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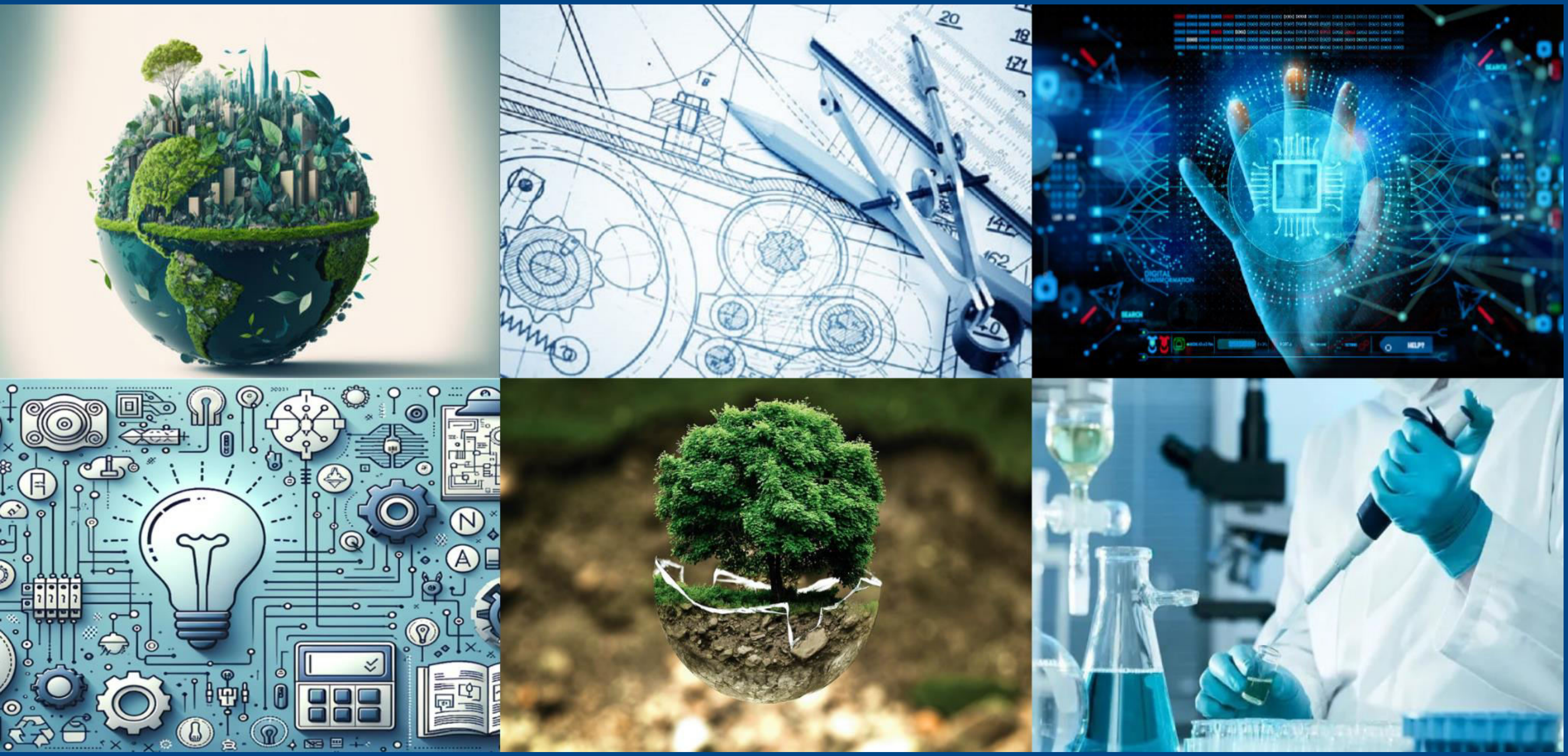

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Production and Characterisation of Diesel-like Fuel via Pyrolysis of Waste Plastics

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ABSTRACT: The escalating generation of plastic waste presents significant environmental and ecological challenges. Thermal conversion technologies, particularly pyrolysis, offer a promising solution by transforming non-recyclable plastics into valuable fuel. This paper investigates the effectiveness of pyrolysis for producing and characterising fuel from low-density polyethylene (LDPE) and mixed municipal plastic waste. The process involved catalytic pyrolysis in an inert atmosphere at 400°C to 500°C, with coal fly ash catalysing the reaction, followed by distillation for purification. The resulting plastic-derived fuels were comprehensively analysed for their physical and chemical properties, including density, calorific value, flash point, and composition, using gas chromatography–mass spectrometry (GC–MS) and Fourier-transform infrared spectroscopy (FTIR), and compared against conventional diesel. The significant findings indicate that both LDPE and mixed plastic-derived fuels offer higher energy density, and mixed plastic fuels show enhanced cold-flow and combustion versatility with diesel, primarily within the C_{10}–C_{21} range. The LDPE fuel exhibited superior energy density due to its long-chain alkanes, while the mixed plastic fuel showed improved cold-flow properties and combustion versatility from its medium-chain fractions and higher aromatic diversity. These findings support the viability of plastic-derived fuels as near-equivalent substitutes for standard diesel, underscoring their potential for waste valorisation and sustainable energy recovery.

KEYWORDS: Thermal catalytic pyrolysis, Waste-to-Fuel, LDPE, Mixed Plastic Waste, Coal Fly Ash, Sustainable Waste Management

I. INTRODUCTION

Plastics represent a broad class of synthetic or semi-synthetic organic substances with a semicrystalline structure, widely used in both industrial and consumer products [1–3]. These materials are composed of high-molecular-weight polymers and often include additives to enhance performance or reduce production costs. Their monomeric building blocks may originate from natural or artificially synthesised organic compounds (such as plastics, polymers, and additives). Plastic, though essential to modern life, poses growing environmental threats. In 2019, global plastic production reached 370 million tons annually. Approximately 9% of the plastic produced was recycled, 12% was incinerated, and the remaining 79% was disposed of in landfills. Approximately 4.5 million tonnes of marine debris, including non-biodegradable plastics, are accumulating in the oceans, leading to the accidental ingestion by marine mammals, disrupting ecological services, and threatening marine species [4,5].

While many plastics are engineered for long-term durability, a significant share—especially packaging—is designed for single-use applications. Despite being theoretically reusable and recyclable, improper disposal, public littering, and weak waste-management infrastructure—particularly in developing regions—have turned plastic waste into a pressing global environmental challenge[6–8]. Global plastic production is increasing at an estimated annual rate of 4–5% and, in the absence of policy interventions, is projected to double by 2050 and triple by 2100 [9,10]. The most common types of plastics include polyethene terephthalate (PET), low-density polyethene (LDPE), high-density polyethene (HDPE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). However, the low recycling rates and the growing burden on landfills and marine environments have sparked interest in advanced waste-to-fuel technologies, such as pyrolysis, which align with global zero-waste and sustainability goals.

Conventional disposal methods—such as landfilling and incineration—present significant environmental challenges, including pollution risks, high land usage, and resource loss [11–13]. Pyrolysis, a thermochemical process conducted in an oxygen-free environment, presents a promising alternative by converting plastic waste into value-added liquid hydrocarbons.

The pyrolysis process employs high temperatures, ranging from 400°C to 500°C, and an inert atmosphere. The type of catalyst plays a vital role in the decomposition of plastic waste, yield and product quality. Catalytic pyrolysis was performed at elevated temperatures, in range of 400 to 600 degrees Celsius, in inert atmospheres like nitrogen or carbon dioxide, or even under vacuum to prevent oxidation and improve product recovery, utilising various catalysts including: clay-based materials such as bentonite and kaolin; zeolite-based catalysts like ZSM-5, Y-zeolite (proton form), recycled fluid catalytic cracking catalysts, and enhanced versions, such as, bentonite impregnated with iron and cobalt [14–20]. Coal fly ash catalysed the reduction of the required reaction temperature. An optimal temperature range of 400°C to 450°C was identified, as it produced the highest heat output, reflected in the maximum volume yield collected [21–23]. Additionally, distillation was performed to purify the crude oil and produce usable fuel.

This study investigates the conversion of low-density polyethene (LDPE) and mixed municipal plastic waste into fuel via pyrolysis, utilising coal fly ash as a catalyst [16,24,25]. We aim to demonstrate the feasibility, efficiency, and environmental potential of plastic-derived fuels as a sustainable alternative that can reduce pollution and meet energy demand. The research seeks to present the efficiency and yield of fuel production from waste plastic, evaluate the properties of the resulting fuel in comparison to conventional diesel, and assess the environmental benefits in terms of reduced plastic pollution and decreased dependence on landfills. Our novel contributions lie in applying coal fly ash as a catalyst in the pyrolysis of mixed plastic and LDPE in a batch-reactor system, achieving an optimal temperature range around 400–450 °C that maximises yield while lowering reaction energy, and characterising the resulting fuel via GC and FTIR to demonstrate near-parity with conventional diesel in terms of physical and chemical properties [26–28].

II. MATERIALS AND METHODS

Two types of materials were used in this project: empty milk pouches (made from LDPE material) and mixed waste plastics commonly found in packaging, including polyethene (PE), polypropylene (PP), and polystyrene (PS). All materials were collected from household waste.

In this study, pyrolysis experiments were performed in a laboratory-scale, (Fig. 1 illustrates Laboratory experimental setup) sealable cylindrical reactor at 400–500°C, catalysed by coal fly ash [29–32]. The pyrolysis gas is condensed into liquid using an ice-water cooling system. The reactor, made of mild steel, is electrically heated to a temperature of around 400°C or higher, with a temperature controller regulating the heat. Insulated with cotton and Plaster of Paris (PoP), the reactor retains heat and minimises energy loss. The condenser cools the vapour, converting it into liquid as the temperature drops to approximately 35–40°C, close to room temperature.

III. PROCESS DESCRIPTION

One kilogram of mixed plastic waste (HDPE, LDPE, PP, and PS) was processed per batch. For comparison, LDPE feedstock (e.g., cleaned, shredded milk pouches) was run separately. All feedstocks were washed, air-dried, and cut into 3–5 cm pieces before being loaded into the reactor [33,34].

The process occurs at high temperatures in the absence of oxygen, with coal fly ash serving as a catalyst. External electric heaters provide the necessary heat to break down the plastics. As the temperature rises, the plastic undergoes thermal liquefaction and begins to vaporise at around 300°C. These vapours are passed through a condenser, where the temperature is reduced from approximately 400°C to 35–40°C, resulting in the production of pyrolytic fuel. Initially, the hydrocarbons begin to decompose, and as the temperature increases, carbon–carbon bonds are broken, leading to the formation of smaller hydrocarbon chains. The residual carbon black left in the reactor can be reused in brick manufacturing or as a tar additive.

Fig. 1: Laboratory experimental setup

Fig. 2a: Collected plastic fuel oil

Fig.2b: Distilled plastic fuel oil

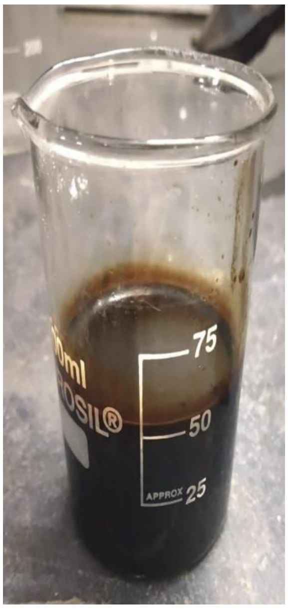

Fig.2c: Remaining residue

Distillation

The crude pyrolytic oil collected as shown in (Fig. 2a) was purified by atmospheric distillation using a heating mantle. The vapours generated were condensed and collected to yield the final fuel product. (Fig. 2b) demonstrate distilled plastic fuel oil. Non-volatile impurities and residues were removed as bottom products, minimising corrosion risks during subsequent use. As shown in (Fig. 2c) The distillation residue was evaluated as a potential additive for bitumen in road construction or as a component in brick manufacturing.

IV. METHODS FOR CHARACTERISATION OF THE FUEL [35–38]

Density

The density of the fuel was determined using a clean, dry density bottle of known volume, typically 10 or 25 mL. The empty bottle was first weighed, then filled with the fuel sample, ensuring no air bubbles were present and weighed again. The difference in weight gave the mass of the fuel, which was then divided by the volume of the bottle to calculate the density using the formula: Density = Mass / Volume.

This method provided an accurate measurement of fuel density, typically expressed in grams per millilitre (g/mL) or kilograms per cubic meter (kg/m^3). It was adjusted for temperature variations as necessary.

Acid number

The acid number was determined by titrating a known quantity of the fuel, typically dissolved in a solvent mixture of toluene and isopropyl alcohol, using a standard potassium hydroxide (KOH) solution. A few drops of phenolphthalein were added as an indicator, and the appearance of a persistent pink colour identified the endpoint. The volume of KOH required to neutralise the acidic components was used to calculate the acid number, expressed in milligrams of KOH per gram of fuel. This value indicated the concentration of free acids in the fuel and helped assess degradation or contamination.

Gross calorific value

The calorific value was determined using a bomb calorimeter, an instrument that measured the heat released during the complete combustion of a known quantity of fuel in a controlled environment. The fuel was placed in a crucible inside the combustion chamber (bomb), which was filled with oxygen. The bomb was then submerged in a known volume of water within the calorimeter. Upon ignition, the heat released raised the water temperature. By recording the temperature change, the calorific value was calculated and expressed in kilojoules per gram (kJ/g) or kilocalories per gram (kcal/g), reflecting the fuel's energy content.

Flash ignition temperature

The flash point was determined using either the Pensky-Martens closed-cup or the Abel closed-cup apparatus, depending on the fuel type and applicable standards. A small quantity of the fuel was gradually heated in a sealed cup, with a test flame passed over its surface at intervals. The flash point was the lowest temperature at which the vapours ignited briefly. This property was critical for determining the ignition risk and safe handling or storage conditions of the fuel.

Specific gravity index

Specific gravity was determined by comparing the fuel's density with the density of water at a standard temperature, typically 15°C or 20°C. This was measured using a hydrometer or a digital densitometer. A fuel sample was placed in a graduated cylinder, and the specific gravity was computed as the ratio of the fuel's density to that of water. This value provided insight into the fuel's composition and energy content, which was necessary for evaluating engine performance and fuel blending properties.

Ash content

Ash content was determined by measuring the inorganic residue left after the complete combustion of the fuel. A known amount of the sample was heated in a muffle furnace at around 775°C until all combustible material was removed, leaving only mineral residue (ash). After cooling in a desiccator, the residue was weighed, and the ash content was calculated as a percentage of the initial sample weight. High ash content indicated contamination or additives and could lead to engine deposits and reduced combustion efficiency.

Volatile matter

Volatile matter was determined by heating the fuel in the absence of air in a covered crucible at about 950°C for a set duration, usually 7 minutes. The process drove off volatile compounds (excluding moisture), and the weight loss was calculated to determine the volatile matter content as a percentage of the original sample. This parameter was essential for assessing combustion behaviour, as fuels with high volatile content ignited more readily and burned with a longer flame.

Moisture content

The moisture content was determined by heating a known amount of the fuel in an oven at 105–110°C until a constant weight was achieved. The weight loss, representing water content, was calculated and expressed as a percentage of the initial sample weight. Accurate moisture measurement was crucial, as excessive moisture reduced the fuel's calorific value, impaired combustion, and could lead to corrosion in fuel systems.

Pour point

The pour point was the lowest temperature at which a fuel remained fluid and could still flow. It was determined by cooling a sample in a standardised test jar at regular temperature intervals, typically using a controlled cooling bath. The jar was tilted at each interval to observe movement. This property was necessary for evaluating fuel performance in cold climates, as high pour points could cause fuel thickening and flow problems in engines and storage systems.

Carbon residue

Carbon residue was measured by heating a known quantity of fuel in the absence of air to simulate combustion conditions. Standard methods such as the Conradson or Ramsbottom tests were used. After all volatile components were driven off, the remaining carbonaceous residue was weighed and expressed as a percentage of the original sample. High carbon residue indicated a tendency for deposit formation in engines and combustion chambers, affecting performance and maintenance.

Sulphur content

Sulphur content was determined using methods such as combustion in a bomb calorimeter, followed by analysis of the resultant gases for sulphur dioxide, or more advanced techniques like X-ray fluorescence (XRF) or ultraviolet fluorescence. Sulphur content was expressed as a percentage by weight. Accurate determination was essential to ensure compliance with emission regulations and to assess the fuel's suitability, especially for engines and industrial burners.

FTIR (Fourier Transform Infrared) analysis

FTIR spectroscopy was used to characterise the molecular composition of the fuel. Infrared light was passed through the sample, and the absorption spectrum was recorded, revealing characteristic peaks corresponding to chemical bonds such as C–H, O–H, and C=O. By comparing the spectrum to reference data, various functional groups, hydrocarbons, oxygenates, and additives were identified. FTIR was a rapid, non-destructive method widely used in quality control and contamination analysis.

GC (Gas Chromatography) analysis

Gas Chromatography (GC) analysed individual hydrocarbon components in the fuel based on their volatility and interaction with the column's stationary phase. The sample was vaporised and carried by an inert gas (e.g., helium or nitrogen) through a capillary column, where compounds were separated based on their retention times. Detection was done using a Flame Ionisation Detector (FID) or a Mass Spectrometer (GC-MS). GC provided detailed compositional data, which was critical for assessing purity, additive content, and overall fuel quality.

V. RESULT AND DISCUSSION

Processing of fuel

The fuel was obtained from waste plastic through the pyrolysis technique, using a temperature range of 400°C to 500°C and coal fly ash as a catalyst. An increase in fuel yield was observed with an increase in temperature. The distillation technique further purified the crude fuel obtained. Further, the fuel was characterised for various physical parameters.

Characterisation of fuel

Fuel quality

The characteristics of the produced alternative fuel are evaluated post-distillation, including the remaining residue. Its physical parameters are then compared with those of standard diesel and gasoline. As illustrated in below Table 1.

Density

Density refers to the concentration of mass within a specific volume. It is calculated as the mass-to-volume ratio and is measured in kilograms per cubic meter (kg/m^3), typically assessed using a hydrometer. The density of diesel fuel, mixed plastic fuel, and LDPE plastic fuel was observed to be in the ranges of 850–920 kg/m³, 760–790 kg/m³, and 730–750 kg/m³, respectively. The density of the diesel fuel obtained from LDPE and mixed plastic fuel is found to be close to that of standard diesel fuel, indicating significant combustion efficiency, energy content, and fuel injection performance.

Acid value

The acid value determines the level of free fatty acids (FFA) in a sample, particularly in fats and oils. It represents the amount of potassium hydroxide (KOH), in milligrams, required to neutralise the FFAs in one gram of the substance. The acid value of diesel fuel was observed to be in the range of 760–840 mg KOH/g. Similarly, the acid values of mixed plastic fuel and LDPE plastic fuel were 778±5% mg KOH/g and 740±5% mg KOH/g, respectively. The acid values of the diesel fuel obtained from LDPE and mixed plastic fuel are found to be close to that of standard diesel, indicating good quality. The lower acid values of these fuels suggest minimal corrosion potential and considerable storage stability.

Gross calorific value

Calorific value refers to the amount of heat energy generated during the complete combustion of a substance with oxygen under standard conditions. The calorific value of diesel fuel was observed to be between 10,030 and 10,750 kcal/kg. Similarly, the calorific values of mixed plastic fuel and LDPE plastic fuel were in the ranges of 9,530–10,533 kcal/kg and 9,213–10,183 Kcal/kg, respectively. The gross calorific values of the diesel fuel obtained from LDPE and mixed plastic fuel are found to be comparable to those of standard diesel fuel, indicating a high energy content. This directly contributes to improved efficiency and performance in combustion applications.

Flash point

The flash point is the critical temperature at which a fuel emits sufficient combustible vapours to ignite upon exposure to a heat source. The flash points of diesel fuel, mixed plastic fuel, and LDPE plastic fuel were observed to be 35–50 °C, 35–50 °C, and 45–50 °C, respectively. The flash points of the diesel fuels obtained from LDPE and mixed plastic sources are similar to those of standard diesel fuel. This indicates the lowest temperature at which the fuel can vaporise to form an ignitable mixture in air, making it a key parameter for evaluating fuel flammability, handling safety, and storage requirements.

Specific gravity

Specific gravity is defined as the ratio of a fuel's density to that of water at a standardised temperature (commonly 4°C for water). It indicates how the fuel's mass per unit volume compares to that of water under the same conditions. The specific gravity of diesel fuel, mixed plastic fuel, and LDPE plastic fuel was observed to be in the ranges of 0.87–0.88, 0.91–0.915, and 0.86–0.87, respectively. No significant difference was observed between the specific gravity of the obtained diesel fuel and that of standard diesel fuel, indicating comparable density relative to water. This parameter is essential for evaluating the fuel's composition, energy content, and suitability for engine performance and blending applications.

Ash content

Ash content refers to the measurement of the amount of inorganic, non-combustible residue left after burning the fuel under controlled conditions. It indicates the presence of metal-containing additives, dirt, and other contaminants. The ash content of diesel fuel was found to be between 0.01% and 0.02%, while that of both mixed plastic fuel and LDPE plastic fuel was less than 0.10%. These findings indicate the presence of inorganic impurities, which can lead to deposits, abrasion, and reduced engine and combustion system efficiency.

Volatile contents

Volatile content refers to the portion of the fuel that evaporates or vaporises when heated under controlled conditions. It primarily consists of light hydrocarbons that influence ignition quality and emissions. The volatile content in diesel fuel was observed to be in the range of 98–99%. Similarly, both mixed plastic fuel and LDPE plastic fuel exhibited volatile matter in the range of 99–100%. The higher volatile content of LDPE and mixed plastic fuel demonstrates their ability to vaporise easily and burn more completely.

Moisture content

Moisture content refers to the amount of water present in the fuel, either dissolved, emulsified, or in free form. Excess water in diesel can lead to engine damage, microbial growth, and fuel degradation. The moisture content in standard diesel fuel was observed to be between 0.04% and 0.06%, whereas for both mixed plastic fuel and LDPE plastic fuel, it was found to be less than 0.40% to 0.50%. This relatively low moisture content in the synthesised fuels suggests better storage stability and reduced risk of corrosion and microbial growth.

Pour point

The pour point marks the lowest temperature at which the fuel remains fluid before becoming semi-solid due to wax crystallisation, which affects its flow and pump ability. The pour points of standard diesel fuel, mixed plastic fuel, and LDPE plastic fuel were determined to be in the ranges of -15 to 35°C, -15 to -10°C, and -4 to -2°C, respectively. The higher pour point values of mixed plastic and LDPE fuels compared to standard diesel suggest their unsuitability for use in low-temperature regions.

Carbon residue

Carbon residue is the solid carbonaceous deposit left after the fuel is evaporated and pyrolysed under controlled conditions. It indicates the fuel's tendency to form deposits in engines. The carbon residue of diesel fuel was found to be less than 0.35%, while that of both mixed plastic fuel and LDPE plastic fuel was less than 0.10%. The lower carbon residue content of LDPE and mixed plastic fuels compared to standard diesel fuel demonstrates their reduced tendency to form deposits in engines and combustion systems, thereby lowering maintenance requirements.

Sulphur content

Sulphur content refers to the amount of sulphur present in the fuel, typically expressed in parts per million (ppm). Sulphur naturally occurs in crude oil and can remain in diesel unless removed through refining. The sulphur content of diesel fuel, mixed plastic fuel, and LDPE plastic fuel was found to be 480–520 ppm, 420–430 ppm, and 355–365 ppm, respectively. The sulphur content in the synthesised diesel fuels was lower than that of standard diesel fuel, indicating a reduced potential for harmful emissions, such as sulphur dioxide (SO_2), which contribute to air pollution and acid rain. Additionally, the lower sulphur content helps prevent corrosion in engine components.

Table 1: Comparison of the Characteristic Values of Alternative Fuels and Diesel Fuel

Parameter	LDPE Plastic Fuel	Mixed Plastic Fuel	Conventional Diesel Fuel
Density (kg/m$^{3)}$	730 - 750	760 - 790	850 -920
Acid Value (mg KOH/gm)	740 ± 5%	778 ± 5%	760 – 840
Gross calorific value (kcal/kg)	9,213 -10,183	9,530 - 10,533	10,030 - 10,750
Flash point (°C)	45 - 50	35 - 50	35 – 50
Specific gravity	0.87 - 0.915	0.91 - 0.915	<=0.880
Ash content (%)	<0.10	<0.10	0.01-0.02
Volatile matter (%)	99 - 100.0	99 - 100.0	98 – 99
Moisture (%)	<0.50	<0.50	0.05
Pour point (°C)	-4 to -2	<-10	-10°C to -35°C
Carbon residue	<0.10	<0.10	<0.35
Sulphur	355-365	420-430	480-520

Fourier Transform Infrared spectroscopy (FTIR) analysis of diesel fuel

FTIR is a technique used to analyse the composition of diesel fuel by measuring the infrared absorption of chemical bonds. It helps identify functional groups and key components, providing valuable insights into the quality of the fuel. FTIR spectroscopic analysis is crucial for characterising the functional groups present in diesel and alternative fuels, allowing for the detection of impurities, degradation products, and additives as part of quality control.

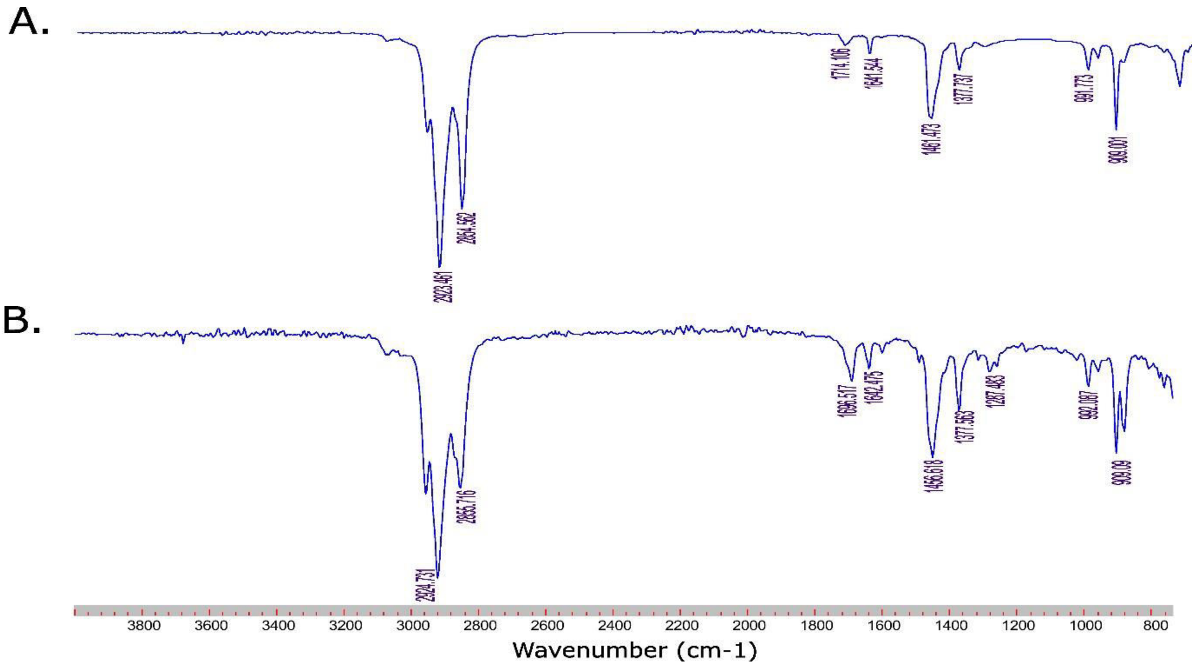

Fig. 3: FTIR Graphical representation of **(A)** LDPE and **(B)** mixed plastic fuel sample

The FTIR spectrum of the LDPE polyfuel (Fig. 3A) reveals characteristic spectral features indicating the presence of specific functional groups. The strong absorption bands at 2923.461 cm^{-1} and 2854.562 cm^{-1} correspond to the hydrocarbon stretching frequencies of alkanes, confirming the presence of extended hydrocarbon chains. The absorption band at 1714.106 cm^{-1} represents C=O stretching, suggesting the presence of carbon-oxygen double-bonded species such as ketones and aldehydes, which are common oxidation products formed during thermal degradation. The C=C stretching peak at 1641.544 cm^{-1} indicates the presence of alkenes, likely produced due to polymer cracking. The peaks at 1461.473 cm^{-1} and 1377.737 cm^{-1} are attributed to methylene ($-CH_2-$) and methyl ($-CH_3-$) bending vibrations, further confirming the presence of hydrocarbon chains with possible branching. Additionally, the C-H out-of-plane bending vibrations at 991.773 cm^{-1} and 909.001 cm^{-1} suggest the presence of vinyl ($-CH=CH_2$) groups, indicating unsaturation in the fuel. Overall, the spectrum confirms that LDPE polyfuel primarily consists of alkanes and alkenes, with minor oxygenated compounds, making it a promising alternative fuel derived from plastic waste.

The FTIR spectrum of the mixed plastic fuel (Fig. 3B) exhibits characteristic spectral features reflecting various functional groups. Prominent peaks at 2924.731 cm^{-1} and 2855.716 cm^{-1} are associated with C–H stretching vibrations of alkanes, confirming the presence of extended hydrocarbon chains derived from polyethylene-based fuels. The peak at 1696.517 cm^{-1} corresponds to C=O stretching, suggesting the presence of carbonyl-containing compounds such as ketones or aldehydes, likely formed through oxidation during thermal degradation. A significant peak at 1642.475 cm^{-1} indicates C=C stretching, signifying the presence of alkenes.

Absorptions at 1456.618 cm^{-1} and 1377.563 cm^{-1} are associated with the bending vibrational modes of methylene ($–CH_2–$) and methyl ($–CH_3$) groups, confirming the hydrocarbon backbone with possible branching. Additionally, peaks at 1287.483 cm^{-1} and 992.087 cm^{-1} represent C–H bending vibrations, with the latter indicating out-of-plane bending of alkenes, suggesting unsaturation in the sample. The peak at 909.099 cm^{-1} further supports the presence of vinyl ($–CH=CH_2$) groups.

Overall, the spectrum confirms that the sample consists mainly of alkanes and alkenes, with minor oxygenated products, indicating its potential as a fuel-like substance derived from the breakdown of polymers.

The FTIR spectra presented in Figure 3 demonstrate the successful conversion of plastic waste into fuel-like substances through thermal degradation processes. Both LDPE (Low-Density Polyethene) and mixed plastic samples exhibit characteristic spectral features that confirm their potential as alternative fuel sources.

LDPE Polyfuel Analysis

The FTIR spectrum of LDPE polyfuel (Figure 3A) reveals distinct absorption bands indicative of a hydrocarbon-rich composition [39][40]. The prominent peaks at 2923 cm^{-1} and 2854 cm^{-1} correspond to C-H stretching vibrations in alkanes, confirming the presence of extended hydrocarbon chains typical of fuel compounds. The absorption at 1714 cm^{-1} indicates C=O stretching from carbonyl groups, suggesting the formation of ketones and aldehydes as oxidation products during thermal breakdown. The C=C stretching peak at 1641.544 cm^{-1} indicates the formation of alkenes through polymer cracking processes. Additional peaks at 1461 cm^{-1} and 1377 cm^{-1} represent methylene and methyl group bending vibrations, while the out-of-plane C-H bending at 991 cm^{-1} and 909 cm^{-1} confirms vinyl group presence, indicating unsaturation in the fuel structure.

Mixed Plastic Fuel Analysis

The mixed plastic fuel spectrum (Figure 3B) shows similar characteristics with slight variations in peak positions. Notable absorptions at 2924 cm^{-1} and 2855 cm^{-1} again confirm alkane presence, while the C=O peak at 1696 cm^{-1} suggests carbonyl compound formation. The C=C stretching at 1642 cm^{-1} and various C-H bending vibrations (1456 cm^{-1}, 1377 cm^{-1}, 1287 cm^{-1}, 992 cm^{-1}, and 909 cm^{-1}) collectively indicate a complex hydrocarbon mixture with both saturated and unsaturated components [40–42].

Both spectra confirm that plastic-derived fuels primarily consist of alkanes and alkenes, with minor oxygenated compounds, closely resembling the composition of conventional diesel fuel. This validation supports the feasibility of converting plastic waste into valuable fuel resources, offering a sustainable solution for both waste management and energy production challenges.

GC-MS characterisation of diesel fuel

Gas Chromatography–Mass Spectrometry (GC-MS) is an advanced analytical technique used to separate, identify, and quantify compounds in complex mixtures. When applied to diesel fuel, GC-MS provides detailed insights into its chemical composition. It is instrumental in characterising the hydrocarbon and additive profiles of both petroleum-derived and bio-based diesel fuels.

GC-MS characterisation of diesel fuel is important because it enables precise identification and quantification of individual hydrocarbon components, additives, and contaminants, providing detailed compositional analysis critical for assessing fuel quality, performance, and compliance with regulatory standards.

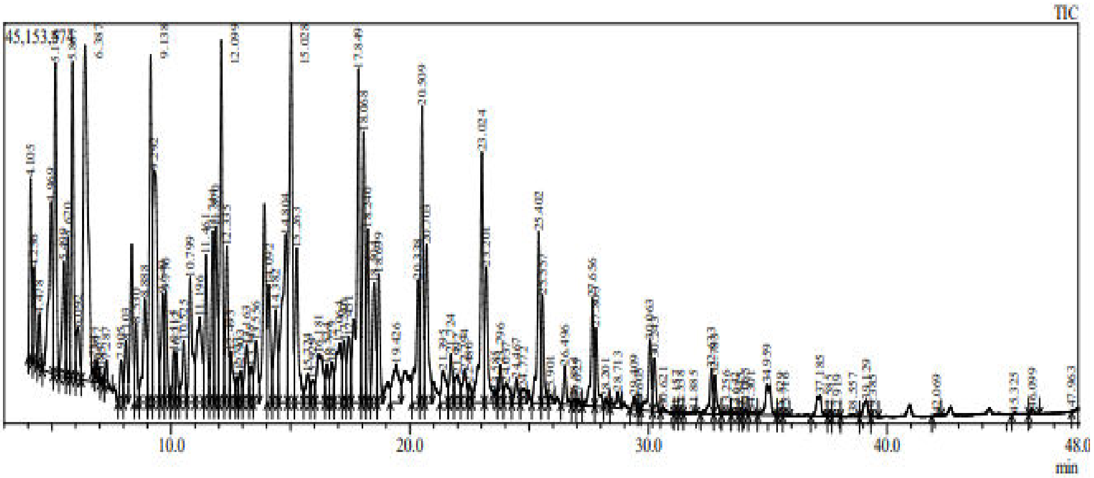

Fig. 4: GC-MS chromatogram of mixed plastic fuel

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The chromatogram obtained via GC-MS illustrated as in Fig 4 shows analysis of fuel produced from the pyrolysis of mixed plastics, highlighting its complex chemical composition. The graph shows numerous sharp and distinct peaks, indicating the presence of a wide range of volatile organic compounds, predominantly hydrocarbons formed through the thermal degradation of plastic waste.

The total ion chromatogram (TIC) spans a retention time from approximately 3 to 48 minutes, with the most intense peaks occurring between 5 and 25 minutes. These prominent peaks correspond to low- and mid-range molecular weight hydrocarbons, which are typical constituents of diesel-type fuels. Peaks appearing at earlier retention times (less than 10 minutes) suggest the presence of lighter hydrocarbons, including short-chain alkanes and alkenes. These compounds are highly volatile and may enhance fuel combustibility, though they can also impact storage stability.

Between 10 and 25 minutes, the chromatogram reveals a dense cluster of major peaks, likely representing C_{10}–C_{20} straight-chain and branched alkanes, cycloalkanes, and possibly aromatic compounds. This region is vital, as it closely aligns with the hydrocarbon range found in conventional diesel fuel, indicating that the pyrolysis product contains a substantial fraction of fuel-grade hydrocarbons. Notably, compounds identified in previous data tables include Eicosane**,** Hexatriacontane**,** Dotriacontane**,** and Bis(2-ethylhexyl) phthalate, among others. The presence of Eicosane ($C_{20}H_{42}$)**,** in particular, is a strong indicator of diesel-range quality.

Beyond the 30-minute mark, the frequency and intensity of peaks gradually decrease, suggesting the presence of heavier hydrocarbons or waxy residues. These components can enhance the energy density of the fuel but may also introduce operational challenges, such as increased viscosity or clogging, if not properly refined.

Overall, the chromatogram reflects a diverse hydrocarbon composition, indicating that the plastic-derived pyrolysis fuel shares significant similarities with diesel, especially in the C_7–C_{21} range. This suggests that the fuel has potential for diesel engine applications, provided it undergoes suitable refining and the addition of performance-enhancing additives. The GC-MS data confirms the presence of both light and heavy fractions, emphasising the fuel's broad volatility profile, an essential factor in evaluating combustion efficiency, performance, and emissions characteristics.

Table 2: Compound list from the GC-MS chromatogram of mixed plastic fuel

Peak	Retention Time (min)	Injection Time (min)	Final Time (min)	Area	Area %	Name of compound
2	4.26	4.19	4.39	71062613	0.76	Heptane, 2,4-dimethyl-
3	4.48	4.39	4.6	36739374	0.39	Cyclopentane,1,1,3,4-tetramethyl-, cis-
4	4.97	4.6	5.06	213923994	2.28	2,3-Dimethyl-2-heptene
5	5.15	5.06	5.3	234683770	2.5	1-Undecene
6	5.5	5.29	5.59	106797022	1.14	Cyclohexane,1,3,5-trimethyl-, (1.alpha.,3.alpha.,5.beta.)-
15	7.91	7.77	7.99	36656401	0.39	Cyclopentene, 1-butyl-
16	8.1	7.99	8.21	55569632	0.59	Benzene, propyl-
17	8.53	8.46	8.66	63277491	0.67	Benzene, 1,2,3-trimethyl-
19	9.12	9	9.23	319651085	3.41	Cyclodecane
22	9.77	9.72	9.97	91329707	0.97	Decane, 4-methyl-
23	10.12	9.97	10.17	42190599	0.45	Mesitylene
24	10.21	10.17	10.34	39286697	0.42	Benzene, 2-propenyl-
25	10.53	10.34	10.66	65578204	0.7	Indane
30	11.87	11.81	11.98	157504538	1.68	3-Hexadecene, (Z)-
31	12.09	11.96	12.23	328440911	3.5	1-Tetradecene

32	12.34	12.23	12.46	149285315	1.59	Dodecane, 2,6,11-trimethyl-
33	12.49	12.46	12.7	55151826	0.59	5-Undecene, (Z)-
34	12.77	12.7	12.83	20134102	0.21	3-Tridecene, (E)-
38	13.56	13.44	13.7	73337699	0.78	Biphenylene,1,2,4a,4b,7,8,8a,8b-octahydro-
39	14.09	14.02	14.23	114569381	1.22	Cycloprop[a]indene,1,1a,6,6a-tetrahydro-
40	14.38	14.23	14.5	117649275	1.25	Biphenylene,1,2,4a,4b,7,8,8a,8b-octahydro-
42	15.03	14.89	15.17	404536517	4.31	1-Tetradecene
43	15.26	15.17	15.55	158894147	1.69	Dodecane, 2,6,11-trimethyl-
47	16.52	16.45	16.63	37728442	0.4	Dodecane, 2,6,11-trimethyl-
48	16.73	16.63	16.83	45773578	0.49	Dodecane, 4,6-dimethyl-
49	17.06	16.83	17.17	109916361	1.17	1H-Indene, 1,3-dimethyl-
50	17.24	17.17	17.33	56067135	0.6	Naphthalene,1,2-dihydro-3-methyl-
52	17.85	17.55	17.97	376954350	4.02	1-Pentadecene
53	18.07	17.97	18.17	238602044	2.54	2,6,10-Trimethyltridecane
58	20.34	20.09	20.41	133671659	1.42	Biphenyl
59	20.51	20.41	20.63	251049365	2.68	1-Tetradecene
60	20.7	20.63	20.95	155752878	1.66	Dodecane, 2-methyl-
61	21.4	21.27	21.61	50317802	0.54	Naphthalene, 1,3-dimethyl-
62	21.72	21.61	21.85	51751906	0.55	Diphenylmethane
64	22.29	22.13	22.43	45166528	0.48	Dodecane, 2-methyl-
65	22.48	22.43	22.61	17914572	0.19	Tetradecane, 2,6,10-trimethyl-
66	23.02	22.61	23.13	260032072	2.77	1-Pentadecene
67	23.2	23.13	23.67	141315299	1.51	Hexadecane
68	23.59	23.51	23.67	959374	0.01	Cyclopentadecane
73	25.4	25.11	25.51	169942293	1.81	1-Nonadecene
74	25.56	25.51	25.81	86248153	0.92	Hexadecane
75	25.9	25.81	26.09	8301325	0.09	9H-Fluorene, 9-methyl-
79	27.66	27.23	27.75	107916435	1.15	1-Nonadecene
80	27.8	27.75	28.39	75458010	0.8	Heptadecane
85	30.06	29.69	30.17	72677666	0.77	1-Nonadecene
86	30.24	30.17	30.51	45982432	0.49	Heneicosane
91	32.63	32.19	32.73	48399819	0.52	1-Nonadecene
92	32.78	32.73	33.07	34722913	0.37	Heneicosane
101	37.19	36.81	37.51	35617694	0.38	Eicosane
105	39.13	38.85	39.34	24872263	0.27	Eicosane

The GC-MS data of plastic-derived polyfuel as represented in above table 2 reveals a broad spectrum of hydrocarbon compounds ranging from C_7 to C_{21}, predominantly within the diesel range. The peaks include light branched alkanes and alkenes such as 2,4-dimethyl-heptane, 2,3-dimethyl-2-heptene, and 1-undecene, which are indicative of the thermal cracking of polymers. A variety of cyclic hydrocarbons—such as cyclopentane, cyclohexane, cyclodecane, and indane—are also present, along with aromatic compounds including benzene derivatives, mesitylene, naphthalene, biphenyl, and diphenylmethane, reflecting contributions from polystyrene or mixed plastic waste.

Notably, there is a strong presence of diesel-range linear and branched alkenes such as 1-tetradecene, 1-pentadecene, and 1-nonadecene, as well as saturated alkanes like hexadecane, heptadecane, eicosane, and heneicosane all of which are typical components of commercial diesel fuels. Identified aliphatic compounds such as 2,6,11-trimethyl-dodecane, 2,6,10-trimethyl-tridecane, and 4,6-dimethyl-dodecane contribute to the complexity and indicate a significant proportion of branched hydrocarbons, which can enhance the cetane value.

Overall, the profile showcases a complex yet diesel-like hydrocarbon mixture, with a balanced presence of alkanes, alkenes, cycloalkanes, and aromatics, demonstrating the effectiveness of plastic pyrolysis and the potential of LDPE-based polyfuel as a viable alternative fuel blend.

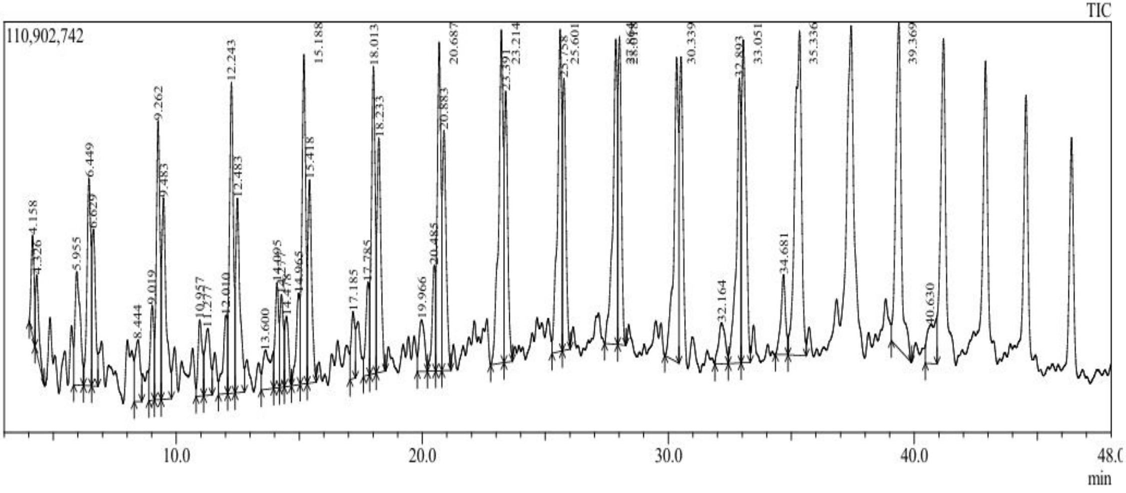

Fig. 5: Gas chromatographic profile of LDPE-derived fuel

The GC-MS chromatogram of LDPE-derived fuel as illustrated in Fig. 5 displays a series of sharp, well-defined peaks spanning a retention time (RT) range of approximately 4 to 48 minutes, indicating a diverse array of hydrocarbon and functionalised compounds. Early-eluting peaks (RT ~4–12 min) correspond to lighter, lower molecular weight compounds such as alkanes, alkenes, and small aromatic molecules—likely derivatives from the initial breakdown of the polymer.

Mid-range peaks (RT ~12–30 min) reflect medium-chain hydrocarbons, including straight and branched alkanes and alkenes such as hexadecane, 1-nonadecene, and carbonic acid esters, which are typical of diesel-range fuels. The most prominent peaks in this region suggest a high concentration of diesel-range compounds.

Late-eluting peaks (RT ~30–48 min) indicate the presence of long-chain hydrocarbons and high-molecular-weight esters, such as hexacontane and decyl pentadecyl ester, pointing to incomplete cracking or the presence of plastic additives. The complexity and variation in peak intensities confirm a broad distribution of hydrocarbons, consistent with the thermal degradation of LDPE.

This analysis highlights the potential of LDPE pyrolysis oil as a viable alternative to conventional fuels, particularly after further refining or blending.

Table 3: Compound list from the GC-MS chromatogram of LDPE-derived fuel

Peak	Retention Time (min)	Injection Time (min)	Final Time (min)	Area	Area %	Name of compound
6	8.44	8.29	8.61	240687028	0.94	Mesitylene
8	9.26	9.12	9.39	789600572	3.09	Cyclodecane
9	9.48	9.39	9.81	685044832	2.68	Octane, 4-methyl-
14	12.48	12.39	12.78	640098532	2.51	Octane, 4-methyl-
18	14.48	14.4	14.68	196969702	0.77	Naphthalene,1,2,3,4-tetrahydro-
21	15.42	15.33	15.69	583402387	2.29	Hexadecane
24	18.01	17.86	18.13	887627191	3.48	1-Nonadecene
26	19.97	19.8	20.22	219974260	0.86	cis-2-Methyl-7-octadecene
28	20.69	20.55	20.8	936028644	3.67	1-Nonadecene
29	20.88	20.8	21.16	685306265	2.68	Hexadecane
30	23.21	22.78	23.32	1167699515	4.57	1-Nonadecene
31	23.39	23.32	23.67	708094285	2.77	Hexadecane
33	25.76	25.69	26.02	697557373	2.73	Hexadecane
36	30.34	29.86	30.43	1039289215	4.07	1-Octadecene
42	39.37	39.07	39.88	1363522417	5.34	Hexacontane
43	40.63	40.45	40.93	283335295	1.11	Octadecane, 3-methyl-

The GC-MS analysis of LDPE-derived fuel as illustrated in table 3 reveals a complex mixture predominantly composed of alkanes, alkenes, and a few aromatic and cyclic hydrocarbons—compounds typically found within the conventional diesel fuel range (C_{10}–C_{22}). Notably, high-abundance peaks such as hexacontane (5.34%), 1-nonadecene (peaks 24, 28, and 30; cumulative ~11.72%), and 1-octadecene (4.07%) indicate a strong presence of long-chain hydrocarbons, which are desirable for energy-rich fuels. The detection of hexadecane across multiple peaks further confirms the diesel-like hydrocarbon profile. Aromatic compounds, such as mesitylene and 1,2,3,4-tetrahydronaphthalene, are present in smaller amounts, indicating a moderate aromatic content. The presence of branched alkanes like 4-methyl-octane and 3-methyl-octadecane implies some degree of isomerisation during thermal cracking. Overall, the distribution of compounds demonstrates that the pyrolysis of LDPE yields a fuel composition closely resembling commercial diesel, making it a promising alternative for energy applications.

The peak areas are derived from the GC-MS Analysis response, which corresponds to the quantity of each compound eluting from the gas chromatograph. Larger peak areas indicate higher concentrations of specific compounds. The area percentages presented in this analysis are calculated as a ratio of the peak area of each compound to the total area of all detected peaks.

LDPE-Derived Fuel Composition Analysis

The Gas Chromatography–Mass Spectrometry analysis of Low-Density Polyethene-derived fuel reveals a composition dominated by diesel-range hydrocarbons, with notable concentrations of specific compounds. The most abundant component is hexacontane, accounting for 5.34% of the total composition with a peak area of 1,363,522,417, indicating a significant presence of long-chain alkanes that contribute to the high energy density. The second most prominent compound is 1-nonadecene at 4.57% (peak area: 1,167,699,515), followed by another 1-octadecene peak at 4.07% (peak area: 1,039,289,215), demonstrating substantial alkene content that enhances combustion characteristics. The fuel composition shows multiple occurrences of hexadecane at different retention times, with concentrations of 2.29%, 2.68%, 2.77%, and 2.73%, totalling approximately 10.47% of the overall composition. This distribution pattern suggests the presence of various hexadecane isomers or co-eluting compounds. Cyclodecane represents 3.09% of the composition, while 4-methyl-octane appears twice with concentrations of 2.68% and 2.51%, indicating the presence of branched alkane structures that improve ignition quality. Aromatic compounds constitute a relatively minor fraction, with mesitylene present at only 0.94% and naphthalene derivatives at 0.77%. This low aromatic content is beneficial for reducing soot formation and polycyclic aromatic hydrocarbon emissions whilst maintaining acceptable fuel lubricity properties.

Mixed Plastic Fuel Compositional Profile

The mixed plastic fuel demonstrates a more diverse hydrocarbon composition with higher concentrations of medium-chain compounds. The dominant component is 1-tetradecene, appearing at two different retention times with concentrations of 4.31% (peak area: 404,536,517) and 4.02% as 1-pentadecene (peak area: 376,954,350), totalling approximately 8.33% of the alkene content. The substantial presence of alkene indicates excellent atomisation and combustion propagation characteristics.

Cyclodecane represents the highest single-component concentration at 3.41% (peak area: 319,651,085), significantly higher than in the LDPE-derived fuel. The presence of various dodecane isomers, including 2,6,11-trimethyl-dodecane at multiple retention times (1.59%, 1.69%, and 0.40%), demonstrates extensive branching that enhances octane rating and combustion stability[43].

Light hydrocarbon fractions exhibit notable concentrations, with 1-undecene at 2.50% and 2,3-dimethyl-2-heptene at 2.28%, which contribute to improved cold-start performance and reduced ignition delay. The 2,6,10-trimethyltridecane content of 2.54% indicates a significant presence of branched alkanes that optimise combustion characteristics.

Aromatic compound diversity is considerably higher in mixed plastic fuel compared to LDPE-derived fuel. Naphthalene derivatives appear at various concentrations (0.54% for 1,3-dimethyl-naphthalene and 0.60% for 1,2-dihydro-3-methyl-naphthalene), whilst biphenyl represents 1.42% of the composition. The presence of diphenylmethane at 0.55% and various benzene derivatives indicates aromatic content derived from polystyrene components in the mixed plastic feedstock.

Comparative Analysis and Performance Implications

The LDPE-derived fuel exhibits higher concentrations of long-chain alkanes, particularly hexacontane and multiple hexadecane isomers, resulting in superior energy density characteristics. The total alkene content, dominated by 1-nonadecene and 1-octadecene, comprises approximately 12.31% of the composition, promoting efficient combustion and flame propagation.

In contrast, mixed plastic fuel exhibits a more balanced hydrocarbon distribution, with enhanced medium-chain alkene content (1-tetradecene and 1-pentadecene, totalling 8.33%), as well as higher aromatic diversity. The cyclodecane concentration of 3.41% in mixed plastic fuel compared to 3.09% in LDPE fuel indicates slightly improved combustion stability characteristics.

The aromatic content analysis reveals that LDPE-derived fuel contains minimal aromatics (approximately 1.71% total), whilst mixed plastic fuel exhibits higher aromatic diversity with approximately 3.5% total aromatic content. This difference has a significant impact on combustion emissions, with LDPE fuel potentially producing lower soot and polycyclic aromatic hydrocarbon emissions.

Fuel Quality Assessment

Both fuel types exhibit diesel-compatible hydrocarbon profiles, with carbon chain lengths predominantly in the C_{10}–C_{21} range.[44–46]. The LDPE-derived fuel exhibits superior energy density potential due to its higher content of long-chain alkanes. In contrast, the mixed plastic fuel offers better cold-flow properties due to its enhanced light hydrocarbon fractions. The retention time distribution spanning 4.26 to 40.63 minutes for mixed plastic fuel and 8.44 to 40.63 minutes for LDPE fuel indicates comprehensive diesel-range hydrocarbon coverage[47].

The quantitative analysis confirms that both plastic-derived fuels possess compositional characteristics suitable for diesel engine applications, with LDPE fuel offering superior energy content and mixed plastic fuel providing enhanced combustion versatility and cold-start performance.

VI. CONCLUSION

Plastic is an integral part of modern life. In 2019, global plastic production reached 370 million tons, with approximately 79% of it becoming waste[48]. Of this, 14 million tons end up in the oceans, resulting in the loss of over 100,000 marine animals. As communities plan for future waste disposal, many are facing challenges due to limited landfill space within or near their jurisdictions, along with a growing interest in minimising the amount of waste sent to landfills. Thermal conversion technologies, such as pyrolysis, significantly reduce the volume of material requiring final disposal. Communities with ambitious sustainability goals are striving for zero waste to landfill and are therefore exploring conversion technologies to recover materials that cannot be recycled.

This research focused on evaluating the effectiveness and practicality of pyrolysis for producing and characterising fuel derived from LDPE and mixed plastic waste. Pyrolysis offers the potential to convert mixed plastic waste into valuable fuel fractions, making it an appealing solution for municipalities seeking efficient and environmentally sustainable methods for managing such waste.

All pyrolysis conversions were conducted within a reaction temperature range of 400–500°C, with coal fly ash serving as a catalyst that successfully lowered the required reaction temperature. The highest fuel yield and calorific value were achieved in the optimal range of 400–450°C, corresponding to the maximum collection of liquid products per batch.

The fuel was characterised by analysing its physical and chemical properties using standard testing methods. When compared to the established parameters of conventional diesel, the fuel conformed to the standards, indicating its potential suitability for practical applications. Further characterisation involved comparing the fuel with diesel using GC-MS and FTIR analyses to evaluate its applicability as a diesel substitute. This comparison further supports the idea that the fuel performs comparably to standard diesel. Mixed plastic fuel exhibits a diverse hydrocarbon profile with significant medium-chain alkenes like 1-tetradecene (4.31%) and 1-pentadecene (4.02%), a high cyclodecane content (3.41%), and elevated aromatic diversity (~3.5%) enhancing combustion versatility and cold-start performance, while LDPE-derived fuel shows higher long-chain alkane content and total alkene concentration (~12.31%), offering superior energy density and lower soot emissions.

In summary, plastic-derived fuels produced via catalytic pyrolysis using coal fly ash as a catalyst exhibit property closely matching those of conventional diesel, including density, calorific value, and molecular composition. This approach offers a viable solution for managing plastic waste while generating alternative fuels and reducing environmental impact. Further work is recommended to optimise the process at scale and assess engine performance in long-term trials.

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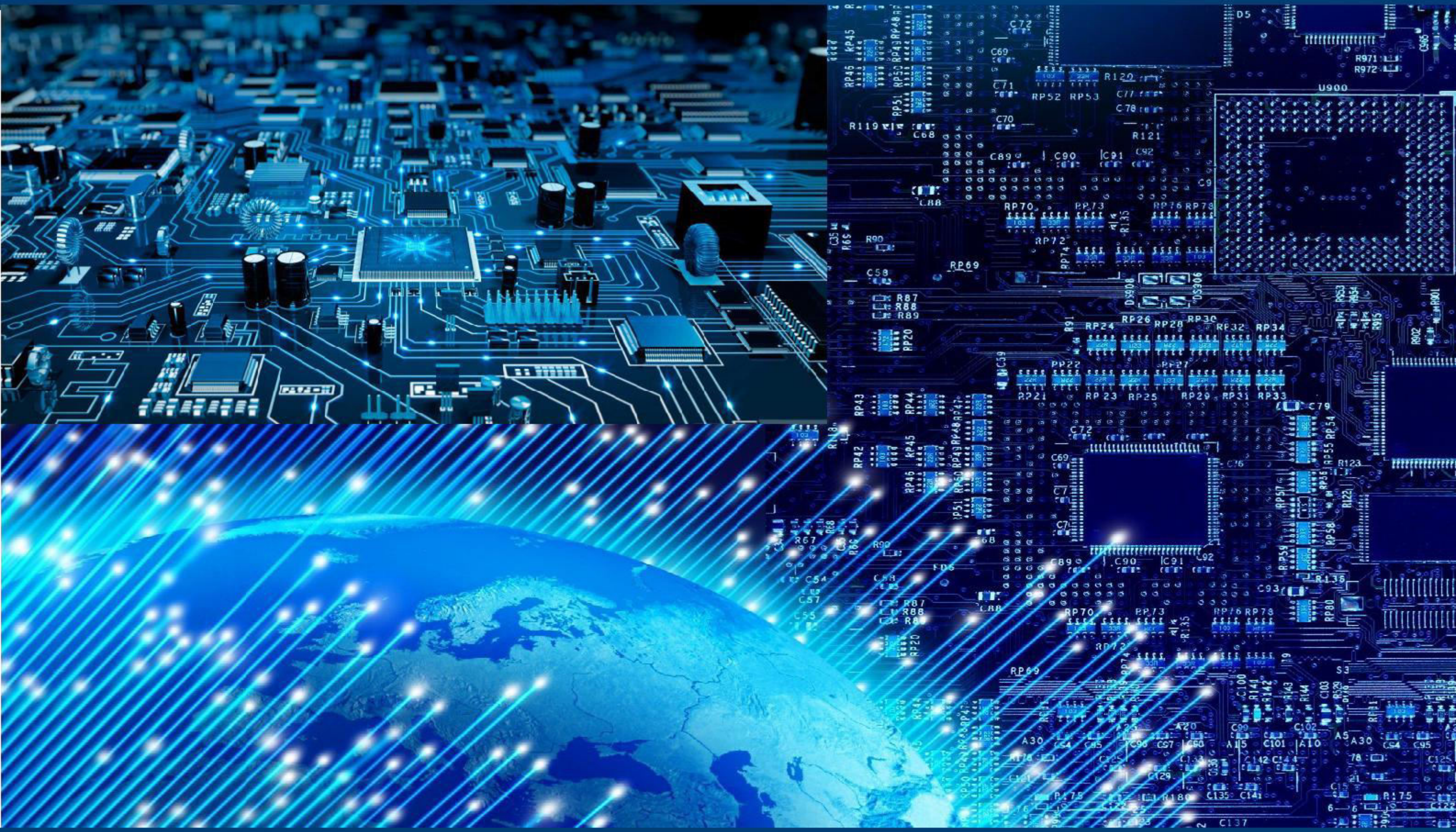

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