low angle X-ray spectroscopy is shown in

Fig. 1a. The appearance of the intense distinctive peak at 2θ degree of 0.94° and 0.97° , which corresponds to [100] and [111] reflection, was evident in the SBA-15 samples. This demonstrated that the samples had ordered structures and the diffraction lines are similar to the Im3 m space group's cubic cage-like structure. The [111] plane progressed towards an angle that was greater, equivalent to the corresponding peak position. The intensity of the peak drop was observed when the Co catalyst was introduced in the sample Co/SBA-15. This result depicts that by adding cobalt, increases the unit cell parameter. This implies that extra-framework of cobalt species can be found at the higher stresses [16].

The high angle X-ray spectroscopy for each sample Co/SBA-15 is displayed in Fig. 1b. Mesoporous silica is characterised by a peak that is centred at $2\theta = 23^\circ$ in all of the samples. They do nonetheless, however, display visible reflections with regard to the extra-framework crystalline species Co. It does not imply that there are no Co atoms. There is no Co peaks even at higher loading. This may be occurred because extremely small crystallites have been embedded inside a pore structure. So, TEM scans will verify the presence of cobalt (Co) within the base (SBA-15) material [47].

3.2. FT-IR spectroscopy

Figure. S4 demonstrate the Infrared spectra of the sample Co/SBA-15 recorded between the wavelength 400 to 4000 cm^{-1} . The basic IR bands of the sample Co/SBA-15 is due the asymmetric stretching vibration and symmetric stretching vibration the Si-O-Si bond was observed around $808 - 1060\text{ cm}^{-1}$. In the niobium loaded SBA-15, the band at 960 cm^{-1} supporting that it is linked to the neighbouring nations integrated metal ion causing disruption the stretching vibration of Si-O, which is part of the silica support. The band within the range of $550\text{--}600\text{ cm}^{-1}$ may suggest the vibration of Co-O-Co bond within the crystalline silica support. The spectroscopic band observed at 1631 cm^{-1} would specify the bending vibration of water molecules inside the SBA-15 framework. This vibration is most likely the result of water being absorbed by samples during the process of compacting KBr pellet. A strong and broad band is seen at 3495 cm^{-1} in all samples and this band is caused by the stretching vibrations by the Si-OH and OH bonds.

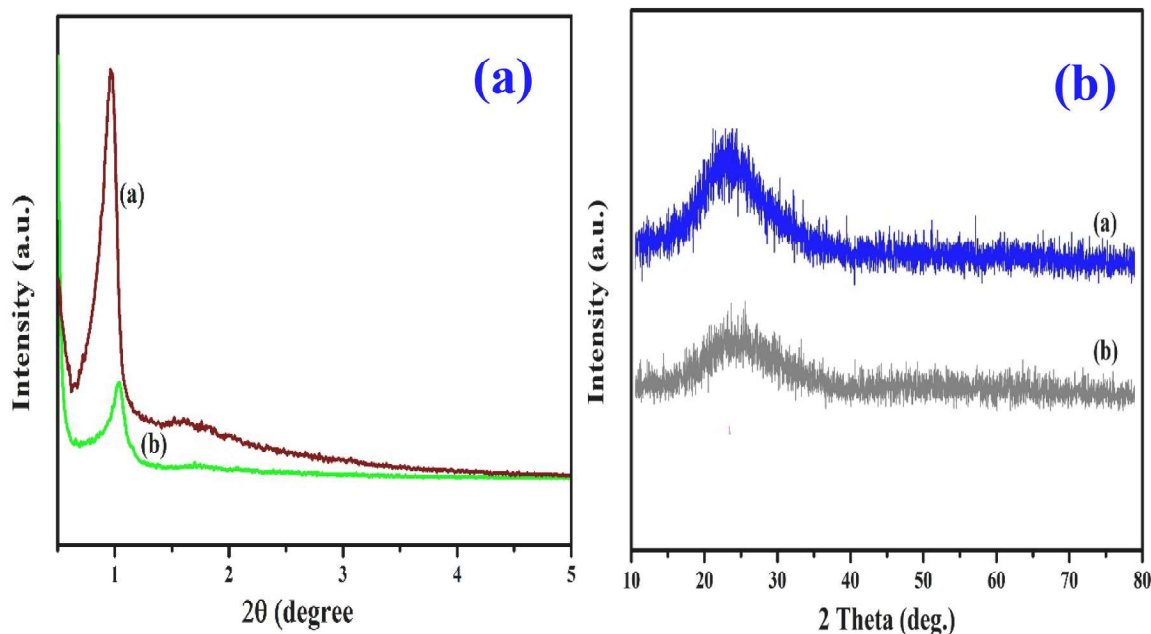


Fig. 1. a. Low angle XRD patterns of (a) SBA-15 and (b) Co/SBA-15. b. High angle XRD patterns (a) SBA-15 and (b) Co/SBA-15.

3.3. Textural properties

Regarding samples Co/SBA-15 the N_2 gas adsorption-desorption isotherms were measured and shown in Fig. 2. Furthermore, the distributions about pore sizes are also computed. Table 2 displays the textural features of the samples Co/SBA-15. The pure SBA-15, and Co/SBA-15 samples, shows the distinctive type-IV adsorption equilibrium isotherm with an H_2 -type of hysteresis loop which verifies the presence of mesoporous (cage-type) structure of the samples. When the amount of niobium in the support is increased, both the overall volume of pores and BET particular surface area decrease dramatically, drop from 1.22 to 0.98 cm^3/g and 688 to 631 m^2/g , respectfully. This could be because SBA-15's mesoporous channels are creating tiny niobium oxide clusters.

3.4. Identification of morphology

The high-resolution TEM images of SBA-15 have been shown in Fig. 3a. The SBA-15 sample demonstrates the presence of highly organised arrays of mesoporous. The TEM images of the Co/SBA-15 sample, obtained before and after the reaction, are displayed in Fig. 3a & 3b, respectively. As the niobium gets embedded and becomes visible, the arrangement of the pores diminishes (Fig. 3b). Following the reaction, the pores' orderliness progressively declines (Fig. 3b). The presence of particles of metal smaller around 20 nm in the SBA-15 indicates a very good dispersion of niobium.

3.5. HR-SEM analysis and elemental mapping

Scanning electron micrographs of the sample pure SBA-15 and Co/SBA-15 are shown in Fig. 4a-4b. Without agglomeration, several morphologies with uneven dimensions are seen in the sample Co/SBA-15. The samples morphologies are not significantly different from one another. The length of the morphological size varies from 200 nm to 3 μm . The slightly rougher surface of morphology may be caused by the fact that each morphology is composed of many particles, each measuring somewhere in the range of fifteen to twenty nm. The EDX spectrum of Co/SBA-15 is displayed in Fig. 4c and only shows peaks for Si, O, and Co. This attests to the material's purity as synthesised [48].

3.6. Elemental mapping analysis

The Co/SBA-15, the elemental mapping process was used to

Table 2

Textural properties of synthesised SBA-15 and Co/SBA-15 catalyst.

Catalysts	S_{BET} (m^2/g)	V_{total} (cm^3/g)	Acidity ($mmol/g$) ²		
			Total	*LT peak	*HT peak
SBA-15	688	1.22	0.72	0.32	0.40
Co/SBA-15	631	0.98	1.55	0.97	0.58

determine the distribution of Si, O, and Co in the sample. The elemental mapping and pictures from electron microscopy of the Co/SBA-15 catalyst are shown in Figure S5. The results demonstrated the consistent distribution of Si, O, as well as Co elements. Niobium is a uniformly distributed element with trace levels of the component present. The results confirmed that no singular event was observed in particular regions of the powdered substances that were the subject of the study.

3.7. Determination of reducible species and total acidity

The ammonia's-TPD (Temperature-programmed desorption) was used to calculate the samples' overall acidity. The relevant TPD profiles of the sample pure SBA-15 and Co/SBA-15 are displayed in Fig. 5a & 5b. At temperatures below freezing, Pure SBA-15 samples Co/SBA-15 shows a single peak that could be classified as weak acid sites that ranged in temperature from 190 to 240 $^{\circ}C$ and it is commonly known that the mesoporous materials lack acidic spots. Therefore, the artificially generated total acidity in the sample Co/SBA-15 may be due to the presence of Co that was intentionally included into the SBA-15 materials. As a result, the overall acidity is determined by the Co content in the SBA-15. As anticipated, the overall acidity (weak and moderate acidity) of the sample Co/SBA-15 rises as cobalt catalyst loaded. In the Co/SBA-15 sample, the peak location moved in the direction of increasing temperature, which is presumably stronger acidic sites had developed. However, as when compared with the other samples, the Co/SBA-15 sample has a higher overall acidity. The peak-centred range of temperature for the sample other than the sample Co/SBA-15 was observed in the range of 140–300 $^{\circ}C$ [49].

3.8. XPS analysis

The surface composition and valence state of the elements in Co/SBA-15 was evidenced by XPS measurement. The survey spectrum and high-resolution spectra of various elements composed of Co/SBA-15

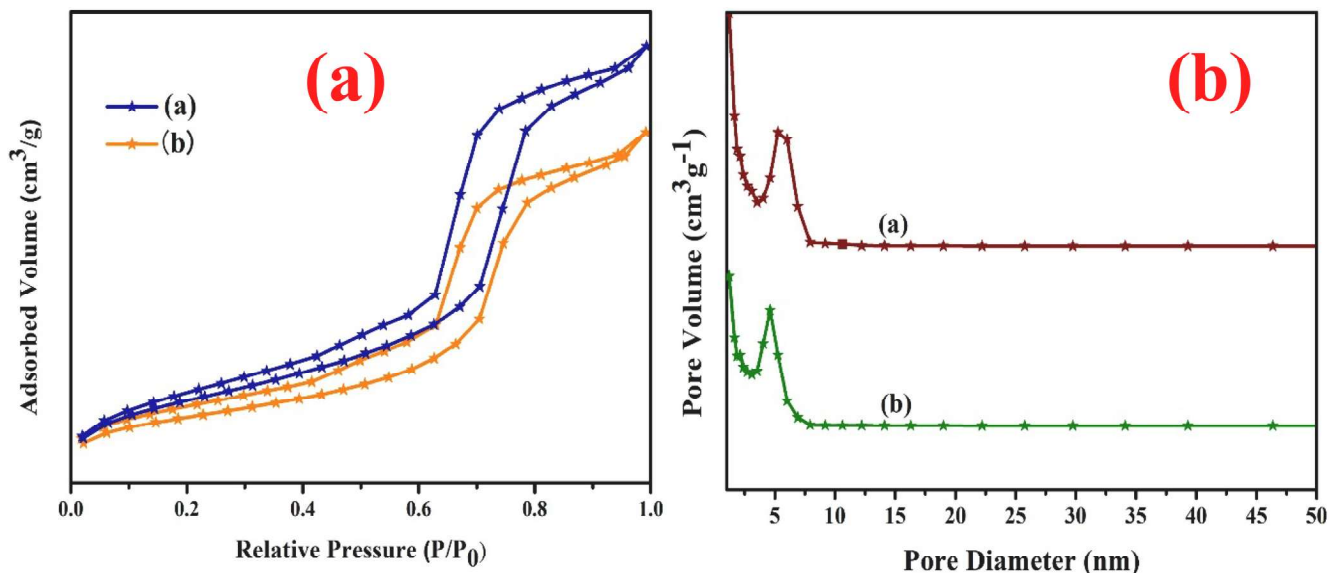


Fig. 2. a Nitrogen adsorption - desorption isotherm and b. pore size distribution of (a) SBA-15 (b) Co/SBA-15.

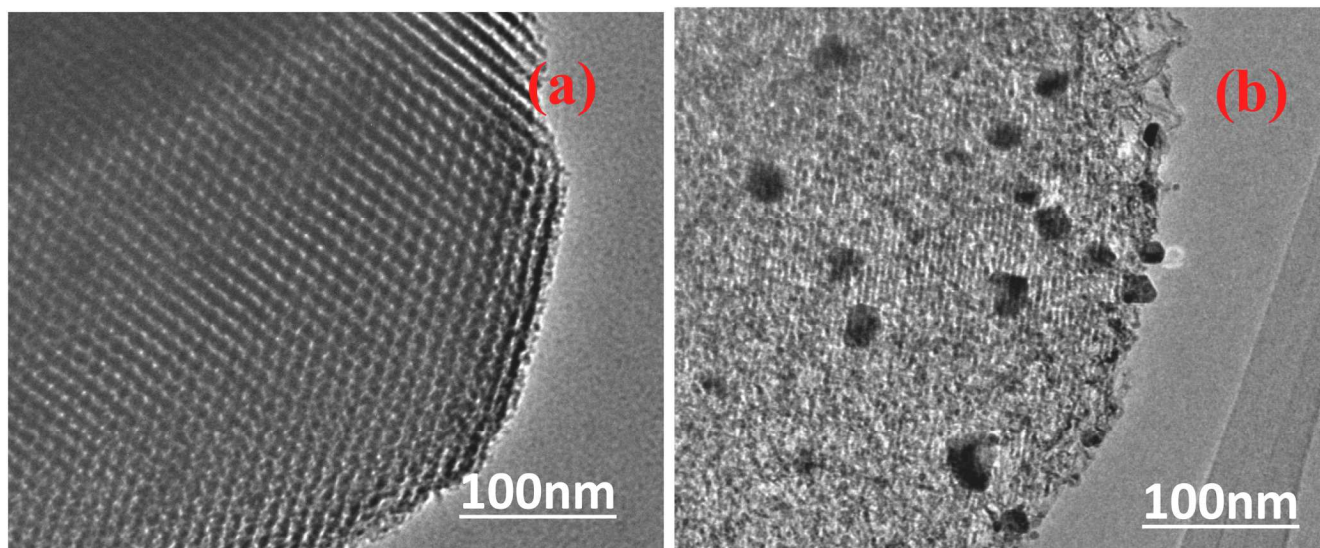


Fig. 3. HR-TEM images of (a) SBA-15 and (b) Co/SBA-15.

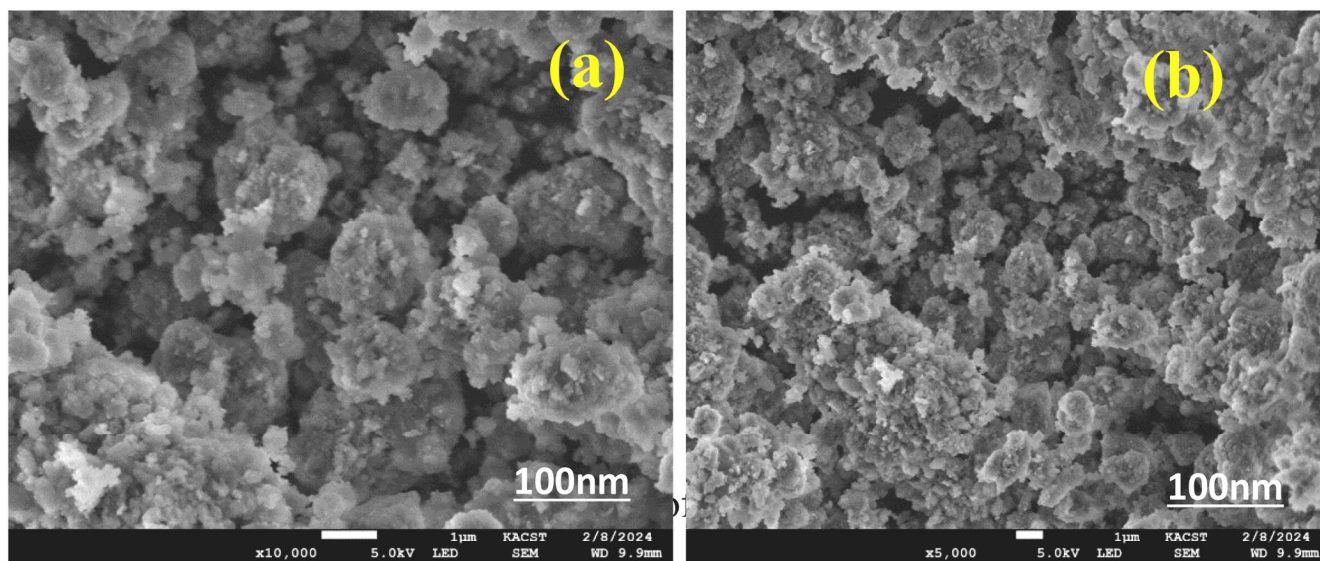


Fig. 4. HR-SEM images of (a) SBA-15 and (b) Co/SBA-15.

exhibit the presence of Si, O and Co elements are shown in Fig. 6a to d. Besides, the binding energies of Cl 2p, O 1s and Si 2p are observed at 200.1, 532.6 and 104.2 eV (Fig. S3 b-d), respectively. The XPS spectrum of Co 2p presents peaks at 532 eV (Fig. 3a), which are attributed to Co (II). These findings further elucidate the loading of the Co on the SBA-15 surface.

3.9. Procedure for pyrolysis

This study used handmade pyrolysis apparatus to perform catalytic pyrolysis of waste tyre pyrolysis oils (WTPO). Figure S1 exhibits the equipment's schematic arrangement. ZSM-5 catalyst and post-consumer WTPO granules were added to the reactor. The ZSM-5 catalyst WTPO granule mixture has a composition ratio of 2:4. WTPO was found to have an oil yield of 90 % and a reaction time and temperature of 50 min and 375 °C, respectively. In another instance, pyrolysis with zeolites acting as a catalyst produced 94.3 % oil. The HWTPO yield that was generated was stable as an oil without producing wax and was a transparent oil with traces of wax.

3.10. Physicochemical properties of WTPO, HWTPO and commercial diesel

The Table 3 displays the results of the physicochemical parameters of commercial diesel, WTPO, and HWTPO for analysis and comparison. The European Committee for Standardisation publishes EN590 as an international standard for diesel, which establishes the maximum physical characteristics that diesel may have beforehand it is permitted to be sold in Europe. Since the mass of fuel injected for a given volumetric feed is determined by the density of diesel, the density variation should be closer to the limitations indicated for engines powered by diesel. In diesel engines, viscosity controls fuel atomization, injection, and flow. Viscosity and density are influenced by the fuel's composition. HWTPO's density and viscosity comply with EN590 requirements. The WTPO was found to be composed of a density of 845 kg/m³, which improved to 912 kg/m³ after hydro processing. It is nearly inside EN590 the boundaries, as Table 3 illustrate. According to EN590 requirements, viscosity at 40 °C should be between 2.0 and 4.5 mm²/s. The viscosity of HWTPO has been found to increase from 1.82 mm²/s to 3.9 mm²/s,

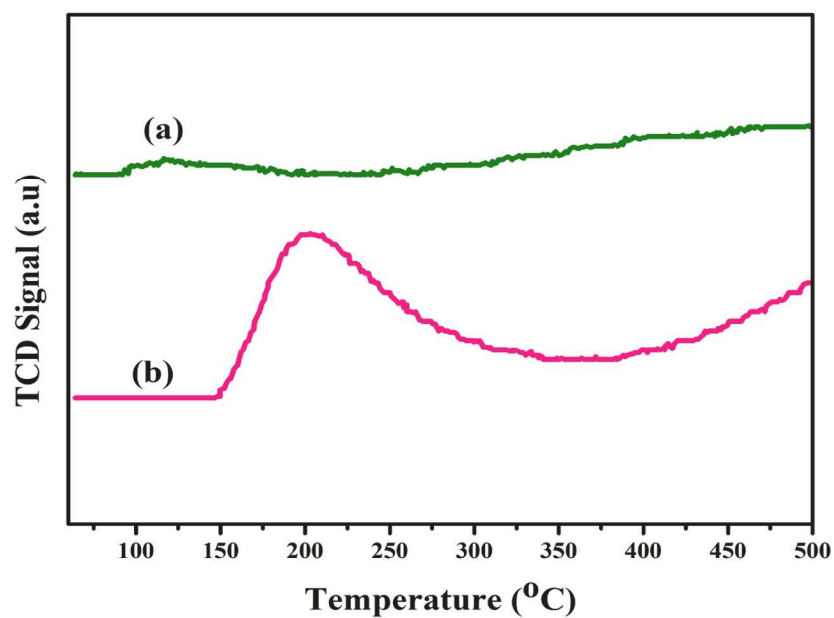


Fig. 5. NH_3 -TPD profiles of the as-synthesized (a) SBA-15 and (b) Co/SBA-15.

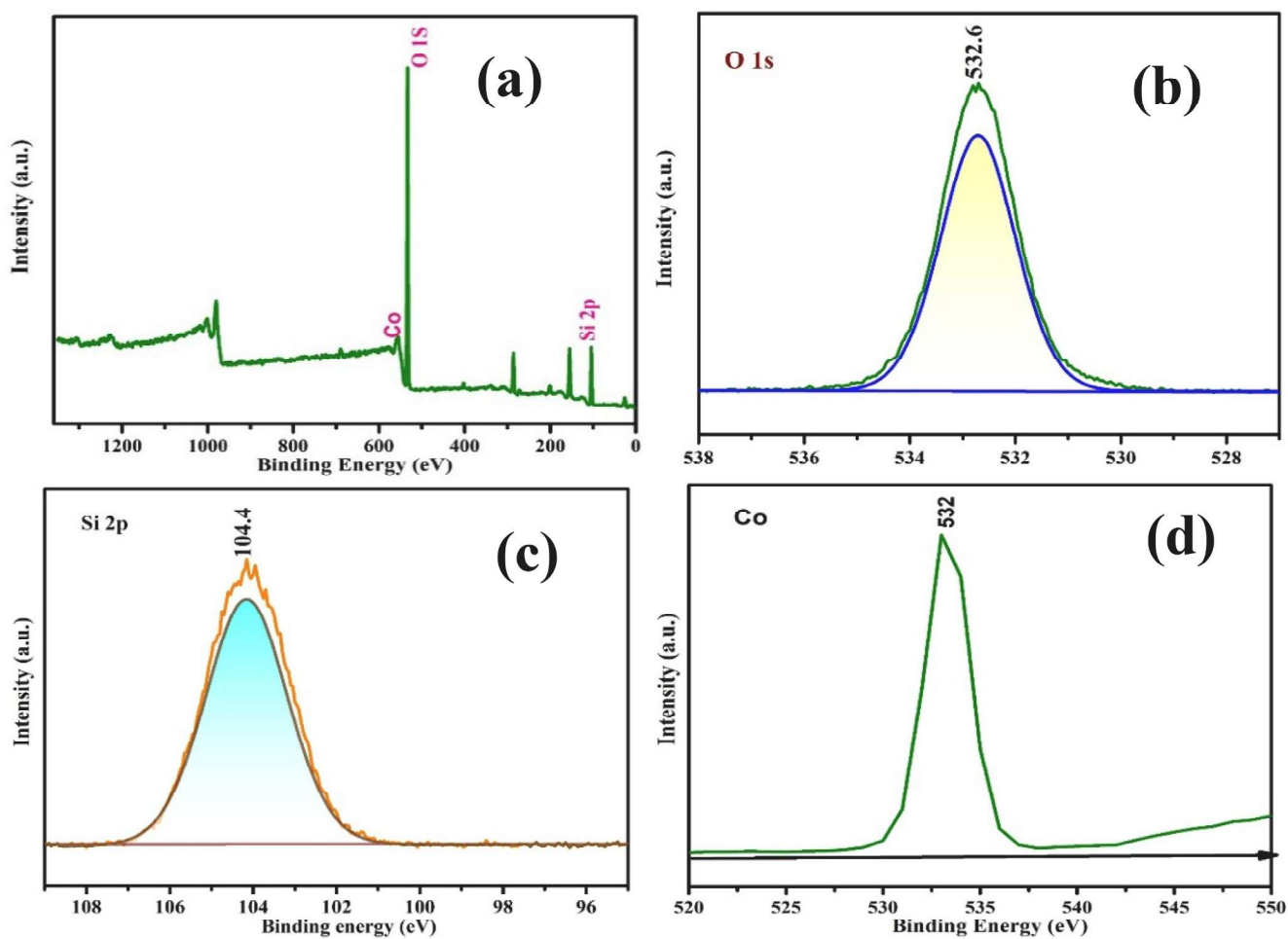


Fig. 6. XPS spectra of as-synthesized Co/SBA-15 catalyst.

Table 3
Physio-chemical properties of WTPO, HWTPO, and Pure Diesel.

S. No	Properties	Units	WTPO	HWTPO	Pure Diesel	Methods for Testing
1.	Gross calorific value	MJ/kg	44.7	48.8	48.9	IS:1448 P:6
2.	Kinematic viscosity, @ 40 °C	cSt	3.8	2.4	2.4	IS:1448 P:25
3.	Flash point	°C	51.5	55.2	56	IS:1448 P:20
4.	Fire point	°C	55	52	59	IS:1448 P:20
5.	Density @ 15 °C	kg/m ³	912	852	845	IS:1448 P:16
6.	Cetane index	–	51.5	56.5	46.4	IS:1448 P:9
7.	Carbon residue	%	0.55	0.39	0.38	IS:1448 P:122
8.	Sulphur content	%	0.26	0.049	0.048	IS:1448 P:33
9.	Ash content	%	0.04	0.01	0.02	IS:1448 P:126
10.	Cl content	%	0.62	0.60	0.55	IS:1448 P:923
11.	Acid Number	mg KOH/g	1.03	0.02	–	ASTM D664–11a

which is within the standard range. In diesel engines, the cetane index (CI) represents the fuel's ability to ignite.

During hydro processing, HWTPO's CI increased from 60 to 64, exceeding the EN590 standards' minimal CI requirements of 55. In other cases, it became apparent that the hydrogenation of mixed waste plastics increased the cetane index from 66.7 to 71.5. The safe transportation and storage of some hydrocarbons may be impacted by temperatures below the EN590 standards' minimum specified flashpoint of 55 °C. After hydro processing, it was discovered that the temperature flash-point of HWTPO increased considerably from 30 °C to 62 °C. Because of the HPPO-B's flashpoint falling under EN590 requirements, it is safe to

store and transport as diesel. For HWTPO, the overall pollution and quantity of water were found to be much below the designated limits. The fuel that is produced has a gross calorific value that is comparable to diesel. HWTPO's physicochemical characteristics are positive, and the mixed fuel's characteristics were assumed to be identical to those of commercial diesel.

3.11. GC–MS analysis

The GC–MS graphs for pure diesel, WTPO, and HWTPO are displayed in Figure S6. The GC–MS results for diesel, WTPO, and HWTPO are explained in Tables S1, S2, and S3. The composition of diesel, WTPO, and HWTPO's alkanes, alkenes, and aromatics are shown in Fig. 7A. According to the GC–MS results, the composition of WTPO is approximately 70 percent alkanes, 30 % alkenes, and trace amounts of aromatics. According to a prior study, 70 % of the olefinic products were generated during WTPO degradation in a fluidized bed reactor using the ZSM5 catalyst. It was noted that in a liquid product made from WTPO, the distribution of the paraffinic, olefinic, and naphthenic hydrocarbon was 72.5 %, 22.8 %, and 14.7 %, separately. According to the HWTPO GC–MS data, alkanes (about 80 wt percent), benzene compounds (about 17 wt percent), and naphthalene compounds (about 3 wt percent) are present. In other cases, it was discovered that the multifunctional catalyst SBA-16/Co was highly effective at the hydrocracking process HWTPO, yielding primarily lighter hydrocarbon products. Higher paraffin, decreased olefin, and aromatic compounds production was reported during the hydrocracking process and the process of hydrogenation. Researchers discovered that all of the olefins had become paraffin due to the process of hydrogenation. The complete conversion of unsaturated molecules to saturated compounds has been demonstrated through the hydrogenation of a feedstock containing a blend of waste cooking oil, straight run petrol oil and WTPO. According to the GC–MS analysis data the pure commercial diesel chemical composition comprises mainly of alkanes (70.2 wt %), benzene compounds (22.4 wt %), and naphthalene compounds (7.4 wt %). Diesel had been discovered to have 22 % aromatics and 78 % becomes saturated earlier [50].

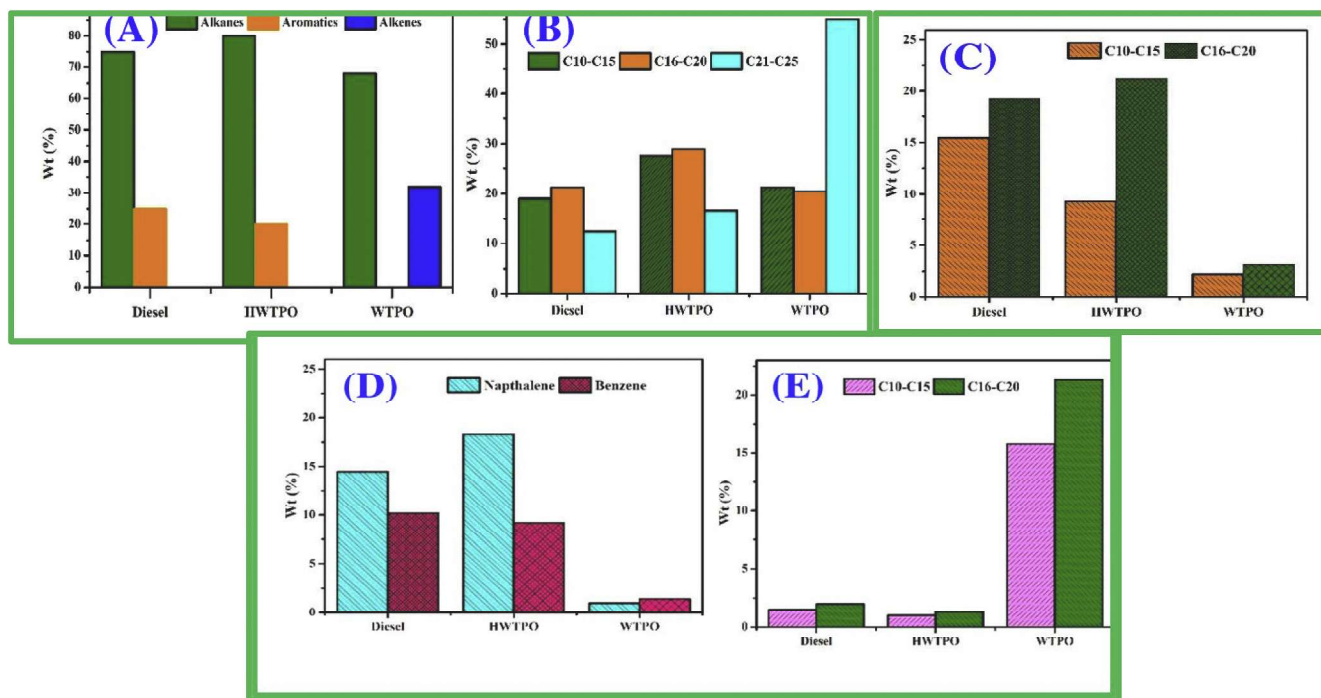


Fig. 7. A. Diesel composition of HWTPO and WTPO. B. Carbon number range of *n*-alkanes in WTPO, HWTPO, and Diesel. C. Carbon number range of isoalkanes in WTPO, HWTPO, and Diesel. D. Aromatic compounds of benzene and naphthalene in WTPO, HWTPO, and Diesel. E. Carbon number range of alkenes in WTPO, HWTPO, and Diesel.

The HWTPO has alkanes of around 8.8 wt percent of the C10–C15 range, 18 wt percent in the C16–C20 range, and 60 wt percent in the C21–C25 range, according to the GC–MS data, which can be arranged in the carbon number range of alkanes. Alkane content in HWTPO after hydrocracking was roughly 26 wt percent in the C10–C15 range, 53 wt percent in the C16–C20 range, and 10 wt percent in the C21–C25 range. Alkane content in diesel is roughly 28.4 wt percent in the C10–C15 range, 39.6 wt percent in the C16–C20 range, and 14.8 wt percent in the C21–C25 range. Although WTPO contained 50 % weight percentage of alkanes in the C21–C25 carbon number range prior to hydrocracking, hydroprocessing results in considerable the hydrocracking process. It was discovered that HWTPO's alkane content matched that of the high-end commercial diesel.

There are two types of alkanes found in commercial diesel: isoalkanes and n-alkanes. For the fuel to burn properly, diesel must have the right ratio of isoalkanes to n-alkanes. N-alkanes have very poor cold flow characteristics but very good cetane numbers. Aromatics have low cetane numbers but good cold characteristics for flow. The cetane and cold flow properties of isoalkanes are moderate, falling between those of n-alkanes and aromatics. Isoalkanes composition can function as a bridge to provide the required cetane and cold flow characteristics [51, 52].

The n-alkanes found in WTPO, HWTPO, and diesel is displayed in Fig. 7B. The only alkanes found in WTPO were n-alkanes after hydro processing; in HWTPO, n-alkanes were found in the C10–C15 range at roughly 18.5 wt percent, the C16–C20 range at 29.5 wt percent, and the C21–C25 range at 15 wt percent. About 17.8 wt percentage of diesel is found in the C10–C15 range, 27.5 wt percent in the C16–C20 range, and 14.7 wt percent in the C21–C25 range. The composition of n-alkanes demonstrates a perfect fit between diesel and HWTPO.

The WTPO was discovered to have no isoalkanes, but HWTPO created 22.4 wt percent isoalkanes by the hydro isomerization activity. In contrast, 28.2 wt percent of commercial diesel contained isoalkanes. The isoalkanes in HWTPO and diesel are ordered according to the carbon number range in Fig. 7C. It was discovered that HWTPO had isoalkanes of roughly 6.2 wt percent in the C10–C15 range and 18.3 wt percent in the C16–C20 range. Isoalkane levels in premium diesel were at 11.3 wt percent in the C10–C15 range and 15.7 wt percent in the C16–C20 range.

The aromatic level of diesel, HWTPO, and WTPO is displayed in Fig. 7D. Aromatization helped to produce about 25 wt percent of aromatics in HWTPO, whereas WTPO was discovered to have only traces of aromatics. Aromatics were discovered to make up 23.5 wt percent of diesel.

The carbon number range of alkene compounds is displayed in Fig. 7E. Before hydro processing, the composition of WTPO included about 32.6 wt percent alkenes. Alkenes were eliminated from HWTPO after hydro processing, demonstrating the efficiency of hydrogenation.

The hydro processing of WTPO employing Co/SBA-15 catalyst produced a composition similar to diesel, according to GC–MS investigations of HWTPO. It had been found elsewhere that the hydro processing of LDTP pyrolysis oil over Co/SBA-15 catalysts promoted the catalytic activity in the primary processes of hydrogenation, hydro isomerization, cracking, oligomerization, and the aromatization [53].

4. The hydro-processing performance

It was discovered that the total alkanes in WTPO and HWTPO were, respectively, 18.6 % and 1.8 % lower than those in diesel. Following treatment, 99 % of the total alkanes in HWTPO matched diesel. The best types of diesel component compounds are alkanes, because these compounds supply the cetane number required for the fuel to ignite early and burn properly in a diesel engine. The accuracy with which the alkane content matches increases the reliability of HWTPO as a diesel fuel. In WTPO, the total aromatics was found to be zero, however after treatment, HWTPO had 10 % more aromatics than diesel. It was

discovered that the total number of n-alkanes in WTPO was 30 % higher than in diesel, while in HWTPO it was 2.5 % higher than in diesel, resulting in a 98.5 % match with diesel fuel [54,55].

While HWTPO displayed 3.1 % more n-alkanes than diesel for the same carbon number, resulting in a 97.4 % match with diesel, WTPO displayed 65 % fewer n-alkanes in carbon numbers C10–C15. WTPO has n-alkanes in the C16–C20 carbon range, which is 44 % less than diesel, while HWTPO had 7 % more alkanes than diesel, which is a 93 % match with diesel. WTPO had 200 % more n-alkanes than diesel in the C21–C25 carbon range; however, HWTPO had 7.2 % fewer n-alkanes than diesel, matching diesel's carbon number by 92.8 %. WTPO possesses more carbon-numbered alkane compounds than HWTPO or diesel, as evidenced by the majority of its n-alkanes being found in the C21–C25 carbon range (200 % more than in diesel). In the C21–C25 carbon range, reducing the amount of n-alkanes from 200 % to 7.2 % demonstrates the technique and catalyst's the hydrocracking process efficacy. It was found that the composition of WTPO included no total isoalkanes, and that the composition of HWTPO contained 10 % less isoalkanes than diesel, meaning that the two materials matched diesel composition by 90 %. HWTPO's isoalkanes content is raised through efficient hydro isomerization made possible by the process and catalyst [56].

4.1. Diesel engine combustion

4.1.1. The cylinder peak pressure and heat release rate (CPP & HRR)

The fluctuation in cylinder pressure at 100 % load and 75 % load, respectively, is depicted in Figs. 8A and 8B. Peak variations in pressure at 100 % load in HWTPO blends were 2.9 % to 3.5 % lower than in diesel blends. Peak pressure variations at 75 % load were found to be 3.1 % to 3.7 % lower than those for diesel. HWTPO blends' peak pressure performance was 98.5 % of commercial quality diesel values. Enhancement of the peak pressure performance is possible if the hydrocracking function reaches 100 % of the diesel values instead of the current 98 %. Higher peak pressure has been observed in PPO experiments in the past, which has been attributed to longer burn times for blended fuels. The HWTPO's ignition delay factor has decreased as a result of the alkene conversion.

The HRR variance for 100 % and 75 % loads is shown in Figs. 8C and 8D, respectively. For HPPO-B blends, the range in HRR at 100 % load is found to be 2.9 % to 3.9 % of the diesel value. It becomes apparent that the HRR variance at 75 % load for HPPO-B blends is 2.1 % to 4.5 % less than that of diesel blends. It was shown that the HRR performance of HPPO-B blends matched diesel values 97 % of the time. In diesel engines, delayed combustion and the ensuing high HRR are largely influenced by ignition delay. The carbon number and composition of the fuel are the main causes of the igniting delay, which is essentially a chemical procedure delay. Increased chemical delay was made possible by WTPO's greater carbon number and the presence of alkenes, which raised HRR. Once the process's hydrocracking efficiency is raised from the current 95 % to 100 %, the HRR performance of HWTPO will be ideal [57,58].

4.1.2. Engine performance

The thermal efficiency of the brake system (BTE) is the network output obtained for a given heat input from the combustion of fuel in diesel engines. It shows how effectively fuel is used to produce work. The following describes the thermal method a diesel engine uses to produce work output:

The net indicated work output of a diesel engine running four strokes

$$= \int_0^{360} P dv$$

(1)

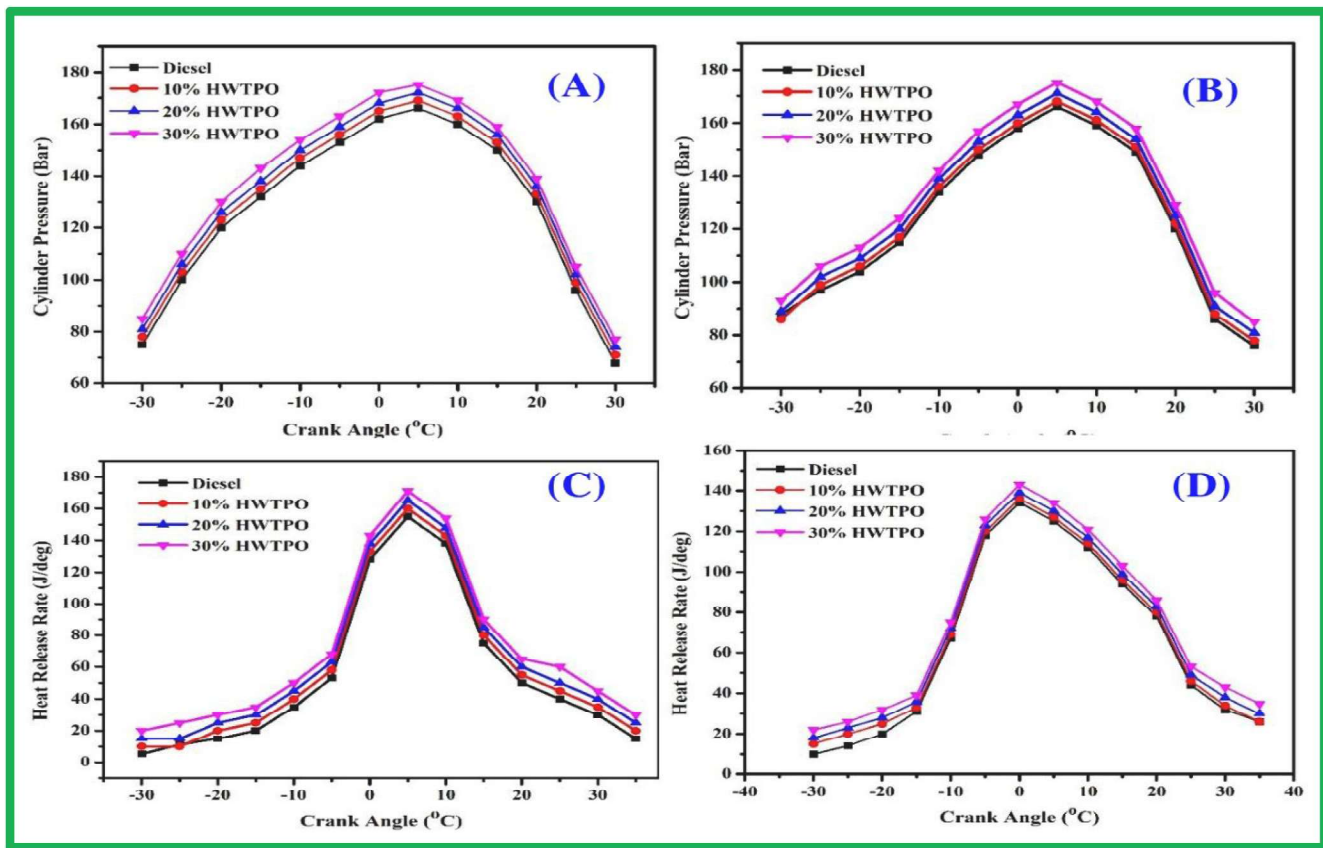


Fig. 8. A. Variation of cylinder pressure for 100 % load. B. Variation of cylinder pressure for 75 % load. C. Variation of heat release rate for 100 % load. D. Variation of heat release rate for 75 % load.

wherein dv is the change in volume and P is the cylinder pressure at any given time in the cycle. The pressure variation in the cylinder in response to the crank angle is the primary factor influencing the work output. Fig. 9A. shows that the HWTPO's combustion pressure matched that of diesel by 99 %. As a result, it is anticipated that the engine's total work output at peak load would match diesel values. Pumping losses in a diesel engine are constant for both HWTPO and diesel; therefore, they have little effect on changes in network output. CI plays a crucial role in ensuring that fuel in diesel engines burns properly. Because HWTPO has a higher cetane index (CI) than commercial diesel, the blends' effective CI remains greater than diesel's. The moment of ignition delay is going to decrease as the fuel's CI rises.

The fluctuation in BTE with load for the diesel and HWTPO combination is shown in Fig. 9A. The difference in BTE of the HWTPO blend at 100 % load was 2.1 % to 3.5 % less than that of the diesel values. The difference in BTE of the HWTPO blend at 75 % load was 2.4 % to 4.7 % less than that of the diesel values. The commercial premium diesel values were 99 % of the BTE performance of the HWTPO blend. Previous research demonstrates that the BTE was lower than diesel for all mixes of PSW pyrolysis oil. Lower BTE for WTPO is the result of increased thermal losses caused by delays in ignition and more powerful HRR [59].

The engine brake specific fuel consumption (BSFC) fluctuation with load for the HWTPO blend and diesel is displayed in Fig. 9B. The HWTPO blend's BSFC varied between 5 % and 8.9 % greater at 100 % load than the diesel readings. The acceptable concentration of BSFC for HWTPO blends at 75 % load was 2.5 % to 9.4 % higher than that of diesel blends.

The temperature changes of the exhaust emissions for both diesel and HWTPO blends with engine load is depicted in Fig. 9C. The exhaust gas temperature variation of the HWTPO blend was 2.9 % to 11.3 % higher than that of diesel at 100 % load. The exhaust gas temperature variation

of the HWTPO blend was 3.2 % to 11.2 % higher than that of diesel at 75 % load.

4.1.3. Engine emission characteristics

The carbon monoxide (CO) fluctuation with load for diesel and HWTPO blend is displayed in Fig. 10A. The result of not having enough oxidizer for the entire combustion process is CO. When the amount of carbon in fuels is more than the amount of air available, CO can also develop. Diesel was found to have CO emission levels of 30 ppm at 100 % load, while HWTPO mixes showed a variance of 4 ppm to 9 ppm higher than diesel, which is quite close to the diesel a value. Diesel was found to have CO emissions of 80 ppm at a 75 % load, while HWTPO blends showed emissions ranging from 9 ppm to 17 ppm greater than that of diesel. At greater loads, the CO emissions were more similar to those of diesel; nevertheless, at low loads, they were found to be 12–35 ppm higher than those of diesel. As was previously noted, higher WTPO into diesel blending ratios lead to increasing CO emissions. Lower CO emissions were seen in earlier experiments on PSW pyrolysis oil with n-Pantanal addition than on PSW pyrolysis oil alone [60].

The carbon dioxide (CO₂) emission levels for commercial diesel and HWTPO blend vary with load, as shown in Fig. 10B. The fuel's last by-product of carbon oxidation is CO₂. Under 100 % load, the HWTPO blend's CO₂ variation was 2.6 % to 9.2 % greater than the diesel values; under 75 % load, the variation was 2.9 % to 9.6 % higher than diesel values. With increasing load, CO₂ emissions rise, and at maximum load, a maximum quantity of CO has been converted to CO₂. The amount of carbon in HWTPO's composition determines the amount of CO₂ emissions. The alkane composition matches diesel values by about 96 %, and assuming the same can be hydro processed to 100 % efficiency, then CO and CO₂ emissions should match diesel values by 100 %.

The fluctuation of NOx emission levels with load for commercial

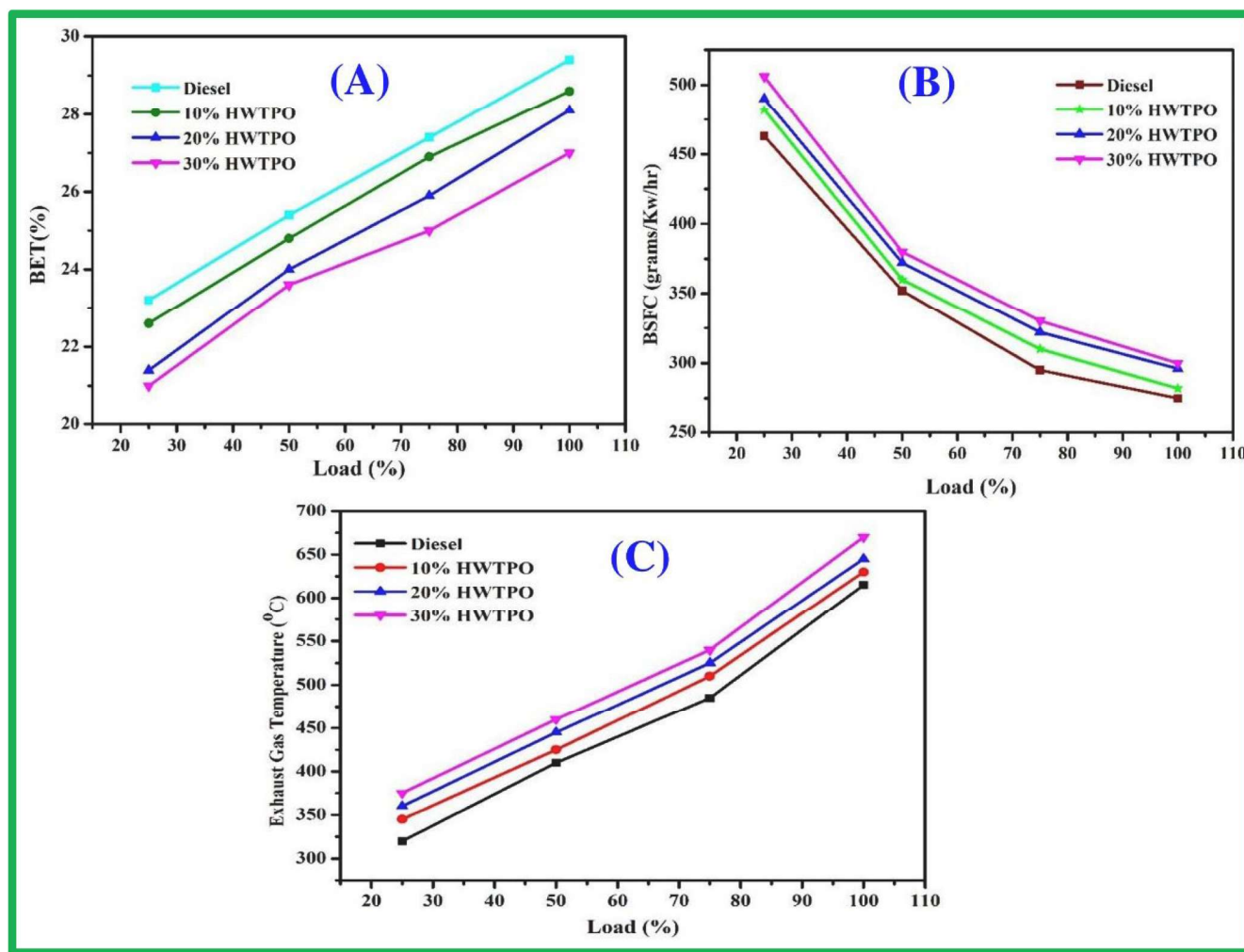


Fig. 9. A. Variation of BTE with load. B. Variation of BSFC with load. C. Variation of exhaust gas temperature with load.

diesel and HWTPO blend is displayed in Fig. 10C. The HWTPO blend's NO_x variance at 100 % load was somewhere around 1.2 % to 3.8 % greater than diesel values. The HWTPO blend's NO_x variance at 75 % load ranged from 2.2 % to 4.8 % greater than diesel values. The HWTPO blend's NO_x emission levels matched diesel perfectly. When compared to diesel, the HDPE pyrolysis oil blend performed better, as evidenced by a 55 % rise in NO_x. When using PSW pyrolysis oil in a CRDI engine without an EGR, we saw a substantial spike in NO_x. Through high carbon alcohols added, the PSW pyrolysis oil was shown to have an 88 % reduction in smoke but an increase of 10.2 % in NO_x when it came to diesel engine performance. The main cause of NO_x is greater combustion temperatures. Elevated HRR will lead to elevated combustion temperature and hence, increased levels of NO_x emissions. The prompt mechanism (Fenimore) relates the kinetics of the hydrocarbon fuel reaction towards the generation of NO_x, with carbon acting as a catalyst in this process. The following reaction demonstrates the rapid mechanism involved in the creation of NO_x.



The quick mechanism suggests that fuel with a higher carbon number can produce more NO_x emissions. The Zeldovich mechanism states that increasing exhaust temperature and HRR promote the production of thermal NO_x. Because HPPO-B's HRR and carbon number values are more similar to those of diesel, its NO_x emission levels are also within

diesel parameters.

The unburned hydrocarbon (UHC) emission variation with load for commercial diesel and HPPO-B blend is displayed in Fig. 10D. The range in HPPO-B blend's UHC at 100 % load was 1.8 % to 9.1 % lower than diesel values. The HPPO-B blend's UHC varied between 1.6 % and 9.5 % less than diesel values at 75 % load. The manufacturing of HPPO-B as a substitute diesel engine fuel was successful since its UHC emission levels considerably lower than those of diesel. Incomplete combustion is the cause of unburned hydrocarbon emissions. Higher blending ratios were associated with an increase in the unburned UHC emissions for plastic pyrolysis oil, according to previous investigations.

4.1.4. Performance of Co/SBA-15 hydro processing catalyst

The fuel HWTPO's physicochemical characteristics, composition, combustion, performance, and emissions are compared to those of HPPO, which is created when WTPO is hydrogenated utilising mono metal Co/SBA-15. WTPO and HWTPO's physicochemical characteristics exhibited comparable outcomes and complied with EN590 specifications. Especially compared to HWTPO, the chemical composition of HPPO-B significantly improved. Compared to the hydrogenation and hydrocracking functions established in HWTPO, the Co/SBA-15 catalyst produced hydrogenation, hydrocracking, hydro isomerization, and aromatization activities. In contrast, only traces of aromatic content were found in HWTPO. Aromatization yielded an aromatic concentration in HWTPO that was 8.2 % greater than diesel. Diesel had observed n-alkanes to isoalkanes ratio of 2.8, while the Co/SBA-15 catalyst

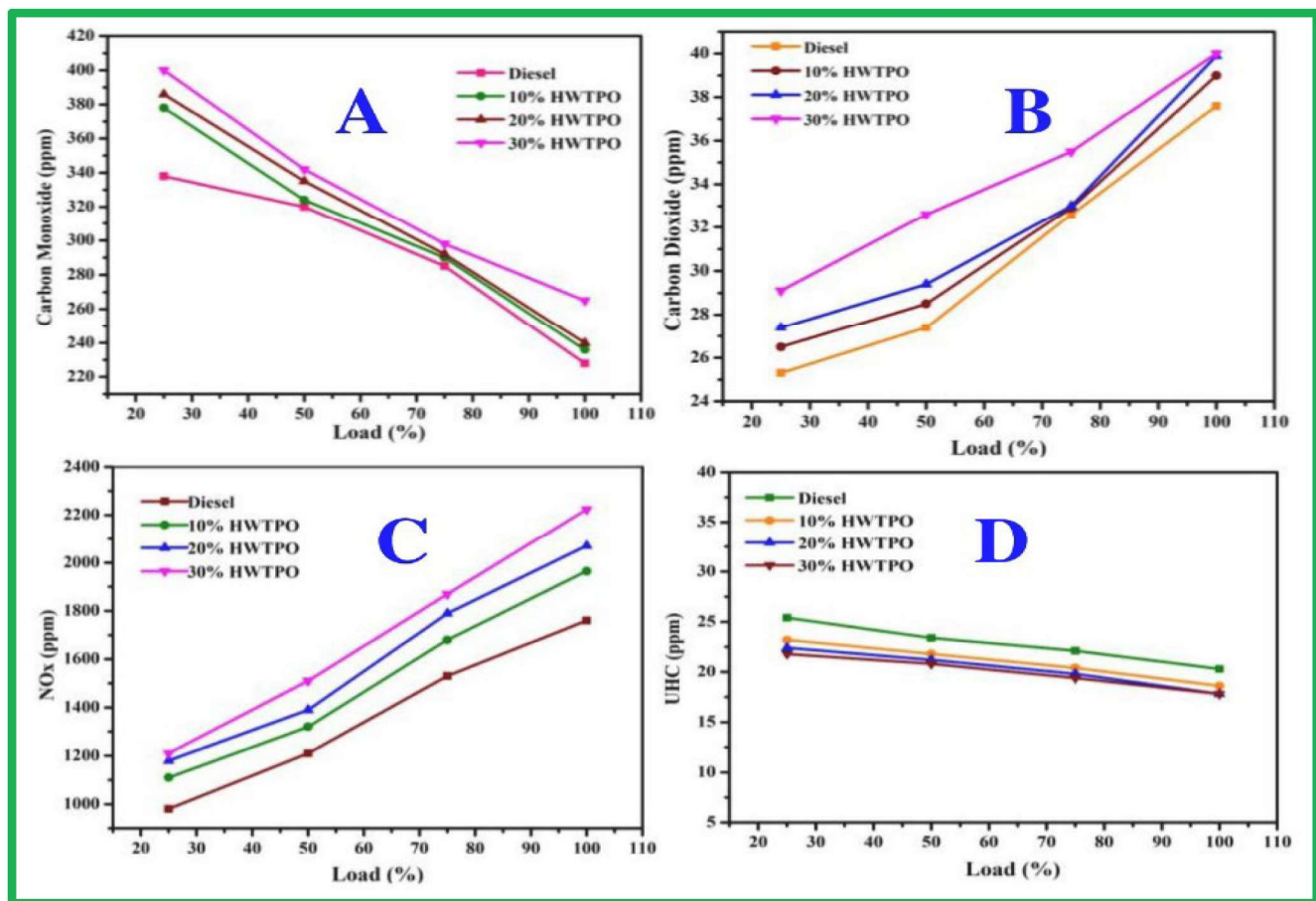


Fig. 10. Variation of (10A) CO with load, (10B) CO₂ with load, (10C) NO_x with load and (10D) HC with load.

produced alkanes known and isoalkanes with a ratio of 2.2. In HWTPO, the monometallic catalyst had the capacity to create aromatics, n-alkanes, and isoalkanes in amounts that were more akin to the composition of diesel. HWTPO produced more efficient combustion and emission results because of its physicochemical characteristics and chemical make-up match with diesel.

In comparison with diesel, the combustion peak pressure variation for HWTPO was less, with a maximum variance of 3.5 %. In the prior investigation, it was noted that for a 30 % blend, HWTPO generated a peak pressure that was approximately 12 % greater than diesel. The greatest departure of the HRR for the HWTPO mix was 4.2 % less than the diesel value, whereas the maximum deviation for the HPPO blend was 12 % greater than the diesel value. For every mix, the HWTPO's peak pressure and HRR performance displayed values that were closer to diesel. The greatest deviation of the BTE of the HWTPO blend was 5.87 % less than that of the diesel. For the 30 % blend, it was found that the BTE readings for HWTPO were 13 % lower than those for diesel. In contrast to conventional diesel, the greatest BSFC deviation seen in HWTPO was 8.2 % higher. For a 20 % blend, it was found that the maximum variation of BSFC for HWTPO was 13 % higher than that of diesel [61-63].

The two HWTPO and WTPO had comparable CO emissions at maximum loads, however HWTPO had emissions at lower loads that were more akin to diesel than WTPO. The maximum CO deviation for HWTPO was found to be 36 ppm greater than diesel at lower loads, and the maximum deviation for HWTPO was found to be 60 ppm higher than diesel. The HWTPO blend's CO₂ emissions were found to be 7.6 % higher than the value of diesel, and its CO₂ concentration was 30 % more than that of diesel. While the 30 % blend of HWTPO demonstrated a 30 % increase in NO_x above diesel, the NO_x for HWTPO was 3.8 % higher

than that of diesel. While HWTPO mixes had UHC emissions that were 12 % higher than diesel, HWTPO itself showed decreased UHC emissions. The performance of the HWTPO blends at 10 and 20 wt % was more like diesel; however, the blends at thirty % of the weight displayed a notable divergence. Across all blends, the Co/SBA-15 catalyst demonstrated a significant improvement in the fuel composition, combustion, performance, and emissions of HWTPO.

5. Conclusion

Research highlights the potential for high-quality, low-sulphur hydrocarbon fuels produced through WTPO hydroprocessing during refining. Investigating various factors is crucial to utilize HWTPO from pyrolysis processes in compression ignition engines. This study aims to determine how ternary blends (HWTPO/Diesel) affect engine efficiency, exhaust emissions, and combustion properties. The findings support using ternary blended fuels (HWTPO/Diesel) as an alternative for diesel engines, aligning with alternative energy research and development goals.

Key Findings includes

- According to EN590 standards, the viscosity of HWTPO improved from 1.82 mm²/s to 3.9 mm²/s at 40 °C, fitting within this range.
- Its flashpoint increased significantly from 30 °C to 62 °C, making it safe for storage and transport as diesel.
- The produced fuel has a gross calorific value similar to diesel. HWTPO's physicochemical properties are favourable, and the mixed fuel's characteristics are comparable to commercial diesel.

- Due to their lower heating values, binary and ternary blends have higher brake specific fuel consumption, while brake thermal efficiency remains similar to standard diesel.
- Simulations closely match experimental data for brake thermal efficiency, effective pressure, torque, power, and specific fuel consumption, with differences within a 10 % margin.
- Noise levels measured at 1.5 and 6 m from the engine are comparable for all blends and standard diesel across various engine speeds.
- Blends emit higher nitrogen oxides (NOx) than standard diesel, likely due to increased flame temperatures. However, CO₂ emissions from ternary blends are lower than those from diesel at all engine speeds.

The study delves into exhaust emissions and diesel engine performance, focusing on exergy and energy characteristics. HWTPO produces 20 % less UHC emissions than diesel. However, achieving ideal HWTPO composition for isoalkanes is not yet realized, with isoalkanes in the C10–C15 range being 43 % lower than diesel levels. Enhancing the effectiveness of Co/SBA-15 catalysts in WTPO hydro processing is necessary to produce more isoalkane compounds with fewer aromatics, aiming for 100 % target efficiency. HWTPO shows a 98 % match to pure diesel in properties, composition, combustion, performance, and emissions. Commercial use of HWTPO up to a 60 % blend can generate clean energy from post-consumer waste. HWTPO offers a safe, environmentally friendly solution for hazardous post-consumer waste tyres converted to plastic oil.

CRedit authorship contribution statement

P. Tamizhdurai: Writing – original draft. **P. Arthi:** Data curation. **V. L. Mangesh:** Methodology. **P. Santhana Krishnan:** Resources. **Nadavalva Siva Kumar:** Writing – original draft. **P. Saravanan:** Writing – review & editing. **A. Subramani:** Data curation. **P. Sasikumar:** Writing – review & editing. **Mohammed F. Alotibi:** Writing – review & editing. **Salwa B. Alreshaidan:** Visualization. **Abdulaziz A.M. Abahussain:** Resources. **Ahmed S. Al-Fatesh:** Methodology. **R. Kumaran:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

The authors do not have permission to share data.

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