Co-published by
Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Committee on Thermodynamics and Combustion
Polish Academy of Sciences

http://www.imp.gda.pl/archives-of-thermodynamics/

ARCHIVES OF THERMODYNAMICS

Production and characterisation of pyrolysis oil from discarded medical plastic (syringe) waste with common rail direct injection engine assessment

Rajkumar Thamizhvel*, Natarajan Vaithianathan, Narayanan Sethuraman, Subramanian Vinodraj, Lenin Ambetharasu, Palani Surendar

Indo French Educational Trust (IFET) College of Engineering, Gangarampalayam, Villupuram 605108, Tamil Nadu, India
*Corresponding author email: rthamizhvel@gmail.com

Received: 13.09.2025; revised: 11.02.2026; accepted: 25.02.2026

Abstract

This study explores the potential of converting syringe plastic waste into an alternative fuel through pyrolysis. Since syringes are primarily made of polypropylene, they were thermally decomposed in a batch reactor, producing a maximum pyrolysis oil yield of 76% at 400–500°C. The produced syringe plastic oil (SPO) was characterised for key fuel properties and blended with diesel at 20%, 30%, and 40% proportions. The performance of the engine and the emission characteristics of these blends were tested experimentally on a common rail direct injection diesel engine. Of the fuels tested, the D80SPO20 mixture proved to be as efficient as diesel with the brake thermal efficiency of 26.9% and brake specific fuel consumption of 0.27 kg/kWh at full load. This mixture was also found to result in a significant reduction in carbon monoxide, hydrocarbons and smoke emission with a slight increment in NO_x relative to diesel. On the whole, the findings show that low-percentage SPO30, especially D80SPO20, provide a favourable combination between engine efficiency and emission reduction, proving the potential of the syringe plastic pyrolysis oil as a sustainable alternative of diesel fuel in part.

Keywords: Pyrolysis; Medical plastic; CRDI engine; Performance; Emission

Vol. 47(2026), No. 2, 201–210; doi: 10.24425/ather.2026.158687

Cite this manuscript as: Thamizhvel, R., Vaithianathan, N., Sethuraman, N., Vinodraj, S., Ambetharasu, L., & Surendar, P. (2026). Production and characterisation of pyrolysis oil from discarded medical plastic (syringe) waste with common rail direct injection engine assessment. *Archives of Thermodynamics*, 47(2), 201–210.

1. Introduction

The high consumption of plastics around the world has caused a high level of plastic waste accumulation, which has been rather threatening to not only the environment but also human health [1]. Of these wastes, medical plastics, with single-use syringes being one exceptional and increasing proportion, are a major cause of concern. Polymers (polypropylene and polyethylene) are the most commonly used materials in the production of syringes because they are mechanically robust, have chemical resistance, and are inexpensive, which are required for use in healthcare practices [2]. However, these properties cause poor biodegradation, which causes long-term pollution of the environment.

The control of medical plastic waste has continued to become increasingly difficult with the growing healthcare services and emergency medical interventions, which are highly dependent on disposable plastic products. The traditional methods of disposal, such as incineration and landfill, cannot be considered sustainable methods anymore. Incineration can also release toxic chemicals like dioxins and furans, and landfilling can also consume unused land resources and contaminate the soil and groundwater [3]. In addition, medical plastic waste may pose serious biological risks when mishandled or improperly disposed of. Consequently, there is an urgent requirement for an alternative mode of waste management that would limit environmental degradation but allow the reuse of useful resources in medical plastic waste [4].

Nomenclature

CO	– carbon monoxide
HC	– hydrocarbon
NO_x	– oxides of nitrogen
SO_x	– oxides of sulphur

Abbreviations and Acronyms

BSFC	– brake specific fuel consumption
BTE	– brake thermal efficiency
CRDI	– common rail direct injection
PM	– particulate matter
SPO	– syringe plastic oil

A lot of focus has been on bio-derived oxygenated fuels, bio-derived biodiesel, and products of thermochemical conversion, as they are renewable and have the potential to lower the environmental effects. Some of the studies highlight the nature of biodiesel and oxygenated fuels' performance and combustion in CI engines. The experiment reported in [5] showed that biodiesel mixtures have a higher combustion efficiency because they contain built-in oxygen, which results in increased brake thermal efficiency under increased loads. Nevertheless, biodiesel had a lower calorific value, which meant that it consumed more brake-specific fuel than diesel.

The same tendencies could be found in [6], where optimisation of the injection parameters was used to overcome the performance penalties related to the use of biodiesel. These are the findings that point to the significance of engine calibration to reap the full advantages of oxygenated fuels.

Research concerns on engine emissions indicate uniform emissions of carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM) that are reduced with the use of biodiesel or bio-derived production. The paper [7] has obtained significant reductions in smoke opacity and PM emissions, which were attributed to better oxidation in combustion. Nevertheless, the rise in nitrogen oxides (NO_x) emissions is still an issue that is here to stay, as research findings have established in [7]. Further combustion plans and post-treatment devices are thus required to deal with this trade-off. It has also discussed the environmental and health effects of exhaust emissions in detail. Another extensive study [8] assessed the oxidative potential and toxicity of the biodiesel-powered engine particulate emissions. The research inference was that biodiesel particulates have a lower potential to cause adverse health effects due to their lower oxidative stress potential than diesel PM. This is in line with the larger environmental analyses that focus on the use of biodiesel in reducing air pollution in urban environments. Renewable fuel production pathways are critically evaluated in terms of their sustainability and life cycle. The paper [9] compared life-cycle greenhouse gas emissions of biodiesel and concluded that the feedstock choice is a very important part of the total sustainability. It was demonstrated that waste-derived and non-edible feedstocks have a huge impact in lowering carbon footprints as compared to the traditional sources of edible oils. To further support this, paper [10] emphasised the potential of using agricultural waste and oils from production processes to generate biofuels, thereby reducing environmental costs and resource loss.

Recent studies talk about the advances in technologies of biomass conversion. A study [11] examined catalytic and thermochemical conversion pathways in the production of biofuels and found that the quality of fuels produced was better and conversion efficiencies were increased. These findings were also confirmed by [12], which showed that optimising the process can help to increase the stability of the fuel and the engine's compatibility. Most recently, the paper [11] provided promising findings on an integrated bioenergy system with a focus on techno-economic feasibility and scalability.

Thermochemical conversion of plastic wastes by the pyrolysis process is one prospective method. One of these techniques is pyrolysis, which involves decomposition of waste plastics at high temperatures in the absence of oxygen [12]. Through this process, long plastic chains are reduced into smaller parts, which are useful materials such as pyrolysis oil, syngas and char. Of these, pyrolysis oil has attracted much attention because of its prospects of being used as a liquid fuel. It has properties similar to those of diesel, which provide the chance to completely or partially replace standard petrol engines.

Current advancements in fuel technology involve the use of alternative forms of fuel in contemporary diesel motors [13]. The common rail direct injection (CRDI) engine is one of them. Fuel atomisation, accurate injection timing and injected pressures are also some of the factors that make common rail direct injection engines achieve better combustion efficiency and lower exhaust emissions [14]. With these merits, CRDI engines are specifically better applied in the experimental studies of using alternative fuels, even waste-based fuels, like plastic pyrolysis oil. Past experimental research on the utilisation of plastic-derived pyrolysis oil as a diesel engine fuel has recorded promising findings [15]. Studies have also proved that the pyrolysis oil can be mixed with standard diesel in any quantity and used successfully in a diesel engine without significant operational problems. The blended fuels have shown satisfactory performance qualities and, in some instances, enhanced thermal efficiency of the brakes. In addition, it has been found that there will be decreases in exhaust pollutants like unburned hydrocarbons and carbon monoxide at specific ratios of blends. Nevertheless, under certain operating conditions, nitrogen oxide emissions are inclined to go up, which shows that additional optimisation and emission control measures are needed.

Although significant advances have been achieved in the recent past regarding the use of plastic waste to obtain energy via its conversion into energy, little attention has been given to the actual application of medical plastic waste and specifically discarded syringes in the pyrolysis oil production [17]. This is a significant gap in the study since, besides being easily accessible, syringe plastics are also high-quality polymers that can undergo thermal degradation [18]. The advantages of converting this form of waste into fuel are also twofold since it not only solves this pressing concern of medical waste disposal but also helps in the energy recovery process. The paper [19] examines the possibility of using the pyrolysis oil by using the old medical syringe plastic as an alternative fuel in a common rail direct injection diesel engine.

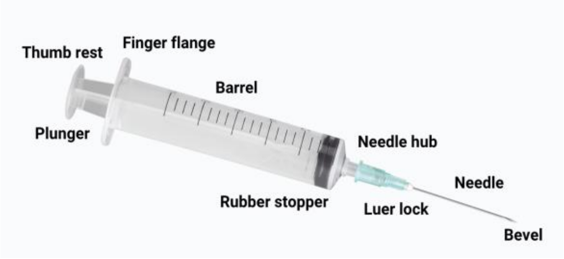

Fig. 1. Parts of syringe [16].

In the work [20], the collection and preparation of medical plastic waste is followed by the pyrolysis oil production, in which controlled thermal decomposition takes place, and the characterisation of the received fuel in greater detail. The properties of important fuels such as viscosity, density, calorific value and flash point are discussed and compared with those of conventional diesel to determine their suitability to be applied in engines [21]. Using a CRDI engine, the engine performance and emission tests with different proportions of pyrolysis oil and diesel have been carried out [22]. The performance parameters that are measured to understand how the engine works include brake thermal efficiency, brake specific fuel consumption, and the in-cylinder exhaust gas temperature and pressure [23]. Moreover, exhaust emissions, such as hydrocarbons, carbon monoxide, nitrogen oxides and smoke opacity, are quantified to evaluate the environmental effect of the alternative fuel blends [24].

This paper gives useful information on the combustion behaviour and performance characteristics, as well as the emission profile of syringe plastic-derived pyrolysis oil in a modern CRDI diesel engine. The study reveals that waste-based fuels are practically applicable by using an innovative method of medical plastic waste treatment in order to generate energy. The research results provide evidence-based information that proves the feasibility of this fuel and can be used to guide future policy, technological advancement and manufacturing to curb plastic waste and to improve energy sustainability. The novelty of the work is the use of the discarded plastic medical syringe as feedstock and a systematic assessment of syringe plastic oil (SPO) in a CRDI engine under controlled experimental conditions. Also, the study underscores the correlation of pyrolysis temperature, properties of fuels, and performance and emissions of the engine, which gives a holistic picture of SPO as an alternative fuel.

2. Materials and methods

2.1. Syringe waste

Syringe plastic waste was selected due to its abundance, consistent polymer composition and environmental concerns. Made mainly of polypropylene and polyethylene, it is ideal for pyrolysis to produce fuel-rich oil. Utilising this waste helps reduce biomedical pollution, avoids harmful incineration by-products, and supports sustainable energy recovery from non-biodegradable plastics, in line with eco-friendly waste management practices [25]. The part of the syringe shown in Fig. 1 and Table 1 represents the materials of syringe components.

Table 1. Materials and properties of syringe components.

Syringe component	Material used
Barrel	Polypropylene (PP)
Plunger	Polypropylene (PP)
Plunger seal (rubber stopper)	Synthetic rubber (e.g., polyisoprene or butyl rubber)
Finger flange	Polypropylene (PP)
Syringe tip (luer lock/slip)	Polypropylene (PP)
Needle hub	Polypropylene (PP) or polyethylene (PE)
Needle	Stainless steel (Grade 304 or 316)
Needle bevel (tip)	Stainless steel
Needle cap	Polyethylene (PE)

2.2. Pyrolysis process

Pyrolysis is a process where syringe plastic waste is heated in the absence of oxygen, breaking it down into liquid oil, gases, and char. The photographic view of the experimental setup is shown in Fig. 2. In a batch reactor, oil is produced by heating waste to temperatures ranging from 300°C to 500°C, which starts the breakdown of polymers. This process efficiently turns non-biodegradable plastic into useful fuel [26], providing a long-term solution for energy recovery and biomedical waste management [27]. The temperature in the reactor first increases at a rate of 8°C/min and then decreases to 3°C/min towards the end of pyrolysis.

Fig. 2. Pyrolysis setup.

3. Testing and analysis

3.1. Proximate analysis

The proximate analysis (Table 2) of medical syringe waste reveals a high volatile matter content of 99.86%, indicating excellent potential for pyrolysis-based fuel recovery. As the moisture content is 0.00%, there is no water interference in thermal conversion [28]. Ash content is minimal at 0.05%, while fixed car-

Table 2. Proximate analysis of medical syringe waste.

Proximate analysis	wt.%
Volatile matter	99.86
Fixed carbon	0.09
Ash	0.05
Moisture	0.00

bon is 0.09%, confirming the material's clean and energy-rich nature, ideal for thermal degradation [29].

3.2. Ultimate analysis

The ultimate analysis (Table 3) shows that medical syringe waste contains a high carbon content of 84.71% and hydrogen at 13.81%, indicating strong potential as a hydrocarbon fuel source. The absence of nitrogen (0.00%) and very low sulphur content (0.07%) suggest minimal emission of harmful gases, making it suitable for clean pyrolysis-based energy recovery applications [30].

Table 3. Ultimate analysis of medical syringe waste.

Elements analysis	wt.%
Carbon (C)	84.71
Hydrogen (H)	13.81
Nitrogen (N)	0.00
Sulphur (S)	0.07

3.3. Thermogravimetry analysis

A thermogravimetric analysis (TGA) was performed on medical syringe plastic waste to assess its thermal decomposition characteristics, as shown in Fig. 3. The sample showed a steady weight loss when heated at a rate of 10°C per minute from room temperature to 800°C in a nitrogen atmosphere. The breakdown started around 250°C, with major weight loss occurring between 300°C and 500°C, suggesting the main thermal decomposition of plastics like polypropylene and polyethylene. The maximum rate of degradation occurred around 400°C, with a steep decline in weight. By 600°C, over 90% of the sample mass had decomposed. A stable residual mass of approximately 5% remained beyond 700°C, likely representing char and inorganic fillers. The TGA curve confirms that syringe waste undergoes major thermal degradation within a specific range, making it suitable for pyrolysis processes targeting liquid fuel recovery while minimising solid residue [31]. This thermal behaviour guides the selection of optimal pyrolysis conditions.

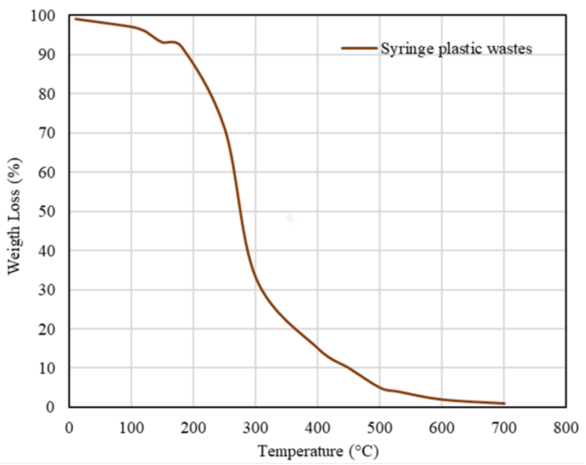

Fig. 3. Thermogravimetric analysis curve.

3.4. Pyrolysis oil yield rate

As seen in Fig. 4, more oil is obtained when using a syringe plastic waste at higher temperatures. At 300°C, the liquid production is more or less 71.2%, the gas and char are 20% and 8.8%, respectively. With a rise in temperature to 400°C, the liquid production increases to 76.4%, and the gas and char fractions decrease to 17% and 6.6%, respectively. Further increase in temperature to 500°C yields the same oil yield of 76.5%, as well as gas and char fractions of 17% and 6.5%, respectively. This shows that the optimum temperature at which the highest output of oil is achieved is between 400−500°C. The oil yield levels off beyond 400°C, giving little indication of further benefits due to high temperature. The selected temperature profile was informed by the preliminary experiments and literature on plastic pyrolysis to maximise the oil production and reduce a lot of excessive degradation by the thermal process.

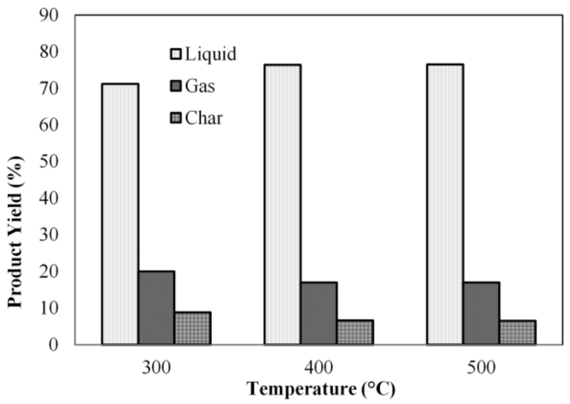

Fig. 4. Pyrolytic product yield rate.

3.5. Gas chromatography – mass spectrometry

To identify the chemical composition of the pyrolysis oil of discarded plastic waste derived from medical syringes, gas chromatography-mass spectrometry (GC-MS) analysis (Fig. 5) was conducted. The chromatogram indicates a wide distribution of hydrocarbon compounds in a retention time span of 0−40 min. The existence of light hydrocarbons, predominantly short-chain alkanes and alkenes (C5–C7) in low-intensity peaks at low retention times (0.05 min (5.10%), 0.15 min (7.12%), and 1.32 min (7.12%)) at early retention times (< 2 min) shows that early polymer chain scission occurred during pyrolysis. The promi-

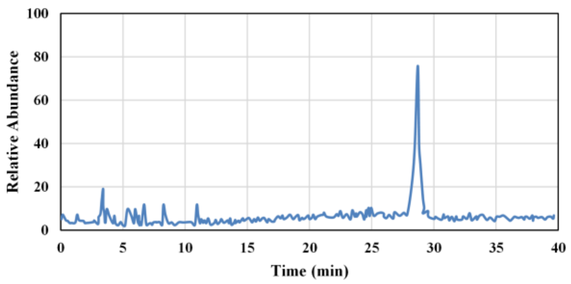

Fig. 5. Gas chromatography-mass spectrometry analysis of syringe plastic pyrolytic oil.

Fig. 6. Syringe plastic oil from pyrolysis process.

nent peaks at 3.30 min (14.06%), 3.41 min (18.98%), and 3.70 min (9.69%) in the low-to-mid retention time range (3−5min) represent the presence of the light olefinic and branched hydrocar-bons (octane, nonane and their unsaturated derivatives). The medium-chain hydrocarbons (decane, undecane, dodecane, etc.) have a boiling point in the gasoline and light diesel ranges (6−10 minutes' retention time) and yield moderate-intensity peaks at 6−12 min (6.69 min (11.71%), 8.26 min (11.71%), and 10.94 min (11.71%)). Higher aliphatic hydrocarbons such as tridecane, tetradecane, pentadecane and cycloalkanes are present, as indicated by the presence of peaks with relative abundances of between 5% and 9% in the mid-to-high retention time region (15 min to 23 min), such as tridecane at 17.83 min (6.72%), tetradecane at 18.43 min (7.09%) and pentadecane at 21.10 min. A large mass cluster is found around the range of 28 min to 29 min with a major peak at 28.71 min indicating the highest relative abundance of 75.77% and the next few masses of 28.46 min (37.75%), 28.81 min (39.02%), 28.91 min (30.83%), which are related to long-chain hydrocarbons, including eicosane, heneicosane and other polypropylene derivatives aliphatic compounds. The heavier hydrocarbons (C20−C30) above 30 min correspond to heavier hydrocarbons that add to the boiling range and viscosity of the oil. In general, the GC-MS data prove that the pyrolysis oil is mainly composed of the alkanes and alkenes of light to heavy fractions, which evidences that this oil can be used as an alternative fuel after proper blending.

Table 4. Physical properties of pyrolysis oil from syringe plastics.

Property	Syringe plastic oil	Standard method
Lower heating value (MJ/kg)	39.5	ASTM D240
Density (g/cm^3 at 15°C)	0.89	ASTM D4052
Kinematic viscosity (mm^2/s at 40°C)	1.92	ASTM D445
Flash point (°C)	39	ASTM D93
Fire point (°C)	48	ASTM D92
Cetane number	46	ASTM D613
Lubricity (μm, HFRR*)	450	ASTM D6079
Cold filter plugging point (°C)	−4	ASTM D6371

*HFRR – high frequency reciprocating rig.

3.6. Properties of syringe plastic oil

Syringe plastic oil (SPO) (Fig. 6), produced through pyrolysis, shows great potential as an alternative source due to its favourable properties (Table 4). It has a higher energy content of 39.5 MJ/kg, with a density of 0.89 g/cm^3 and viscosity of 1.92 mm^2/s. Its flash point is 39°C and fire point is 48°C. These features make SPO comparable to conventional diesel, indicating its suitability for energy applications [32].

4. Experimentation

4.1. Common rail direct injection engine specification

The engine to be considered in this study is a common rail direct injection (CRDI) engine (Fig. 7), because it has accurate control of the fuel injection, better combustion efficiency, and reduced emissions. The following conditions were used to operate the engine: injection pressure − 2000−2300 bar; injection timing − 230° before top dead centre (BTDC); injection strategy − multiple injections per cycle; compression ratio − 17.5:1. To measure the combustion and performance characteristics of alternative fuels, such as syringe plastic pyrolysis oil and mixtures with diesel, these settings were selected. High injection pressure, optimised timing and multiple injection strategy enable the engine

Fig. 7. Common rail direct injection engine setup.

Table 5. Engine specifications.

Parameter	Specification
Engine type	4-cylinder, 4-stroke, double overhead camshaft (DOHC), water-cooled
Engine capacity	1248 cc
Bore × stroke	69.6 mm × 82 mm
Compression ratio	17.5:1
Rated power	74 BHP at 4000 rpm
Maximum torque	190 Nm at 2000 rpm
Fuel injection system type	Common rail direct injection (CRDI)
Injection pressure	1400–1600 bar
Injection timing	23° BTDC (typical for CRDI diesel)
Rated engine speed	4000 rpm
Operating speed range	1000–4000 rpm

to achieve effective fuel atomisation and full combustion, making the engine ideal in the study of effects of pyrolysis oil on efficiency, emissions and combustion behaviour. The engine specifications are provided in Table 5.

4.2. Uncertainty analysis

The accuracy of experimental measurements of the data is highly reliant on an appropriate uncertainty analysis, which is necessary to determine the accuracy of the instrumentation and measurements. An appropriate choice of instruments, proper operating conditions, proper configuration of experiment parameters, and proper carrying out of calibration, observation, and testing procedures can help in minimising measurement errors [33].

The root sum square (RSS) method was used to determine the total experimental uncertainty in the current experiment by examining each of the uncertainties related to brake power (BP) and specific fuel consumption (BSFC), brake thermal efficiency (BTE) and exhaust emissions (CO, HC, and NO_x). It is determined by the uncertainties of the pressure transducer (δP), the crank angle encoder ($\delta\theta$), the exhaust emission measurements of nitrogen oxides (δNO_x), hydrocarbons (δHC) and carbon monoxide (δCO), the fuel consumption measurement (δFC) and the manometer (δM):

$$\text{Total uncertainty of the experiment} = \sqrt{(\delta P)^2 + (\delta\theta)^2 + (\delta \mathrm{NO_x})^2 + (\delta \mathrm{HC})^2 + (\delta \mathrm{CO})^2 + (\delta \mathrm{FC})^2 + (\delta \mathrm{M})^2}.$$

Substituting the relevant numbers into the formula using consistent units, the following is obtained:

$$\text{Total percentage uncertainty} = \sqrt{(1.2)^2 + (1.5)^2 + (2.0)^2 + (1.8)^2 + (1.0)^2 + (1.5)^2 + (1.8)^2}.$$

According to this analysis, the overall uncertainty of the experiment readings was determined as being within the range of about ±4%.

5. Results and discussion

The generation of bio-oil from medical plastic waste through pyrolysis is an innovative and environmentally significant process with the potential to address waste management and energy needs for the CRDI engine.

5.1. Performance characteristics

5.1.1. Brake thermal efficiency

Figure 8 shows how the brake thermal efficiency (BTE) changes with brake power in a CRDI engine with diesel-based and SPO-diesel blends. In all test fuels, the BTE increases with the load, which can be explained by the increased combustion efficiency at the higher brake power as a result of reduced relative heat losses and an increased use of the provided fuel energy. Diesel has the highest BTE of 27.2, with D80SPO20 having a nearly similar value (26.9%) and D70SPO30 (25.7%). The marginal decrease in BTE with an increase in the proportion of SPO is mainly due to the lower calorific value and increased viscosity of the syringe plastic oil relative to diesel that can negatively influence the atomisation of the fuel and the air-fuel mixture, mainly at reduced loads. Nevertheless, the fact that the D80SPO20 blend is nearly diesel highlights that at lower SPO concentrations, the increased volatility and oxygenated character of the blend fosters increased combustion during CRDI injection conditions [34]. This is because the negative effects of SPO properties are further reduced by the high injection pressure and the enhanced spray properties of the CRDI system, allowing efficient combustion at higher loads.

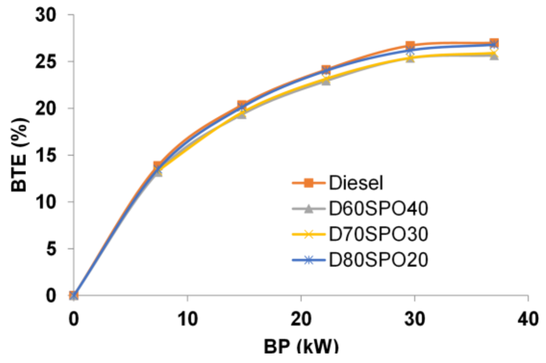

Fig. 8. Brake thermal efficiency vs. load for diesel and SPO-diesel blends.

These trends are in line with the previous studies of plastic pyrolysis oil-diesel blends in CRDI engines [35], where even blends with as much as 20% pyrolysis oil had a BTE value similar to diesel due to phasing up of combustion and low ignition lag at higher loads.

5.1.2. Brake specific fuel consumption

Figure 9 illustrates the change in the brake specific fuel consumption (BSFC) with the brake power of diesel and SPO-diesel blends in a CRDI engine. In all test fuels, we find that BSFC decreases significantly with increasing load, and this is mainly because of the better combustion efficiency and the low relative friction and heat loss at higher brake power. Diesel at low loads (10 kW) has a BSFC of approximately 0.512 kg/kWh, whereas higher values are observed in the SPO-diesel blends, with D60SPO40 and D70SPO30 actually being around 0.55 kg/kWh and 0.60 kg/kWh, respectively.

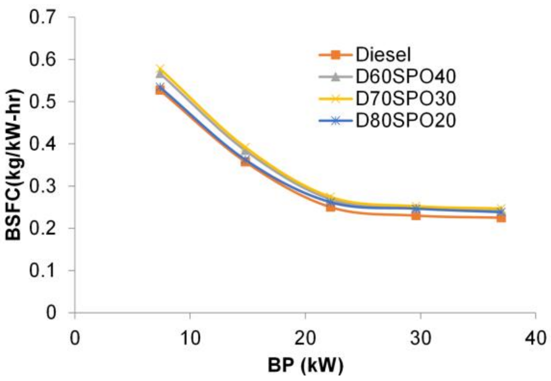

Fig. 9. Brake specific fuel consumption vs. load for diesel and SPO-diesel blends.

It can be explained by the higher BSFC of the blends with a high percentage of SPO at low loads, as the calorific value and viscosity of the syringe plastic oil negatively influence the process of spray atomisation, leading to incomplete combustion of the air-fuel mixture and increased fuel consumption. The in-cylinder temperature and pressure increase with the load and improve fuel evaporation and combustion performance of all blends [36]. Accordingly, when the loads increase (approaching 35 kW), the values of the BSFC of all fuels become almost equal to approximately 0.27 kg/kWh. D80SPO20, of the SPO blends, is also always found to have lower BSFC at all loads with an almost similar operation to that of the diesel.

5.2. Emission characteristics

5.2.1. Carbon monoxide

Figure 10 shows how carbon monoxide (CO) emissions depend on the brake power of the CRDI engine for diesel and SPO-diesel blends. The CO emissions of diesel are comparatively higher at low load states (approx. 5 kW) of approximately 0.10% vol., and this may be associated with incomplete combustion because of lower in-cylinder temperatures and the lack of oxidation of CO. Conversely, the D80SPO20 blend has the least CO emission of about 0.06% (vol.), stating that combustion behaviour is better even at light loads. This is reduced with the improved spray atomisation and oxidation properties that are generated by the fuel properties of the blended SPO at the high-pressure injection of the CRDI engine.

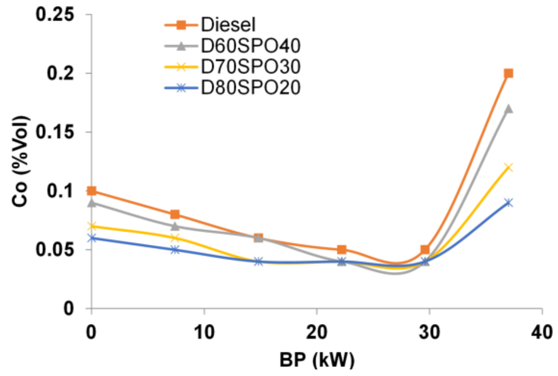

Fig. 10. Carbon monoxide emissions vs. load for diesel and SPO-diesel blends.

Increasing the brake power, the CO emissions of all test fuels decrease to about 25–30 kW as a result of high combustion temperatures, better air-fuel mixing, and a long effective oxidation period, which favour complete combustion [37]. But, over this range of loads, there is an abrupt rise in CO emissions of all the fuels. This increase with higher loads is primarily a result of a higher rate of fuel injection, locally rich mixtures of fuel and air, low oxygen supply, and the shortness of residence time of oxidation reactions [38]. Diesel has the highest CO emission at 35 kW of approximately 0.21% (vol.), and D80SPO20 has a relatively lower amount of about 0.13% (vol.). This lower CO emission of D80SPO20 was consistent with the trend of the study previously reported on plastic oil in CRDI engines because of its improved combustion efficiency.

5.2.2. Unburnt hydrocarbons

Figure 11 shows the change in the emission of hydrocarbon (HC) with the brake power of diesel and SPO-diesel mixtures used in a CRDI engine. At low loads (approx. 5 kW), diesel has a higher value of HC emissions of about 46 ppm (parts per million) and the lowest value of about 34 ppm at D80SPO20. This is mainly because of the incomplete combustion at the low in-cylinder temperatures, such that incomplete oxidation results in the persistence of unconsidered hydrocarbons. The comparatively reduced HC emissions of SPO blends, especially

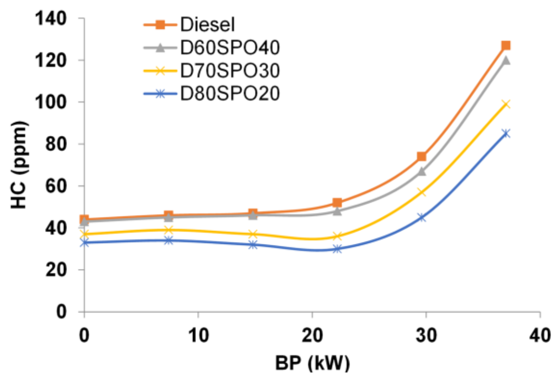

Fig. 11. Hydrocarbon emissions vs. load for diesel and SPO-diesel blends.

D80SPO20, are indicative of better combustion properties with better spray atomisation, as well as better mixing under high-pressure injection during CRDI.

The emissions of HC increase gradually with the brake power, and increase sharply after 30 kW, regardless of the test fuel. At higher loads, higher rates of fuel injection also result in locally rich fuel-air mixtures and re-shortened residence time available to allow complete oxidation and, thus, increasing HC formation. Diesel has the highest level of HC of approximately 130 ppm, whereas D60SPO40, D70SPO30 and D80SPO20 have lower values of about 120 ppm, 105 ppm and 95 ppm, respectively. The relatively smaller HC emissions of D80SPO20 indicate that an intermediate level of SPO as a blend would support further complete combustion even during the high load status. Other past research has reported similar HC emission trends in CRDI engines using plastic pyrolysis oil-diesel blends [28], where blends with up to 20% pyrolysis oil had lower unburned hydrocarbons as a result of enhanced combustion efficiency and a favourable fuel-air interaction [29].

5.2.3. Nitrogen oxides

Figure 12 shows that the emissions of nitrogen oxides (NO_x) depend on the brake power of diesel and SPO-diesel mixtures in a CRDI engine. The emissions of NO_x go proportionate to load in all test fuels because of the increased in-cylinder temperatures and the greater ability to form thermal NO_x with increased combustion intensity. At low loads, the level of NO_x is relatively low in all fuels, indicating low peak temperatures and low oxidation rates. The combustion is also conducive to NO_x formation, as the increase in brake power causes an increase in the quantity of fuel injection and efficiency of the combustion, which results in the enhancement of the flame temperature. The highest NO_x emission of around 850 ppm is generated by the D60SPO40 blend, followed by the emissions of D70SPO30 and D80SPO20 being around 750 ppm and 700 ppm, respectively, and the lowest emission level, at 640 ppm, recorded for diesels. This is because the increased NO_x emissions of SPO blends are due to the enhanced combustion properties like reduced ignition delay and increased rates of heat release, which elevate peak temperatures in the cylinder. Moreover, the availability of lighter hydrocarbon fractions and oxygenated compounds in syringe plastic oil intensifies oxidation reactions, which further contributes to the formation of NO_x.

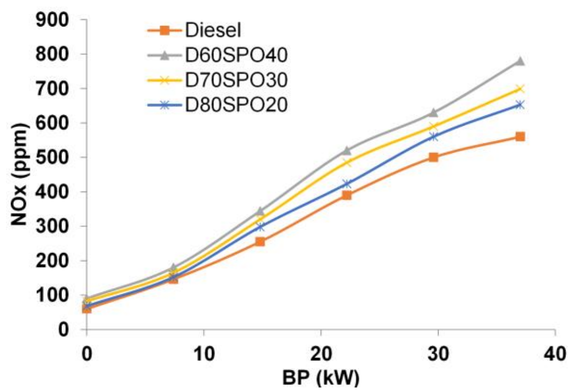

Fig. 12. Nitrogen oxides emission vs. load for diesel and SPO-diesel blends.

Despite the fact that SPO-diesel blends show better brake thermal efficiency and lower CO and HC emissions compared to diesel, the trade-off is, however, exhibited through higher emissions of NO_x [39]. D80SPO20 is the most desirable of the blends investigated, and it has significantly lower NO_x than higher SPO-percentage blends without compromising the advantages of the improved combustion [40].

5.2.4. Smoke emission

Figure 13 demonstrates the change in smoke emissions with brake power of diesel and SPO-diesel combinations in a CRDI engine. There is a steady increase in the smoke opacities with increasing load in all test fuels, primarily due to increased volumes of fuel injection, localised rich fuel-air blends and shorter time of oxidation at high brake power. Under low load levels, the smoke emissions are relatively low because of the adequate oxygen supply, as well as improved combustion conditions. With increased load, the increase in in-cylinder pressure and fuel supply causes incomplete combustion and increased quantity of soot formation, which causes more smoke. Diesel has the highest smoke emission at full load (35 kW), which is approximated to be about 72 HSU (Hartridge smoke units); D60SPO40, D70SPO30 and D80SPO20 have lower values of about 58 HSU. The relatively greater emission of smoke by diesel is linked with less oxidation of soot particles by fuel-rich conditions at high loads.

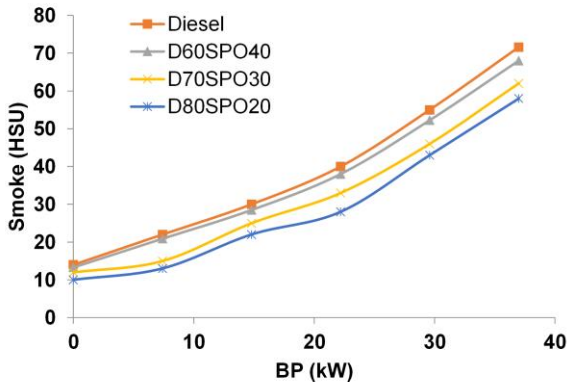

Fig. 13. Smoke opacity vs. load.

The lower levels of smoke emissions recorded with SPO-diesel blends, especially D80SPO20, can be explained by the fact that there were superior combustion properties during CRDI engine injection, which included better spray atomisation and better oxidation of the soot precursors. Moreover, the occurrence of lighter fractions of hydrocarbons in syringe plastic oil helps to promote more complete combustion, and thus, inhibits the development of particles [41]. D80SPO20 was selected as the best soot oxidation blend, showing the lowest smoke emissions at all loads, and, therefore, the best behaviour [42].

6. Conclusions

This study investigated the viability of syringe plastic oil (SPO) as an alternative fuel for a common rail direct injection (CRDI) diesel engine by characterising the properties of fuel, pyrolysing it, and assessing its performance and emissions. According to the results, the following conclusions are made:

1) Syringe plastic waste was found to contain a very high proportion of volatile matter (99.86%), which proved that it is very suitable for pyrolysis conversion. During pyrolysis at 400-500°C, the highest percentage of liquid oil produced was up to 76%, implying the efficient thermal breakdown of the substance within this temperature range.
2) The SPO that was obtained had a lower heating value of 39.5 MJ/kg, similar to diesel; its density (0.89 g/cm^3) and kinematic viscosity (1.92 mm^2/s) were within the tolerable blending ranges, and it was possible to operate the engine with it without alteration.
3) A test on engine thermal efficiency (BTE) showed that brake thermal efficiency increased with load, across all fuels. However, the D80SPO20 mixture produced BTE values at the level of 0.89% of those of diesel at the full load, indicating its ability to burn under the altered fuel characteristics through CRDI engine injection.
4) Brake specific fuel consumption decreased with load for all fuels, with D80SPO20 consistently showing lower BSFC than higher SPO-percentage blends, confirming improved fuel utilisation at moderate SPO proportions.
5) Emission measurements indicated that D80SPO20 cut down CO, HC and smoke emissions by an average of 35−45% as compared to diesel under heavy load conditions, which demonstrated improved oxidation and suppression of soot. Even though NO_x emissions at increased SPO fractions increased due to increased combustion temperatures, the D80SPO20 blend constrained the increase in NO_x compared with higher SPO concentrations.

Overall, the findings show that a 20% SPO blend offers the best balance between performance improvement and emissions. It is observed that the D80SPO20 blend is both technically feasible and eco-friendly as an alternative fuel in CRDI diesel engines, which justifies the successful use of medical plastic waste in the recovery of energy.

References

[1] Ibn-Mohammed, T., Mustapha, K.B., Godsell, J., Adamu, Z., Babatunde, K.A., Akintade, D.D., Acquaye, A., Fujii, H., Ndiaye, M.M., Yamoah, F.A., & Koh, S.C.L. (2021). A critical analysis of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. *Resources Conservation and Recycling*, 164, 105169. doi: 10.1016/j.resconrec.2020.105169

[2] Ahmed, M.M., Pali, H.S., & Khan, M.M. (2024). Allometry of nanoparticles in diesel-biodiesel blends for CI engine performance, combustion and emissions. *Archives of Thermodynamics*, 45(1), 99–108. doi: 10.24425/ather.2024.150442

[3] Apevienyeku, H., Ampofo, J., & Amoako, J.A. (2024). Recycling potential of medical plastic waste. *Discover Environment*, 2, 69. doi: 10.1007/s44274-024-00109-2

[4] Senthil, R., Thamizhvel, R., Ashok, M., & Sudagar, S. (2026). Experimental investigation in CI engine using automobile plastics waste as bio oil (pyrolytic oil). In *Lecture Notes in Mechanical Engineering* (pp. 461–474). Springer, Singapore. doi: 10.1007/978-981-95-2239-2_40

[5] Arefin, M.A., Nabi, M.N., Akram, M.W., Islam, M.T., & Chowdhury, M.W. (2020). A review on liquefied natural gas as fuels for dual fuel engines: Opportunities, challenges and responses. *Energies*, 13(22), 6127. doi: 10.3390/en13226127

[6] Chowdhury, M.W., Nabi, M.N., Arefin, M.A., Rashid, F., Islam, M.T., Gudimetla, P., & Muyeen, S.M. (2022). Recycling slaughterhouse wastes into potential energy and hydrogen sources: An approach for the future sustainable energy. *Bioresource Technology Reports*, 19, 101133. doi: 10.1016/j.biteb.2022.101133

[7] Hassan, T., Rahman, M.M., Rahman, M.A., & Nabi, M.N. (2022). Opportunities and challenges for the application of biodiesel as automotive fuel in the 21st century. *Biofuels Bioproducts and Biorefining*, 16(5), 1353–1387. doi: 10.1002/bbb.2375

[8] Hedayat, F., Stevanovic, S., Milic, A., Miljevic, B., Nabi, M.N., Zare, A., Bottle, S.E., Brown, R.J., & Ristovski, Z.D. (2016). Influence of oxygen content of the certain types of biodiesels on particulate oxidative potential. *Science of the Total Environment*, 545-546, 381–388. doi: 10.1016/j.scitotenv.2015.12.036

[9] Hossain, F.M., Nabi, M. N., Rahman, M.M., Bari, S., Van, T.C., Rahman, S.M.A., Rainey, T.J., Bodisco, T.A., Suara, K., Ristovski, Z., & Brown, R.J. (2019). Experimental investigation of diesel engine performance, combustion and emissions using a novel series of dioctyl phthalate (DOP) biofuels derived from microalgae. *Energies*, 12(10), 1964. doi: 10.3390/en12101964

[10] Hossain, F.M., Nabi, M.N., Rainey, T.J., Bodisco, T., Bayley, T., Randall, D., Ristovski, Z., & Brown, R.J. (2019). Novel biofuels derived from waste tyres and their effects on reducing oxides of nitrogen and particulate matter emissions. *Journal of Cleaner Production*, 242, 118463. doi: 10.1016/j.jclepro.2019.118463

[11] Hossain, F.M., Nabi, M.N., Rainey, T.J., Bodisco, T., Rahman, M.M., Suara, K., Rahman, S.M.A., Van, T.C., Ristovski, Z., & Brown, R.J. (2017). Investigation of microalgae HTL fuel effects on diesel engine performance and exhaust emissions using surrogate fuels. *Energy Conversion and Management*, 152, 186–200. doi: 10.1016/j.enconman.2017.09.016

[12] Islam, M.R., Nabi, M.N., & Islam, M.N. (2003). The fuel properties of pyrolytic oils derived from carbonaceous solid wastes in Bangladesh. *Jurnal Teknologi*, 38(A), 75–80. doi: 10.11113/jt.v38.484

[13] Kannan, D., Nabi, M.N., & Hustad, J.E. (2009). Influence of ethanol blend addition on compression ignition engine performance and emissions operated with diesel and Jatropha methyl ester. *Powertrains, Fuels and Lubricants Meeting*, June 15, Florence, Italy, SAE Technical Papers. doi: 10.4271/2009-01-1808

[14] Mitchell, B.J., Zare, A., Bodisco, T.A., Nabi, M.N., Hossain, F.M., Ristovski, Z.D., & Brown, R.J. (2017). Engine blow-by with oxygenated fuels: A comparative study into cold and hot start operation. *Energy*, 140(1), 612–624. doi: 10.1016/j.energy.2017.08.115

[15] Verma, A., Budiyal, L., Sanjay, M.R., & Siengchin, S. (2019). Processing and characterization analysis of pyrolyzed oil rubber (from waste tires)-epoxy polymer blend composite for lightweight structures and coatings applications. *Polymer Engineering and Science*, 59(10), 2041–2051. doi: 10.1002/pen.25204

[16] Landry, J. (2026). *Parts of a syringe: Diagram and components*. Respiratory Therapy Zone. https://www.respiratorytherapyzone.com/syringe-parts/ [accessed 10 Jan. 2026].

[17] Singh, T.S., Rajak, U., Dasore, A., Muthukumar, M., & Verma, T.N. (2021). Performance and ecological parameters of a diesel engine fueled with diesel and plastic pyrolyzed oil (PPO) at vari-

able working parameters. *Environmental Technology & Innovation*, 22, 101491. doi: 10.1016/j.eti.2021.101491

[18] Singh, A.K., Pali, H.S., & Khan, M.M. (2024). Experimental investigations of CI engine performance using ternary blends of n-butanol/biodiesel/diesel and n-octanol/biodiesel/diesel. *Archives of Thermodynamics*, 45(1), 109–118. doi: 10.24425/ather.2024.150443

[19] Senthil, R., Thamizhvel, R., Sudagar, S., & Sathiyaraj, P. (2026). A comparative analysis of bio-oil production from plastic and biomass with aid of nano particles through pyrolysis process. In *Lecture Notes in Mechanical Engineering* (pp. 423–435). Springer, Singapore. doi: 10.1007/978-981-95-2239-2_37

[20] Dubba, S.K., Pisini, R., Kelli, D., Bammidi, R., Vanam, J.P., & Turali, N. (2025). Experimental investigation of the performance and emission characteristics of cotton seed biodiesel/diesel blends with titanium dioxide nanoparticles. *Archives of Thermodynamics*, 46(3), 151−161. doi: 10.24425/ather.2025.156587

[21] Kumar, D., Kumar, N., & Chaudhary, R. (2024). Use of butanol, pentanol and diesel in a compression ignition engine: A review. *Archives of Thermodynamics*, 45(4), 27–35. doi: 10.24425/ather.2024.151994

[22] Kaczmarczyk, T.Z. (2024). Experimental research of a pumping engine in a micro-ORC system with a low-boiling medium. *Archives of Thermodynamics*, 45(4), 125–140. doi: 10.24425/ather.2024.152002

[23] Rai, I., & Kumar, R. (2025). Heat transfer analysis of a longitudinal fin attached to a beta-type Stirling engine. *Archives of Thermodynamics*, 46(3), 51–60. doi: 10.24425/ather.2025.156578

[24] Kumar, A., Kumar, S., Verma, V.K., Singh, S., Shukla, R., Jain, A., Bist, A.S., Vishnoi, P., Kumar, V., & Bhandari, P., (2025). Experimental analysis of ethanol-diesel blends stabilised with Jatropha methyl ester: Engine Performance and emission characteristics. *Archives of Thermodynamics*, 46(3), 229−236. doi: 10.24425/ather.2025.156593

[25] Banoth, K., Banoth, M., & Mukuloth, S. (2025). Investigating the impact of TiO_2 nanoparticles on waste plastic pyrolysis oil and DEE diesel blends for diesel engine performance and emission optimisation. *Archives of Thermodynamics*, 46(3), 237−245. doi: 10.24425/ather.2025.156594

[26] Subramani, S., Kumar, P.D., Govindasamy, R., & Iyamperumal, M.S. (2025). Comparative analysis of cylinder-to-cylinder variation of parameters of an automotive CRDI engine. *Archives of Thermodynamics*, 46(4), 105–115. doi: 10.24425/ather.2025.156841

[27] Senthil, R., Thamizhvel, R., Sudagar, S., & Ahamadu, B.A. (2025). Production of high-grade fuels from biomass and waste plastics and its influence in a CI engine. *Polymer Bulletin*, 82, 6095−6114. doi: 10.1007/s00289-025-05740-4

[28] Ramalingam, S., Rajkumar, T., Subramanian, S., & Palani, S. (2024). Investigation of combustion, emission, and performance parameters of a natural antioxidant additives using hydrogen and biodiesel as dual fuel in CI engine operation. *International Journal of Hydrogen Energy*, 110, 44–54. doi: 10.1016/j.ijhydene.2025.01.425

[29] Thamizhvel, R., Sethuraman, N., Sakthivel, M., & Prabhakaran R. (2020). Experimental investigation of diesel engine by using paper cup waste as the producer gas with help of down-draft gasifier. In *IOP Conference Series: Materials Science and Engineering*. 988, 012015. doi: 10.1088/1757-899X/988/1/012015

[30] Senthil, R., Thamizhvel, R., & Sudagar, S. (2024). A comparative analysis of pyrolytic oil from medical waste and its suitability as fuel in a compression ignition engine. *Energy Sources Part A: Recovery Utilization and Environmental Effects*, 46(1), 2040–2058. doi: 10.1080/15567036.2024.2302369

[31] Subramanian, S., Thamizhvel, R., Ashokan, A., Rajendran, S., Venkatesan, E.P., Alwetaishi, M., Hussain, F., & Keçebaş, A. (2026). Integrated NiO_2-catalyzed reforming of sesame stalk for hydrogen-enriched producer gas and dual-fuel CI engine performance evaluation. *International Journal of Hydrogen Energy*, 209, 153333. doi: 10.1016/j.ijhydene.2025.153333.

[32] Thamizhvel, R., Naveen Raj, S., & Krishna Raj, S. (2025). Production of oil from plastic waste through thermal degradation process. *Turkish Journal of Engineering*, 9(3): 409–416. doi: 10.31127/tuje.1535115.

[33] Thamizhvel, R., Manikandan, A., Praveen Kumar, S., & Sivasankaran, S. (2023). Potential use of cathode ray tube as an abrasive particle in abrasive jet machine. In *2023 International Conference on Energy, Materials and Communication Engineering* (*ICEMCE*) (pp. 1–6). Madurai, India. doi: 10.1109/ICEMCE57940.2023.10434107

[34] Thamizhvel, R., Suryavarman, K., Velmurugan, V., & Sethuraman, N. (2021). Comparative study of gasification and pyrolysis derived from coconut shell on the performance and emission of CI engine. *Materials Today: Proceedings*, 47(4), 978–983. doi: 10.1016/j.matpr.2021.05.350

[35] Sethuraman, N.K., Surya Varman, K., Venkatakrishnan, R., & Thamizhvel, R. (2021). An experimental investigation of crude glycerol into useful products by using IC engine in dual fuel mode. *Materials Today: Proceedings*, 44(5), 3914–3918. doi: 10.1016/j.matpr.2021.02.160

[36] Kadupu, R.V., Priyadharsini, S., Ananthi, K., Thamizhvel, R., Sudagar, S., & Silambrasan, R. (2024). Assessing the thermal insulation properties of thermoplastic bricks for energy-efficient building solutions. *Matéria (Rio de Janeiro)*, 29(4). doi: 10.1590/1517-7076-rmat-2024-0583

[37] Ramalingam, S., Thamizhvel, R., Sudagar, S., & Silambrasan, R. (2023). Production of third generation bio-fuel through thermal cracking process by utilizing Covid-19 plastic wastes. *Materials Today: Proceedings*, 72(3), 1618–1623. doi: 10.1016/j.matpr.2022.09.430

[38] Sethuraman, N., Karthikeyan, D., Vinodraj, S., Thamizhvel, R., & Kumarasamy, G. (2023). Performance and emission characteristics on CI engine by using waste cooking oil and waste transformer oil as substitute fuel with coconut shell as a catalyst. *Materials Today: Proceedings*, 72(4): 2469–7245. doi: 10.1016/j.matpr.2022.09.457

[39] Thamizhvel, R., Molly Irine, G.S., Vaithianathan, N., Ganesh, M. (2023). Evaluating the performance and emission characteristics of jackfruit seed as bio-oil in CI engine. *Materials Today: Proceedings*, 2214–7853. doi: 10.1016/j.matpr.2023.08.100

[40] Narayanan, S., Vinodraj, S., Thamizhvel, R., & Vaithianathan, N. (2025). Machine learning optimisation of CI engine characteristics with WSA algorithm and Prosopis juliflora biofuel. *Archives of Thermodynamics*, 46(4), 117–125. doi: 10.24425/ather.2025.156842

[41] Madhuvanesan, D.M., & Babu, J.M. (2024). Impact of nano cerium oxide addition with pyrolysis waste plastic oil on combustion, performance and emission characteristics of CRDI diesel engine. *Engineering Research Express*, 6, 045551. doi: 10.1088/2631-8695/ad923e

[42] Khandal, S.V., Khan, T.M.Y., Badruddin, I.A., Kamangar, S., Saleel, C.A., Baig, M.A.A., & Ahmed, N.J.S. (2021). Performance and emission analysis of multicylinder common rail direct injection diesel engine powered with blends of tyre pyrolysis oil-ethanol diesel. *Journal of Engineering Research*, 10(1B), 167–192. doi: 10.36909/jer.8583