Characterization of Oils Obtained through Pyrolysis of Waste LDPE, HDPE and Mixed Plastic Streams.

A thesis
by

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DEPARTMENT OF MECHANICAL ENGINEERING
SONARGAON UNIVERSITY (SU)

SEPTEMBER 2025

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Submitted to the
DEPARTMENT OF MECHANICAL ENGINEERING
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of
BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

SEPTEMBER 2025

APPROVAL

This is to certify that the thesis " Characterization of Oils Obtained through Pyrolysis of Waste LDPE, HDPE and Mixed Plastic Streams.". By Papon Chandra Das (ID: ME2201026020), Md. Ahsan Habib (ID: ME2201026021), Md. Nahid Hasan (ID: ME2201026047), Md. Foisal Hossain (ID: ME2201026086), Md. Fazle Alahi Nurani (ID: ME2201026339) has been carried out under my supervison. The thesis has been carried out in partial fulfillment of the degree requirement of Bachelor of Science (B.Sc.) In Mechanical Engineering for 2025, its style and contents have been approved.

Signature of the Supervisor

Niloy Sarkar
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LETTER OF TRANSMITTAL

September 2025
To
Niloy Sarker
Assistant Professor
Department of Mechanical Engineering.
Sonargaon University.

Subject: Submission of Project Report.

Dear Sir,

We are pleased to submit the thesis report on " Characterization of Oils Obtained through Pyrolysis of Waste LDPE, HDPE and Mixed Plastic Streams.". It was a great pleasure to work on such an important topic. The thesis has been done per your supervision instructions and according to the requirements of Sonargaon University.

We expect that the concerned authority will accept the project and we will remain happy to experiment further with what you may feel is necessary.

Thank You

Sincerely Yours,

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DECLARATION

This dissertation has been submitted as a thesis entitled " Characterization of Oils Obtained through Pyrolysis of Waste LDPE, HDPE and Mixed Plastic Streams." to the Sonargaon University (SU) in partial fulfillment to the requirements for the degree of Bachelor of Science in Mechanical Engineering, Sonargaon University, Dhaka, Bangladesh. No part of the work referred to in the thesis has been submitted to support an application for another degree or qualification of this or any other university or institute of learning.

Authors

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Authors

ABSTRACT

Plastic use is growing rapidly around the world, but much of it ends up in the environment, causing serious problems especially plastics that don’t break down, like LDPE, HDPE, Polypropylene, and Polystyrene. One promising way to tackle this issue is pyrolysis, a process that heats plastic in the absence of oxygen to turn it into useful liquid oils. These oils could potentially be used as fuels or raw materials for chemicals. In this study, we looked at the oils produced from LDPE, HDPE, and a mix of LDPE, HDPE, PP and PS. We examined their appearance, smell, thickness, density and how they burn, among other properties. Our findings show that all these plastics can be turned into hydrocarbon-rich oils but the details vary depending on the type of plastic and the conditions of the process. This research shows that waste plastics don’t have to be useless trash they can become valuable fuels, helping recover energy and supporting a more circular, sustainable economy.

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Chapter 1
Introduction

1.1 Introduction

Plastics have become an indispensable part of modern life. Their lightweight, durability and versatility make them a key component in everyday items, ranging from packaging and construction materials to automotive parts and consumer products. However, this widespread use comes with a significant downside most plastics do not break down easily in nature. Global plastic production continues to rise, yet only a small fraction is effectively recycled, while the majority ends up in landfills, oceans or incineration facilities, creating serious environmental challenges.[2]

One promising solution to this problem is pyrolysis, a process that thermally breaks down plastics in the absence of oxygen, transforming them into valuable products such as liquid oils, gases, and solid char. Among these, the liquid product, known as pyrolytic oil, is particularly interesting because it can be refined into transportation fuels or used as raw materials for chemical production. The type of plastic and the conditions under which pyrolysis is carried out have a strong influence on the quality and composition of the resulting oil.[1]

Common plastics like low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS) make up a large portion of household and municipal waste. LDPE and HDPE are typically found in films, bottles, and containers, PP is used in packaging, textiles, and automotive components, and PS is commonly found in insulation, electronics, and food packaging. Understanding how each type of plastic affects the properties of pyrolytic oil is crucial for optimizing the process and exploring its potential as an alternative to fossil fuels.[3]

Although pyrolysis has gained attention as a waste-to-energy technology, understanding the qualitative composition of the oils produced is essential. Pyrolytic oils from LDPE, HDPE, PP, and PS contain a mix of hydrocarbons, aromatics, and other compounds that can affect fuel quality, stability, and environmental impact. Without detailed analysis, it is difficult to determine whether these oils can be safely and efficiently used as alternative fuels or industrial feed stocks.[3,4]

This study is important because it sheds light on the composition and potential uses of pyrolysis oils derived from common plastics. By examining these oils, it becomes possible to compare their characteristics, evaluate how closely they resemble conventional fuels such as gasoline, kerosene or diesel, identify possible challenges like impurities or unstable compounds and contribute to more sustainable approaches to plastic waste management and energy recovery.[2]

1.2 Objectives

The main objective of this study is to perform a qualitative analysis of oils derived from the pyrolysis of LDPE, HDPE & Mixed Plastics. Specific objectives include:

1. To produce liquid oil from the pyrolysis of LDPE, HDPE & Mixed Plastic under controlled conditions.
2. To conduct different kind of experimental analysis.
3. To characterize the chemical composition of the obtained oils using analytical techniques FTIR.
4. To compare and contrast the qualitative characteristics of the oils derived from the different plastics.
5. To evaluate the potential of these oils as alternative fuels or petrochemical feed stocks.

Chapter 2
Literature Review

2.1 Background

Thermal pyrolysis is a promising recycling method that converts waste plastics into valuable products such as liquid hydrocarbons (pyrolysis oil), gases, and char. The yield and composition of pyrolysis products depend on the type of polymer, processing conditions (temperature, heating rate, residence time), and the use of catalysts or co-feed stocks. Interest in pyrolysis is driven by its potential to recover high-calorific fuels, reclaim monomers (e.g., styrene from polystyrene), and convert polyolefin waste (LDPE, HDPE, PP) into useful chemicals or fuels.[3]

2.2 Polymer-specific trends

Polystyrene (PS): PS depolymerizes easily to aromatic monomers like styrene, α-methylstyrene, and toluene. Its pyrolysis oil is rich in aromatics, has a high calorific value, and produces relatively low char.

Polyolefins (LDPE, HDPE, PP): Polyethylene (LDPE, HDPE) yields long-chain aliphatic hydrocarbons and waxy fractions, while polypropylene (PP) produces more branched aliphatic compounds and mid-distillates (C5–C20).

Mixtures: In mixed-plastic pyrolysis PS increases the aromatic content whereas polyolefins contribute aliphatic hydrocarbons.[3]

2.3 Pyrolysis Mechanism

Polyolefins mainly degrade via random and chain-end scission, forming alkanes, alkenes and cyclic compounds. PS undergoes depolymerization through radical mechanisms, producing styrenic monomers and condensed aromatics. Processing conditions and catalysts influence the balance between primary monomer formation and secondary cracking or condensation.[4]

2.4 Common analytical techniques

-Fourier Transform Infrared Spectroscopy (FTIR): fast screening of functional groups (aromatic ring vibrations, C–H stretches, oxygenated functionalities) and useful for comparing broad chemical class differences between PP/PE (aliphatic) and PS (aromatic).[3]

- Physical property tests: Density, viscosity, calorific value, Flashpoint, pH .

2.5 Product Characteristics

PS oils: Rich in styrene and aromatics.[3]

PE oils: Long-chain aliphatic hydrocarbons with waxy fractions.[3]

PP oils: Branched aliphatic hydrocarbons yielding lighter distillates.[3]

.

Chapter 3
Methodology

3.1 Raw Materials

The raw materials used for this study are four common plastic types: Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE) & Mixed of LDPE, HDPE, Polypropylene (PP) and Polystyrene (PS). These plastics are widely used in daily life and contribute significantly to plastic waste. The samples were collected from municipal solid waste streams then Cleaned, dried and shredded before pyrolysis.

3.2 Low-Density Polyethylene (LDPE)

Source: Plastic bags, cling films, packaging wraps.

Properties: Flexible, transparent, lightweight, low tensile strength.

Reason for Selection: LDPE is among the most commonly discarded single-use plastics and has high potential for pyrolysis oil production.



Fig 3.1: Low-Density Polyethylene (LDPE)

3.3 High-Density Polyethylene (HDPE)

Source: Milk jugs, detergent bottles, water pipes, shampoo containers.

Properties: Rigid, opaque, high tensile strength, resistant to chemicals.

Reason for Selection: HDPE is a durable polymer that produces heavier oil fractions resembling kerosene and diesel.



Fig 3.2: High-Density Polyethylene (HDPE)

3.4 Polypropylene (PP)

Source: Food containers, bottle caps, straws, medicine bottles, packaging films.

Properties: Semi-crystalline, lightweight, resistant to heat, higher melting point compared to LDPE and HDPE.

Reason for Selection: PP is one of the fastest-growing plastic waste streams and produces pyrolysis oils with broad hydrocarbon ranges.



Fig 3.3: Polypropylene

3.5 Polystyrene (PS)

Source: Disposable cups, cutlery, CD cases, packaging foam (Styrofoam).

Properties: Lightweight, brittle, good thermal insulation, aromatic polymer.

Reason for Selection: PS is widely used in packaging and produces pyrolysis oils rich in aromatics (especially styrene monomers).



Fig 3.4: Polystyrene

3.6 Environmental Benefits

Pyrolysis of scrap plastic offers environmental benefits by diverting plastic waste from landfills and reducing the reliance on incineration, which can lead to harmful emissions. Discussing the ecological benefits of pyrolysis helps raise awareness of its role in mitigating plastic pollution and addressing climate change.

3.7 Size Reduction & Pre-Treatment

Collected plastics are reduced into flakes or granules (5–10 mm) using a granulator or cutting tools. Smaller, uniform size ensures efficient heat transfer during pyrolysis and improves reaction reproducibility.

Washing and cleaning for Remove dirt, food residues, oils and additives that can interfere with pyrolysis and analytical characterization. Initial cold-water rinse to remove dust and loose contaminants. Detergent wash at 40–50 °C for 5–10 minutes with stirring.

Rinse with distilled water until neutral pH is achieved. If adhesive residues remain, small-scale solvent cleaning (ethanol or isopropanol) is applied.

Washed plastics are dried in a convection oven at 60 ± 5 °C for 2–4 hours to remove residual moisture. Moisture can lead to unwanted steam formation, secondary cracking reactions, and reduced oil yield.

3.8 Pyrolysis Setup



Fig 3.5: Pyrolysis unit

The pyrolysis process involved chopped and dried plastic as the raw material introduced into the reactor. A total of 01 kg of plastic was loaded into the reactor.

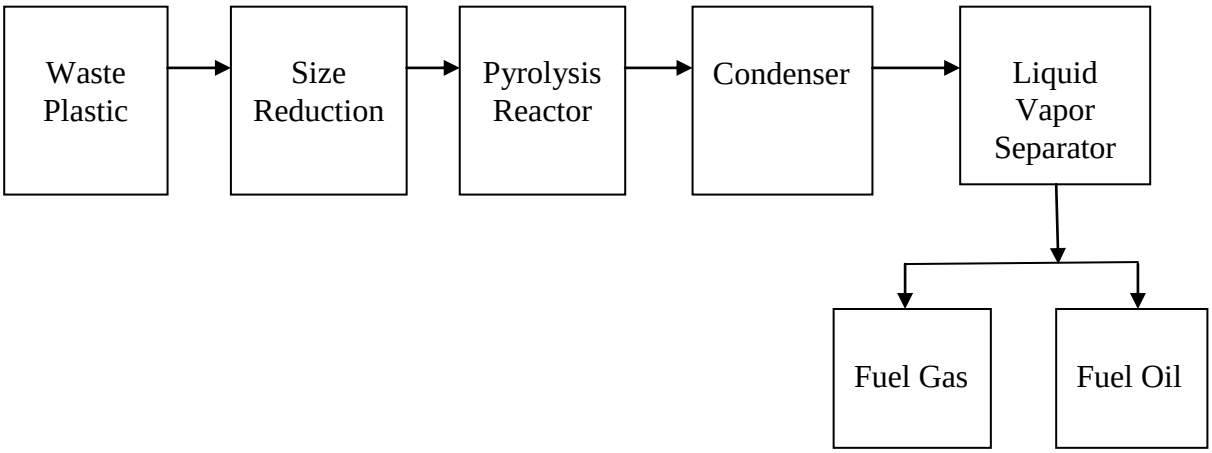


Fig: Flowchart Of pyrolysis process

The pyrolysis process lasted for 4 hours and was carried out at a temperature range of 250-350°C. The energy source used during pyrolysis was a stove that utilized LPG gas. The energy source turned off when the temperature during pyrolysis reached 350°C.

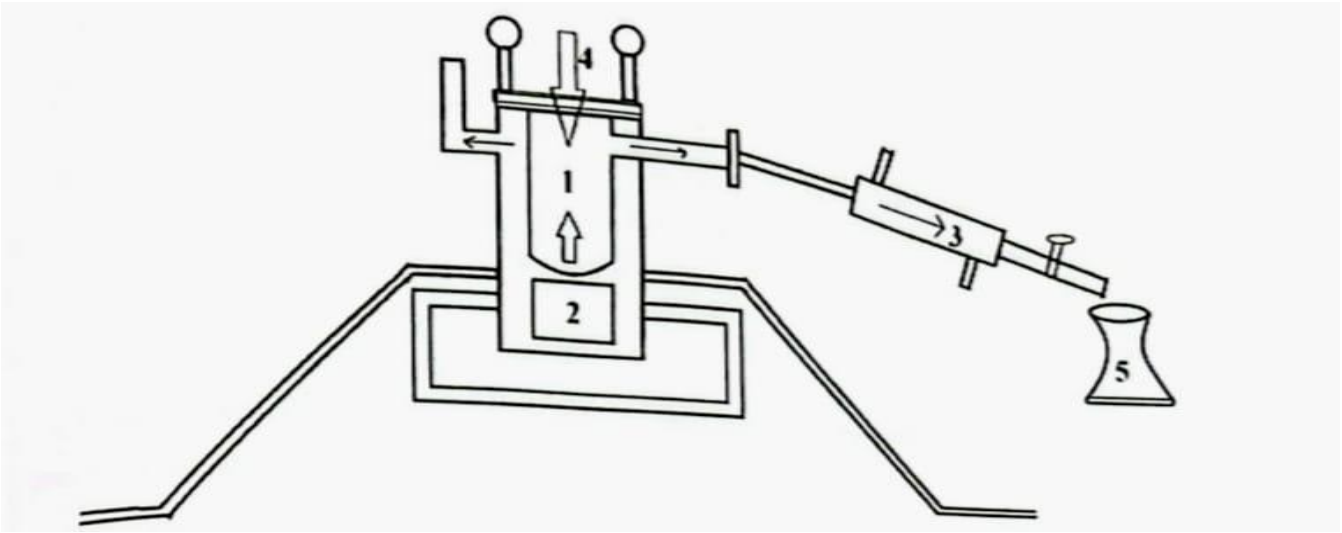


Fig 3.6: Line diagram of Pyrolysis Unit.

3.9 Pyrolysis Data

Different oil types are extracted from other plastic waste in the pyrolysis reaction. For our thesis, we used LDPE, HDPE & Mixed of LDPE,HDPE, Polypropylene & Polystyrene plastic for analysis. Finally we produced pyrolysis oil. Such oil acts as the petrol, diesel and kerosene. The same pyrolysis reaction produces 10% gas, which acts as LPG.

3.9.1 Low-Density Polyethylene

Total weight of LDPE: 01 kg
Total extract oil: 55 ml



Fig 3.7: Pyrolysis oil of LDPE

SL No	Time	Temperature (˚C)	Pressure (kgf/cm^2)	Remarks
1.	19:15	32	0	Start Time
2.	19:25	121	0.1	(Oil & Gas release both valve close)
3.	19:35	170	0.2	
4.	19:45	195	0.8	
5.	19:55	222	-	(Oil & Gas release both valve open)
6.	20:05	201	-	Oil Extraction start Time: 20:00
7.	20:15	195	-	Total Oil at this time- 05 ml
8.	20:25	178	-	Total Oil at this time- 08 ml
9.	20:35	185	-	Total Oil at this time- 10 ml
10.	20:45	192	-	Total Oil at this time- 15 ml
11.	20:55	200	-	Total Oil at this time- 25 ml
12.	21:05	198	-	Total Oil at this time- 40 ml
13.	21:15	175	-	Total Oil at this time- 45 ml
14.	21:25	165	-	Total Oil at this time- 55 ml End time

Table 3.1: Experimental Data of LDPE pyrolysis oil

Total Residue Weight: 0.408 kg

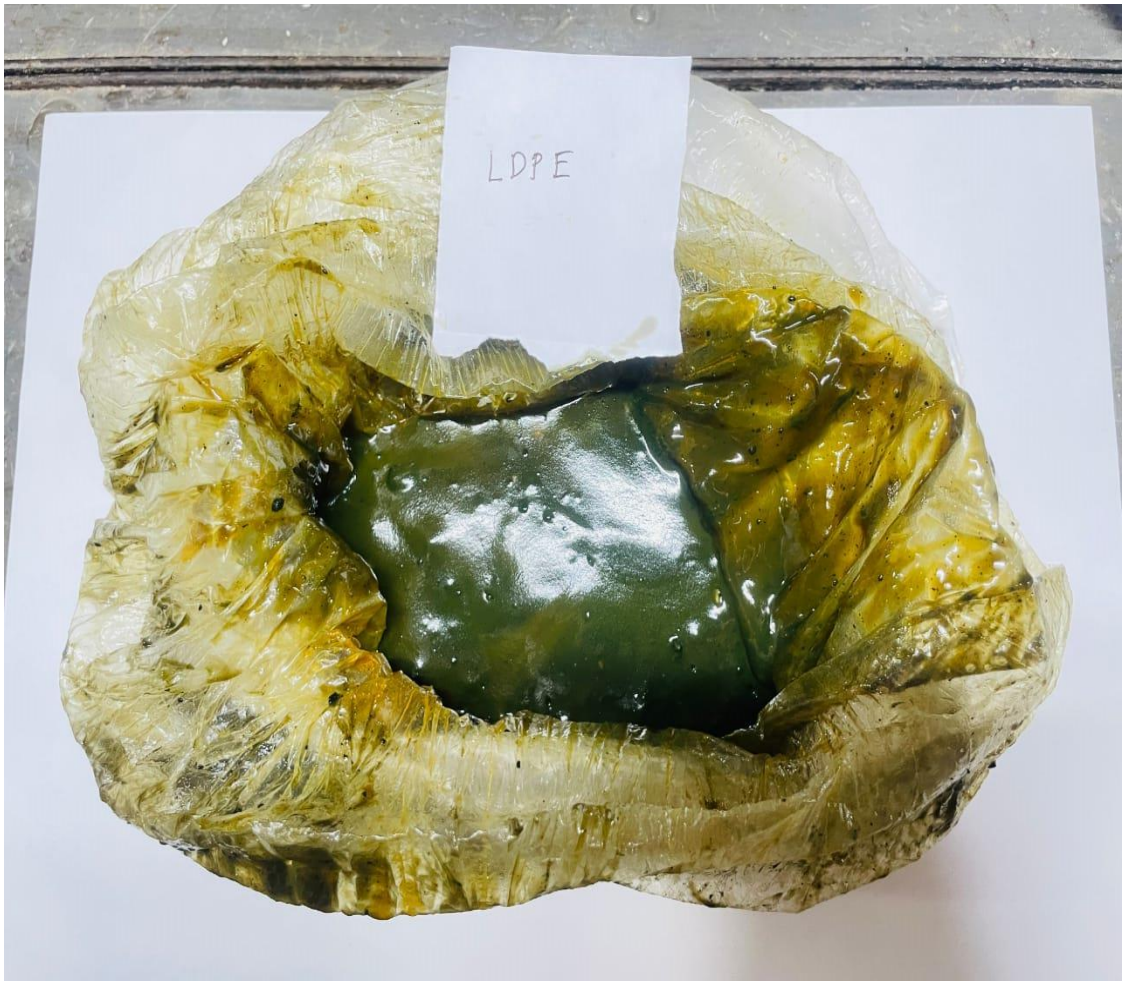


Fig 3.8: Residue of LDPE



Fig 3.9: Flame of emitted gas.



Fig 3.10: Flame of LDPE pyrolysis oil.

3.9.2 High-Density Polyethylene (HDPE)

Total weight of HDPE: 01 kg
Total extract oil: 365 ml



Fig 3.11: Pyrolysis oil of HDPE

SL No	Time	Temperature (˚C)	Pressure (kgf/cm^2)	Remarks
1.	15:20	31	0	Start Time
2.	15:30	108	0.1	(Oil & Gas release both valve close)
3.	15:40	154	0.3	
4.	15:50	191	0.6	
5.	16:00	215	-	(Oil & Gas release both valve open) Oil Extraction strat Time: 15:52 Total Oil at this time- 30 ml
6.	16:10	210	-	Total Oil at this time- 70 ml
7.	16:20	206	-	Total Oil at this time- 110 ml
8.	16:30	200	-	Total Oil at this time- 175 ml
9.	16:40	195	-	Total Oil at this time- 280 ml
10.	16:50	190	-	Total Oil at this time- 325 ml
11.	16:55	181	-	Total Oil at this time- 365 ml End time

Table 3.2: Experimental Data of HDPE pyrolysis oil

Total Residue Weight: 0.478 kg



Fig 3.12: Residue of HDPE



Fig 3.13: Flame of Emitted Gas



Fig 3.14: Flame of HDPE pyrolysis oil.

3.9.3 Mixed (Mixed of LDPE, HDPE, Polypropylene & Polystyrene):

Total weight of LDPE: 0.250 kg
Total weight of HDPE: 0.250 kg
Total weight of Polypropylene: 0.250 kg
Total weight of Polystyrene: 0.250 kg
Total extract oil: 450 ml



Fig 3.15: Pyrolysis oil of Mixed plastic

SL No	Time	Temperature (˚C)	Pressure (kgf/cm^2)	Remarks
1.	13:10	30	0	Start Time
2.	13:20	105	0.2	(Oil & Gas release both valve close)
3.	13:30	141	0.6	
4.	13:40	179	0.9	
5.	13:50	200	-	(Oil & Gas release both valve open) Oil Extraction strat Time: 13:50
6.	14:00	210	-	Total Oil at this time- 70 ml
7.	14:10	206	-	Total Oil at this time- 190 ml
8.	14:20	195	-	Total Oil at this time- 300 ml
9.	14:30	190	-	Total Oil at this time- 450 ml

Table 3.3: Experimental Data of Mixed pyrolysis oil

Total Residue Weight: 0.347 kg



Fig 3.16: Residue of mixed Plastic



Fig 3.17: Flame of emitted gas

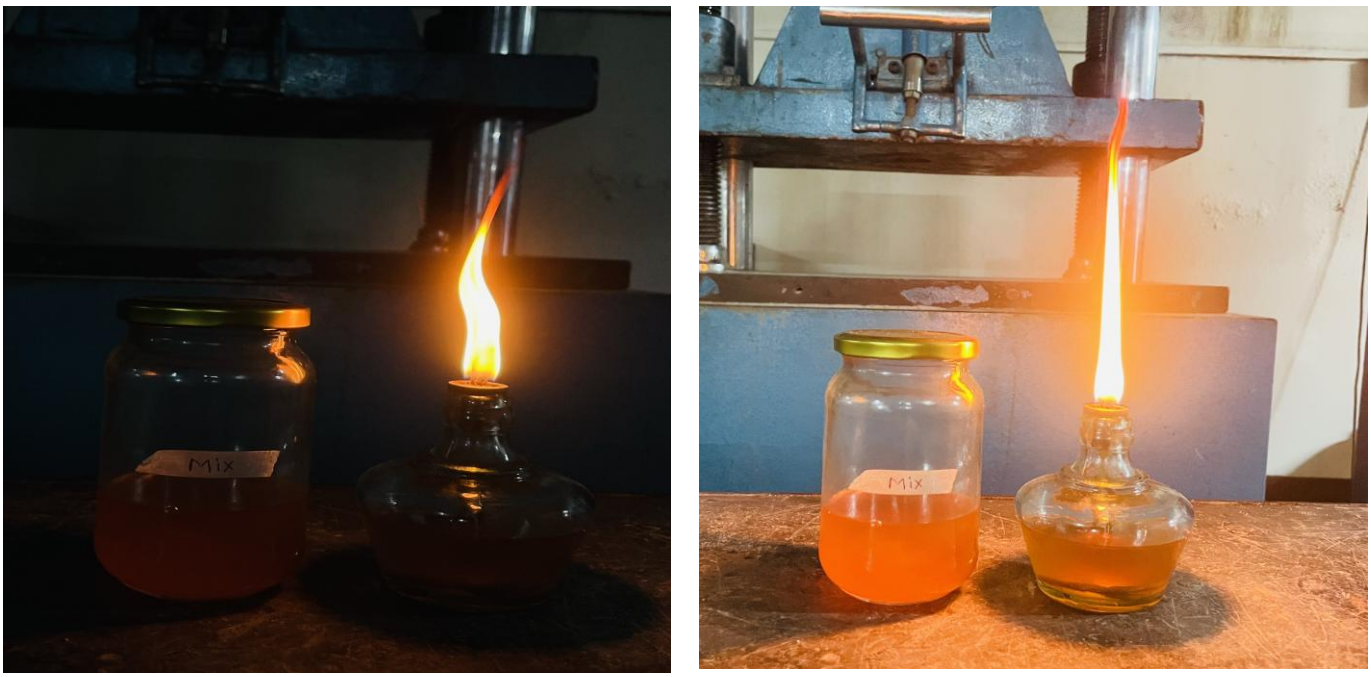


Fig 3.18: Flame of Mixed Plastic pyrolysis oil.

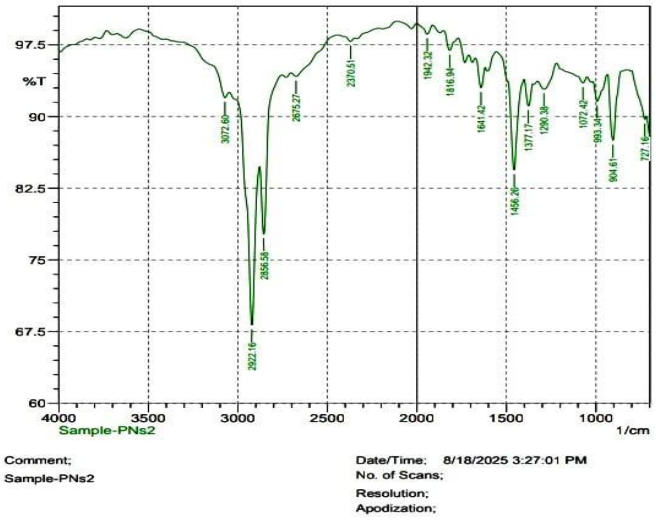
Chapter 4
Results and Discussion

4.1 FTIR Analysis:

Fourier Transform Infrared Spectroscopy (FTIR) is commonly used to characterize the chemical composition of pyrolysis oil derived from waste plastics. During pyrolysis, long-chain polymers break down into smaller hydrocarbon compounds, producing a mixture of alkanes, alkenes, aromatics and oxygenated species. FTIR helps identify the functional groups present in this oil by detecting their characteristic vibrational frequencies. Typical FTIR spectra of pyrolysis plastic oil show absorption bands corresponding to C–H stretching (alkanes/alkenes), C=C stretching (olefins, aromatics), and sometimes C=O or O–H groups if oxygenated compounds are present. This analysis is crucial for assessing the quality of the oil, its similarity to conventional fuels and its potential applications in energy or chemical industries.

4.1.2 FTIR Analysis of LDPE's oil

4.1.2.1CARS,DU Report:



SHIMADZU

CARS, DU

	Peak	Intensit	Corr. In	Base (H	Base (L	Area	Corr. Ar
1	727.16	89.694	0.673	800.46	721.38	2.856	0.114
2	904.61	87.503	7.039	933.55	831.32	3.626	1.186
3	993.34	91.589	2.282	1016.49	935.48	2.617	0.454
4	1072.42	93.517	0.679	1107.14	1051.2	1.534	0.084
5	1290.38	92.874	1.476	1325.1	1222.87	2.891	0.455
6	1377.17	91.109	2.556	1400.32	1354.03	1.626	0.31
7	1456.26	84.413	9.353	1490.97	1402.25	4.135	1.665
8	1641.42	93.012	2.545	1674.21	1618.28	1.393	0.31
9	1816.94	96.923	1.747	1851.66	1770.65	0.774	0.282
10	1942.32	98.63	1.021	2000.18	1913.39	0.3	0.181
11	2370.51	97.853	0.418	2405.23	2347.37	0.48	0.046
12	2675.27	94.198	0.813	2704.2	2441.88	4.297	0.383
13	2856.58	77.69	8.721	2877.79	2754.35	6.482	1.173
14	2922.16	68.184	18.54	3047.53	2879.72	13.117	4.457
15	3072.6	91.975	1.045	3302.13	3049.46	5.111	0.136

Fig 4.1: FTIR Analysis report by CARS,DU

4.1.2.2 FTIR Peak Assignments

3072.6 cm^{-1} (weak) — =C–H stretch (aromatic or vinyl C–H). Indicates presence of unsaturated (vinyl/olefinic) or aromatic hydrogens.

2922.16 cm^{-1} (strong) — aliphatic C–H (asymmetric stretch, CH_2/CH_3). Typical for long-chain saturated hydrocarbons.

2856.58 cm^{-1} (strong) — aliphatic C–H (symmetric stretch, CH_2/CH_3). Confirms high aliphatic content (paraffinic).

2675.27 cm^{-1} / 2370.51 cm^{-1} — likely atmospheric CO_2 (2370 cm^{-1}) and possible weak overtone/combination bands or instrument artifacts (2675 cm^{-1}). Treat with caution — probably not chemically significant in the liquid oil.

1942–1816 cm^{-1} region (peaks at 1942 and 1817 cm^{-1}) — unusual for simple hydrocarbons; may be combination/overtone bands, or (less likely) strained carbonyls/anhydrides. These peaks are weak — recommend corroboration with GC–MS or more sensitive carbonyl detection.

1641.42 cm^{-1} (moderate) — C=C stretching (alkene) or possibly conjugated C=O (but conjugated carbonyl typically nearer 1680–1700 cm^{-1}). Given the other evidence, this most likely indicates alkene (olefinic) content from pyrolysis.

1456.26 & 1377.17 cm^{-1} (strong/mid) — CH_2/CH_3 bending (methylene scissoring / methyl deformation). Typical of paraffinic chains (LDPE-derived).

1290.38 cm^{-1} (weak–moderate) — can be C–H bending or various C–O/C–C skeletal vibrations; possible oxygenated fragments (ethers/alcohols) if accompanied by clear C–O stretch.

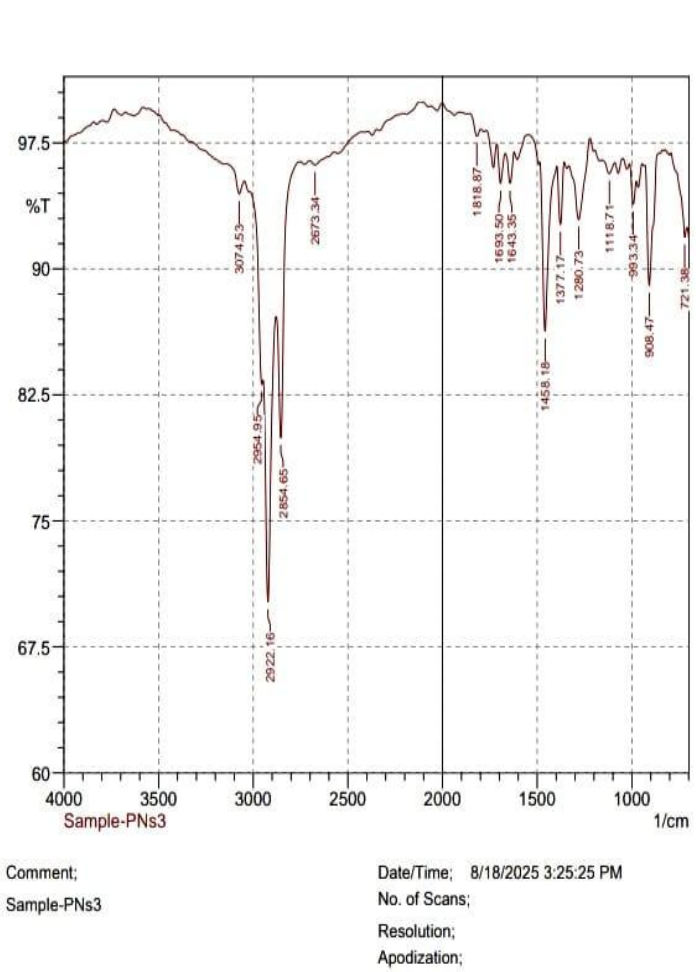
1072.42 cm^{-1} (weak) — typical region for C–O stretching (alcohols, ethers) — suggests some oxygenated species in the oil (from oxidation or minor contaminants).

993.34 & 904.61 cm^{-1} / 727.16 cm^{-1} (weak–moderate) — out-of-plane C–H bending of =C–H (vinyl/mono-substituted alkenes) and aromatic ring C–H bending (727 cm^{-1} can indicate mono-or para-substituted aromatics or long-chain methylene rocking). Presence of these peaks supports some aromatic/olefinic components**.**

The strong CH stretches (2856/2922 cm^{-1}) and CH bending indicate fuels-like hydrocarbons — consistent with diesel/light fuel fractions.
However, olefinic and aromatic fractions (1641, 3073, 993, 727 cm^{-1}) increase sooting tendency, instability (polymerization/gelation on storage) and may affect combustion emissions.
Small C–O features (1072 cm^{-1}) point to oxygenates — these can increase acidity, corrosiveness, and water affinity.
Unsaturations (C=C) lead to oxidative instability (autoxidation, polymerization). Expect the oil to darken and form gums over time. Recommend antioxidant testing/stabilization if using as fuel/lubricant feed.
Aromatics/olefins can swell or soften some elastomers (nitrile rubber, some polyurethanes) — test seals and hoses if the oil will contact them.
Oxygenates and low level acids (if present) can accelerate corrosion in non-inert materials — run metal coupon corrosion tests (steel, copper, aluminum) if application involves metallic components.

4.1.3 FTIR Analysis of HDPE's oil

4.1.3.1 CARS,DU Report:



	Peak	Intensit	Corr. In	Base (H	Base (L	Area	Corr. Ar
1	721.38	91.883	1.289	792.74	707.88	2.079	0.079
2	908.47	89.006	7.368	929.69	856.39	2.223	1.103
3	993.34	93.847	1.858	1012.63	975.98	0.847	0.153
4	1118.71	95.669	0.713	1159.22	1091.71	1.174	0.099
5	1280.73	92.926	3.974	1332.81	1222.87	2.438	0.961
6	1377.17	92.639	3.588	1396.46	1357.89	0.975	0.331
7	1458.18	86.276	9.973	1485.19	1398.39	3.047	1.582
8	1643.35	95.089	1.824	1668.43	1622.13	0.816	0.185
9	1693.5	95.087	2.095	1712.79	1668.43	0.758	0.2
10	1818.87	97.889	0.756	1857.45	1797.66	0.397	0.078
11	2673.34	96.178	0.297	2700.34	2628.98	1.155	0.048
12	2854.65	79.954	8.877	2877.79	2750.49	4.981	0.996
13	2922.16	70.17	14.605	2947.23	2879.72	6.933	2.27
14	2954.95	83.121	1.208	3016.67	2949.16	3.069	0.077
15	3074.53	94.459	1.055	3142.04	3047.53	1.906	0.128

Fig 4.2: FTIR Analysis report by CARS,DU

4.1.3.2 FTIR Peak Assignments

3074.53 cm^{-1} (weak) — =C–H stretch (aromatic or vinyl C–H). Suggests some unsaturation or minor aromatic content.

2954.95 cm^{-1} (weak–moderate) — C–H stretch (asymmetric CH_3/CH_2) — typical aliphatic methyl/terminal CH_3.

2922.16 cm^{-1} (strong) — aliphatic C–H asymmetric stretch (CH_2 abundant in long chains). Classic sign of long paraffinic chains.

2854.65 cm^{-1} (strong) — aliphatic C–H symmetric stretch (CH_2/CH_3) — confirms paraffinic backbone.

2673.34 cm⁻¹ — likely an overtone/combination or contaminant/CO_2 artifact; treat cautiously.

1818.87 cm⁻¹ (weak) — unusual for simple hydrocarbons; may indicate strained carbonyls, anhydrides, or combination/overtone bands. Needs corroboration.

1693.50 cm⁻¹ (weak–moderate) — C=O stretch (conjugated carbonyl) or C=C (conjugated); possibility of ketones/aldehydes or conjugated unsaturations produced during pyrolysis/oxidation. Verify with GC–MS / NMR.

1643.35 cm⁻¹ (weak–moderate) — C=C stretching (olefins/alkenes). Expected in pyrolysis oils from β-scission.

1458.18 cm⁻¹ (strong) — CH_2 scissoring / CH_3 deformation — typical paraffinic signature.

1377.17 cm⁻¹ (moderate) — CH_3 deformation — methyl groups; branching or chain ends.

1280.73 cm⁻¹ (weak–moderate) — C–H bends or possibly C–O (ethers/alcohols) — small oxygenated fraction possible.

1118.71 cm⁻¹ (weak) — C–O stretching (ethers/alcohols) or C–C skeletal modes; again suggests tiny oxygenated content/contaminants.

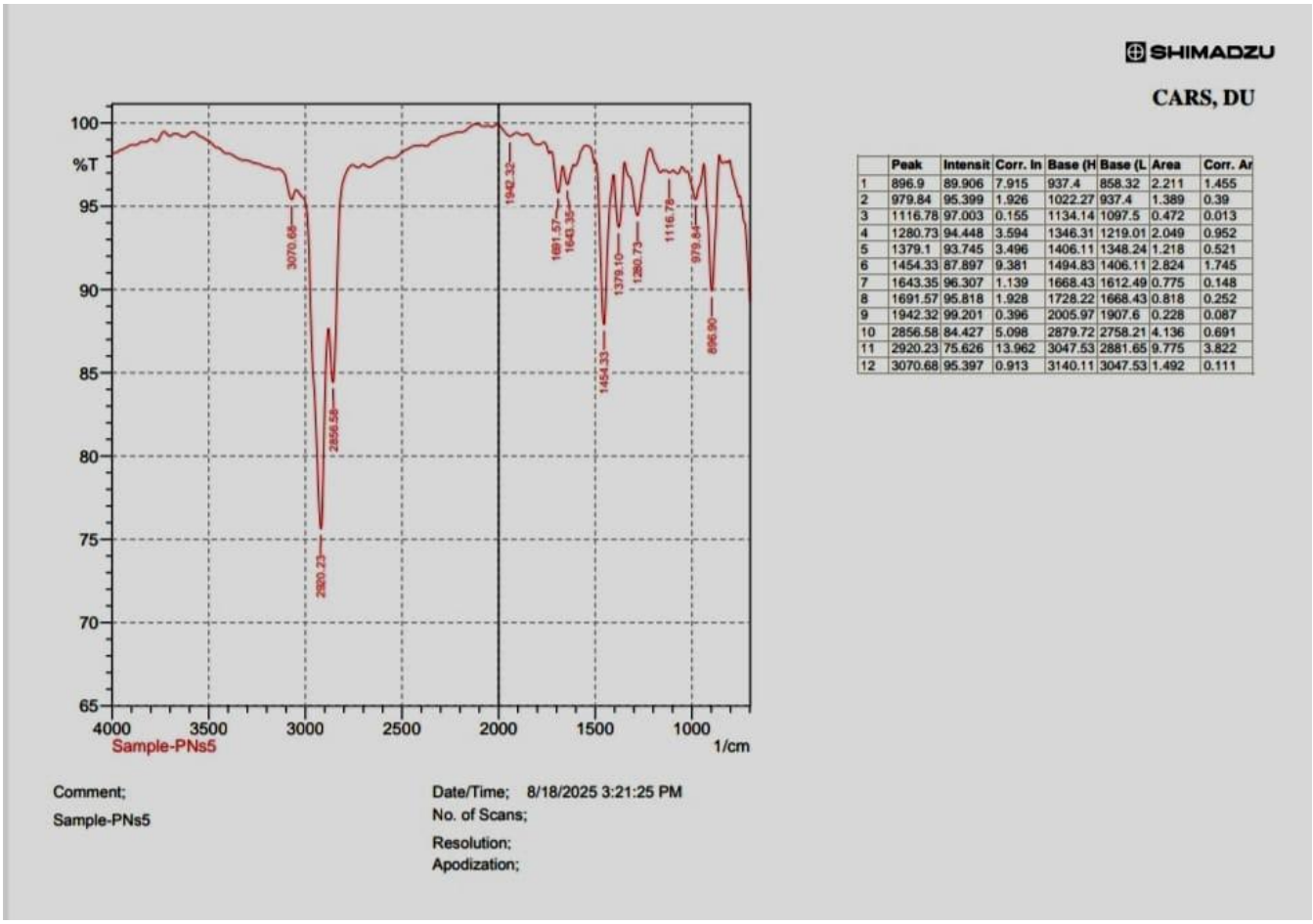
993.34 cm⁻¹ & 908.47 cm⁻¹ (weak) — out-of-plane =C–H bending for mono- or di-substituted alkenes (vinyl groups). Confirms olefin presence.

721.38 cm⁻¹ (strong) — strong methylene rocking (long -CH_2- sequences) typical of linear long-chain alkanes (wax/paraffin); can also indicate CH_2 rocking in long-chain paraffins.

Paraffinic content resembles diesel/naphtha fractions (so fractionation can yield useful fuel cuts).Olefins and aromatics increase soot and emission propensity; oxygenates and carbonyls alter combustion characteristics. If planning engine trials, perform full fuel spec testing first (flash point, cetane number surrogate tests, distillation curve, sulfur).
Olefins = propensity for oxidation and polymerization → gum formation, filter clogging. HDPE-derived oils with waxy components may crystallize/solidify at modestly low temperatures. Anti-oxidants or hydrotreating (hydrogenation) will improve stability.
Waxes/long chains: higher pour point and viscosity — pumping and atomization in mechanical systems can be problematic at low temperatures.olefins and aromatics may swell/damage certain rubbers (nitrile, some polyurethanes). Small oxygenates may increase corrosion rates in some metals. Recommend compatibility tests.

4.1.4 FTIR Analysis of Mixed Plastic's oil

4.1.4.1 CARS,DU Report:



	Peak	Intensit	Corr. In	Base (H	Base (L	Area	Corr. Ar
1	896.9	89.906	7.915	937.4	858.32	2.211	1.455
2	979.84	95.399	1.926	1022.27	937.4	1.389	0.39
3	1116.78	97.003	0.155	1134.14	1097.5	0.472	0.013
4	1280.73	94.448	3.594	1346.31	1219.01	2.049	0.952
5	1379.1	93.745	3.496	1406.11	1348.24	1.218	0.521
6	1454.33	87.897	9.381	1494.83	1406.11	2.824	1.745
7	1643.35	96.307	1.139	1668.43	1612.49	0.775	0.148
8	1691.57	95.818	1.928	1728.22	1668.43	0.818	0.252
9	1942.32	99.201	0.396	2005.97	1907.6	0.228	0.087
10	2856.58	84.427	5.098	2879.72	2758.21	4.136	0.691
11	2920.23	75.626	13.962	3047.53	2881.65	9.775	3.822
12	3070.68	95.397	0.913	3140.11	3047.53	1.492	0.111

Fig 4.3: FTIR Analysis report by CARS,DU

4.1.4.2 FTIR Peak Assignments

3070.7 cm^{-1} (Medium) —=C–H stretch (aromatic or olefinic C–H) Medium — indicates presence of aromatics or terminal unsaturation.

2920.2 cm^{-1} (High) —aliphatic C–H asymmetric stretch (–CH_2–, –CH_3) — together with 2856 cm^{-1} confirms substantial aliphatic content.

2856.6 cm^{-1}(High) — aliphatic C–H symmetric stretch (–CH_2–, –CH_3) — typical for saturated hydrocarbons.

1643.4 **cm^{-1}(** Medium) — C=C stretching (alkenes) and/or conjugated C=O weak contribution — commonly alkene C=C; if strong, may indicate olefins/unsaturated fractions.

1691.6 **cm^{-1}(** High) —Carbonyl C=O stretching (ketone, aldehyde, conjugated ester) — near 1700 cm^{-1} is typical of ketones/aldehydes/carboxylic derivatives; confirms oxygenates.

1454.3 **cm^{-1}(** High) — CH_2/CH_3 bending (scissoring) — typical for aliphatic chains.

1379.1 **cm⁻¹(** High) — CH_3 bending (umbrella) — supports methyl-rich aliphatic content.

1280.7 **cm⁻¹ (cm⁻¹)** C–O stretching (ethers/esters), or CH deformations — supports oxygenated compounds (ethers/esters).

1116.8 **cm⁻¹(** Medium) — C–O stretch (alcohols/ethers/esters) or aromatic C–H in-plane — often seen when oxygenates (ethers/esters) are present.

979.8 **cm⁻¹(** Low Medium) — =C–H out-of-plane bending (vinyl/terminal $=CH_2$) or monosubstituted alkene — typical for vinyl/terminal unsaturation.

896.9 **cm⁻¹(** Low Medium) — =C–H out-of-plane (disubstituted vinyl or aromatic C–H wag) — supports unsaturation/aromatic substitution patterns.

1942.3 **cm⁻¹** (Low — unusual) —Weak overtone/combination band or CO_2 artifact / very conjugated species; often an overtone or instrumental artifact. Check background/cell.

Major fraction: aliphatic hydrocarbons (paraffinic) — good fuel-like characteristics (heating value) but variable viscosity.
Unsaturated content: indicated by C=C and =C–H features — increases reactivity (polymerization, gum formation) and may affect thermal stability.
Oxygenates present: carbonyl (1691 cm^{-1}) and C–O bands (1116, 1280 cm^{-1}) indicate ketones/aldehydes/esters/ethers — these lower heating value, increase polarity, may increase acidity and water affinity.Combustion & engine use: oxygenates and unsaturates can alter combustion timing, reduce calorific value, increase soot or deposits; blending and upgrading likely needed before direct use as fuel.unsaturated and oxygenated compounds accelerate aging (polymerization, insoluble gums), promoting filter/clogging issues.oxygenated species (especially acids/aldehydes) can be corrosive to some metals and elastomers — verify TAN (acid number) and perform corrosion tests.
Lubricity & seals: low-molecular oxygenates and aromatics can swell or harden elastomers differently than hydrocarbons — test common seal materials (NBR, Viton).

4.1.5 Comparison

LDPE
• Strong bands at 2922 cm^{-1} (CH stretching) and 1456 cm^{-1} (CH bending) → higher aliphatic hydrocarbon content.
• Moderate peak at 1641 cm^{-1} (C=C stretch) → unsaturation present.
• Broader O–H/C–O regions (~1290–1377 cm^{-1}).
➡Indicates balanced mixture of aliphatic hydrocarbons with oxygenated compounds.

HDPE
• Stronger peak at 2922 cm^{-1} (14.6 absorbance) compared to PNs2 → more aliphatic CH groups.
• Additional C=C stretching at 1693 cm^{-1} not as strong in PNs2 → slightly more unsaturated/aromatic hydrocarbons.
• Lower intensity oxygenated peaks compared to PNs2.
➡ Indicates more hydrocarbons, less oxygenated content, meaning potentially better fuel quality.

Mixed Plastic

• Very strong CH stretch at 2920 cm^{-1} (13.9 absorbance, highest among all) → highest aliphatic content.

• Strong aromatic/alkene signals: 1454 cm^{-1}, 1643 cm^{-1}, 1691 cm^{-1}.

• Oxygenated functional peaks (1280–1380 cm^{-1}) still visible but weaker.

➡Indicates more refined hydrocarbon profile, closest to conventional fuel properties.

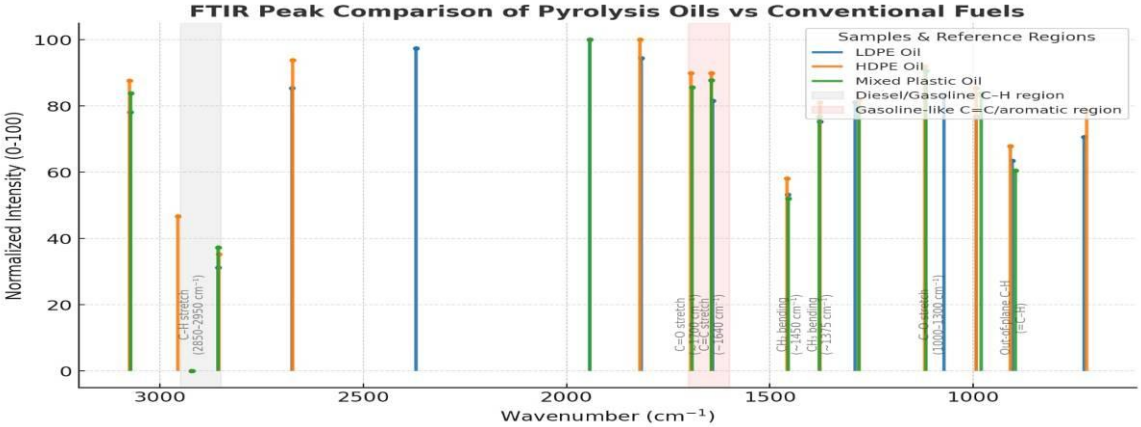


Fig 4.4: FTIR Peak comparison of pyrolysis oil with conventional fuels

FTIR analysis of pyrolysis oils (PNs2, PNs3, PNs5) confirmed the presence of major hydrocarbon groups (alkanes, alkenes, aromatics) with varying levels of oxygenated species. PNs2 exhibited stronger oxygenated functional groups, while PNs3 and PNs5 showed progressively reduced oxygenates and stronger C–H stretching peaks. Among them, PNs5 demonstrated the most fuel-like characteristics, with dominant aliphatic and aromatic hydrocarbons and minimal oxygenates. This trend suggests higher energy density and stability, making PNs5 the most suitable candidate for upgrading into biofuel.

Comparative Summary

Peak Region (cm^{-1})	Assignment	LDPE	HDPE	Mixed Plastic
720–730	=C–H bending (alkenes/aromatics)	Strong	Strong	Strong
900–1100	C–O/C–C stretching	Clear	Moderate	Weaker
1280–1380	C–O stretch (oxygenates)	Strong	Moderate	Weak
1450–1470	CH_2/CH_3 bending	Strong	Strong	Strongest
1640–1690	C=C stretching	Moderate	Stronger	Strongest
2850–2950	C–H stretching	Strong	Very Strong	Highest

Table 4.1: Comparative Summary of FTIR of pyrolysis oils.

4.2 Flash Point

The flash point is the lowest temperature at which a fuel releases enough vapors to ignite momentarily in the presence of an ignition source.

- It indicates the flammability of the fuel.
- Lower flash point = higher fire hazard during handling and storage.
- Higher flash point = safer to store and transport.

4.2.1 Experimental Data

LDPE oil:

Oil=3ml

$T_{primary}$= 29.5 ˚C

Sl No	T_{flash} (˚C)	Flash Time
1	58.5	0 minute 55 second.
2	56.4	0 minute 54 second.
3	57.2	0 minute 56 second.

Table 4.2: Experimental data of Flash point of LDPE pyrolysis oil.

T_{flash}= 57.4 ˚C

Flash Time= 0 minute 55 second.

HDPE oil:

Oil=3ml

$T_{primary}$= 28.8 ˚C

Sl No	T_{flash} (˚C)	Flash Time
1	38.2	0 minute 33 second.
2	37.9	0 minute 32 second.
3	38.0	0 minute 30 second.

Table 4.3: Experimental data of Flash point of HDPE pyrolysis oil

T_{flash}= 38.0 ˚C

Flash Time= 0 minute 32 second.

Mixed Plastic oil:

Oil=3ml

$T_{primary}$= 29.7 ˚C

Sl No	T_{flash} (˚C)	Flash Time
1	52.1	0 minute 52 second.
2	53.2	0 minute 51 second.
3	52.4	0 minute 50 second.

Table 4.4: Experimental data of Flash point of Mixed pyrolysis oil

T_{flash}= 52.6 ˚C

Flash Time= 0 minute 51 second.

4.2.2 Comparative Discussion

LDPE Oil (57.4 °C)

- Higher flash point than HDPE and mixed oil.
- Safer for handling and storage.
- Indicates presence of heavier hydrocarbons that require more heat to vaporize.

HDPE Oil (38.0 °C)

- Lowest flash point among the three.
- Highly flammable and poses greater storage risk.
- Indicates a higher fraction of light hydrocarbons, which vaporize easily.

Mixed Oil (52.6 °C)

- Close to LDPE oil, and significantly safer than HDPE oil.
- Balanced composition between lighter and heavier hydrocarbons.
- Good compromise between safety and usability.

4.2.3 Comparison with Conventional Fuels

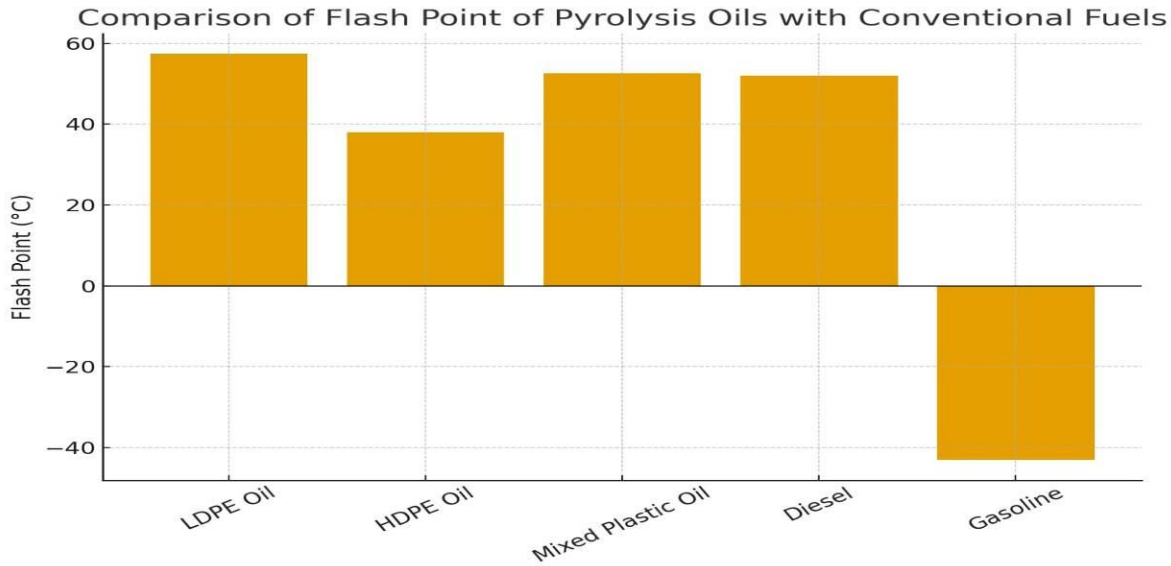


Fig 4.5: Comparison of Flash Point of Pyrolysis oil with conventional fuels

Diesel: ~52 °C

Gasoline (Petrol): ~−43 °C

- Mixed plastic oil and LDPE oil have flash points similar to diesel, which makes them safer compared to gasoline.
- HDPE oil's flash point is much lower, indicating higher risk.

4.2.4 Implications

- LDPE and Mixed oils are better suited for storage and transport due to higher flash points.
- HDPE oil requires additional refining or blending to improve safety.
- Compared to gasoline, pyrolysis oils are much safer, but they are still less stable than diesel in terms of consistency.

4.3 Viscosity

Viscosity is the measure of a liquid's resistance to flow.

- Low viscosity = thinner liquid (flows easily, better atomization in combustion).
- High viscosity = thicker liquid (harder to pump, poor fuel atomization).

For fuels, viscosity influences:

- Spray characteristics in engines.
- Combustion efficiency.
- Wear and tear in pumps and injectors.

4.3.1 Experimental Data

LDPE Oil:

Total Oil= 5ml
Total Water = 5ml
We know,

$$\eta_{oil} = \eta_{water} \times (t_{oil}/t_{water})$$

Where,

η_{oil}= Viscosity of oil.
η_{water}= Viscosity of water.
t_{oil} = Time taken by oil.
t_{water} = Time taken by water.

SL No	η_{water} (mPa.s)	t_{oil} (s)	t_{water} (s)	η_{oil} (mPa.s)
1	0.8509	748	462	1.38
2	0.8509	750	470	1.36
3	0.8509	740	466	1.35

Table 4.5: Experimental data of Viscosity of LDPE pyrolysis oil

Final Result: (1.38+1.36+1.35)/3 =1.36 mPa.s

HDPE Oil:

Total Oil= 5ml
Total Water = 5ml
We know,

$$\eta_{oil} = \eta_{water} \times (t_{oil}/t_{water})$$

Where,

η_{oil}= Viscosity of oil.
η_{water}= Viscosity of water.
t_{oil} = Time taken by oil.
t_{water} = Time taken by water.

SL No	η_{water} (mPa.s)	t_{oil} (s)	t_{water} (s)	η_{oil} (mPa.s)
1	0.8509	664	462	1.22
2	0.8509	672	470	1.21
3	0.8509	654	466	1.19

Table 4.6: Experimental data of Viscosity of HDPE pyrolysis oil.

Final Result: (1.22+1.21+1.19)/3 =1.21 mPa.s

Mixed plastic Oil:

Total Oil= 5ml

Total Water = 5ml

We know,

$$\eta_{oil} = \eta_{water} \times (t_{oil}/t_{water})$$

Where,

η_{oil}= Viscosity of oil.

η_{water}= Viscosity of water.

t_{oil} = Time taken by oil.

t_{water} = Time taken by water.

SL No	η_{water} (mPa.s)	t_{oil} (s)	t_{water} (s)	η_{oil} (mPa.s)
1	0.8509	592	462	1.09
2	0.8509	590	470	1.07
3	0.8509	594	466	1.08

Table 4.7: Experimental data of Viscosity of Mixed pyrolysis oil

Final Result: (1.09+1.07+1.08)/3 =1.08 mPa.s

4.3.2 Comparative Discussion

LDPE Oil (1.36 mPa·s)

- Highest viscosity among the three.
- Thicker, slightly harder to atomize in engines.
- May cause incomplete combustion if not blended.

HDPE Oil (1.21 mPa·s)

- Lower viscosity than LDPE oil.
- Flows more easily and is closer to desirable range for diesel substitution.

Mixed Oil (1.08 mPa·s)

- Lowest viscosity, very close to water-like behavior.
- Best atomization during fuel injection → cleaner and more efficient combustion.

4.3.3 Comparison with Conventional Fuels

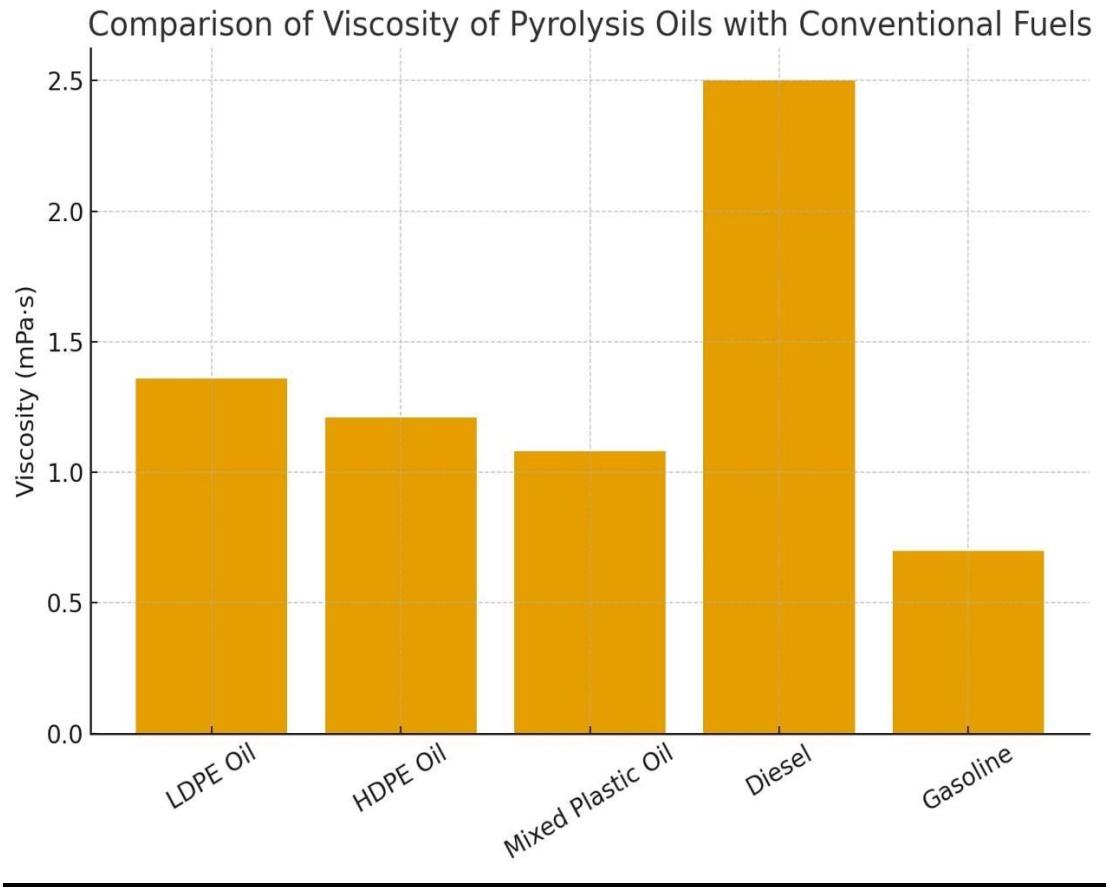


Fig 4.6: Comparison of Viscosity of Pyrolysis oil with conventional fuels
Diesel fuel: ~2–4 mPa·s
Gasoline: ~0.4–0.8 mPa·s

- Pyrolysis oils (1.08–1.36 mPa·s) are lower than diesel but higher than gasoline.
- This means they are more volatile than diesel but less than gasoline, which can be advantageous for blending.

4.3.4 Implications

- Mixed oil (1.08 mPa·s) is the most engine-friendly due to lower viscosity.
- LDPE oil might require blending with lower-viscosity oils or diesel to improve flow.
- All three are within a usable range but may need viscosity adjustment for optimal engine performance

4.4 pH

pH is a measure of the acidity or alkalinity of a liquid:

- pH < 7 → acidic
- pH = 7 → neutral
- pH > 7 → alkaline

For fuels, pH is important because:

- Highly acidic fuels can cause corrosion of storage tanks, pipelines, and engine parts.

- A near-neutral pH (close to 7) indicates better chemical stability and lower risk of corrosion.

4.4.1 Experimental Data

- LDPE oil: pH = 6
- HDPE oil: pH = 5
- Mixed Plastic oil: pH = 6

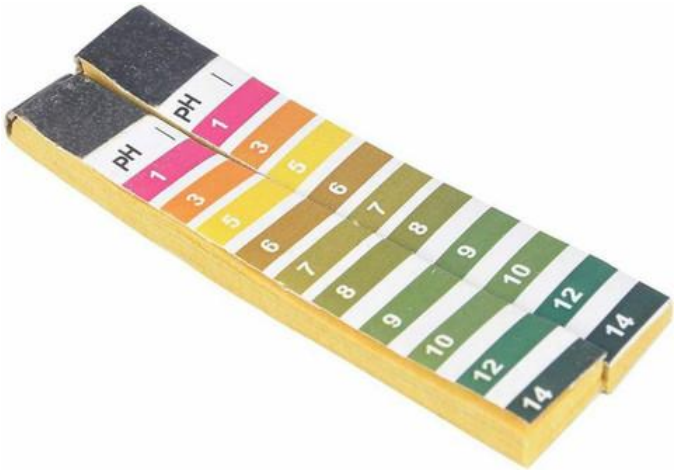


Fig 4.7: pH Paper

4.4.2 Comparative Discussion

LDPE Oil (pH 6)

- Slightly acidic, close to neutral.
- Less corrosive, safer for storage.

HDPE Oil (pH 5)

- More acidic than LDPE and mixed oils.
- Indicates higher potential for corrosion in storage and engine components.

Mixed Oil (pH 6)

- Similar to LDPE oil, near neutral.
- Represents a balanced composition, less corrosive risk.

4.4.3 Comparison with Conventional Fuels

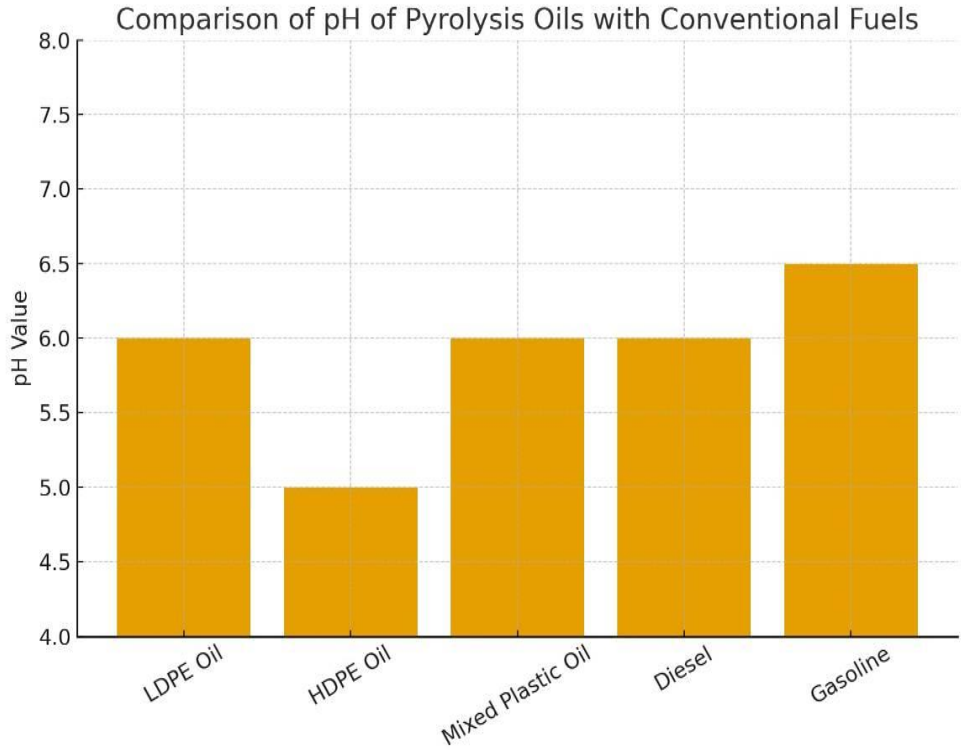


Fig 4.8: Comparison of pH of Pyrolysis oil with conventional fuels

Diesel fuel: pH ~ 5.5–6.5 (slightly acidic, due to sulfur compounds).
Gasoline: pH ~ 5.5–7.0 (slightly acidic to neutral).

- Pyrolysis oils (pH 5–6) fall within the same acidic range as diesel and gasoline.
- This means corrosion risks are comparable to conventional fuels, but HDPE oil (pH 5) is on the more corrosive side.

4.4.4 Implications

- HDPE oil may require neutralization or refining to reduce acidity.
- LDPE and mixed oils are safer but still slightly acidic.
- Proper storage and additives (anti-corrosion inhibitors) are recommended for long-term use.

4.5 Density

Density is the mass per unit volume of a fuel (kg/m³).
It affects:

- Fuel injection & atomization (lower density fuels spray more easily).

- Energy content per volume (denser fuels carry more mass → more energy in the same volume).
- Engine performance & emissions (too high or too low density causes imbalance).

4.5.1 Experimental Data

LDPE Oil:

Mass of oil,m= 0.006 kg

Volume of oil,v = 5×10^{-6} m^3

Density= (m/v)

$=(0.006/5\times10^{-6})$

$= 1200 kg/m^3$

HDPE Oil:

Mass of oil,m= 0.005 kg

Volume of oil,v = 5×10^{-6} m^3

Density= (m/v)

$=(0.005/5\times10^{-6})$

$= 1000 kg/m^3$

Mixed plastic Oil:

Mass of oil,m= 0.004 kg

Volume of oil,v = 5×10^{-6} m^3

Density= (m/v)

$=(0.004/5\times10^{-6})$

$= 800 kg/m^3$

4.5.2 Comparative Discussion

LDPE oil (1200 kg/m³)

- Highest density.
- Carries more energy per liter but may cause heavy spraying and incomplete combustion.

HDPE oil (1000 kg/m³)

- Moderate density, close to water (1000 kg/m³).
- Balanced fuel property, but still heavier than conventional diesel.

Mixed oil (800 kg/m³)

- Lowest density.
- Closest to diesel, meaning better atomization and easier use in engines.

4.5.3 Comparison with Conventional Fuels

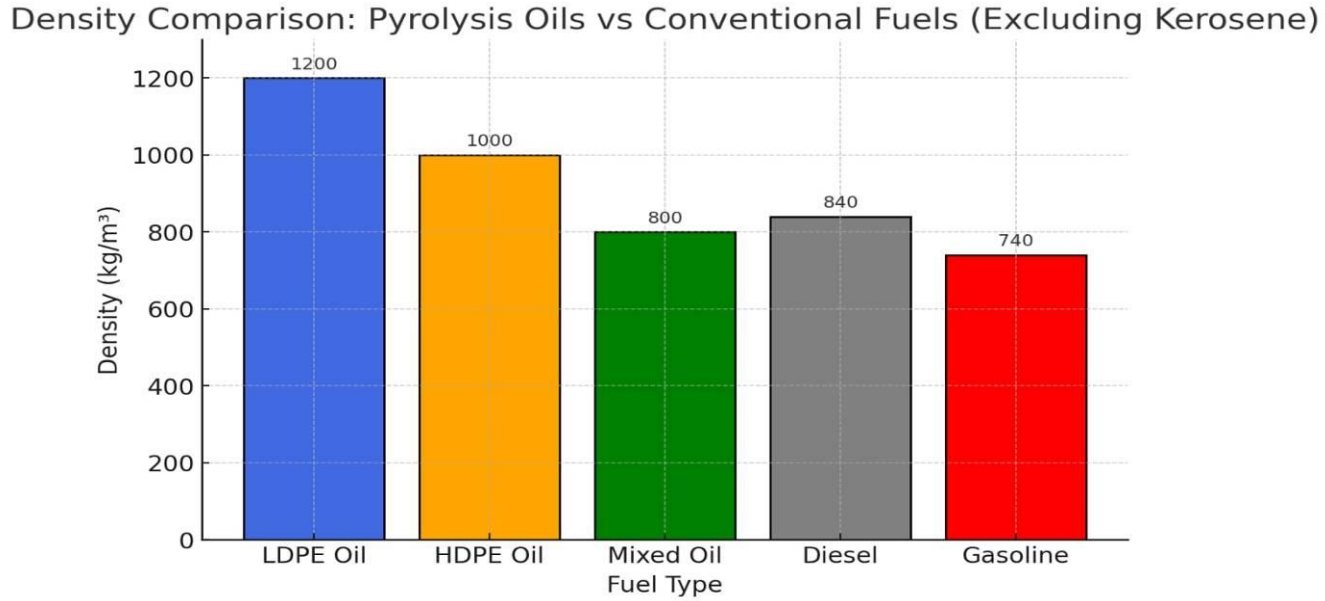


Fig 4.9: Comparison of Density of Pyrolysis oil with conventional fuels
Diesel: ~820–860 kg/m³
Gasoline (Petrol): ~720–780 kg/m³

- Mixed oil (800 kg/m³) is closest to diesel range, making it the most engine-compatible.
- LDPE oil (1200 kg/m³) is significantly denser than both diesel and gasoline → may need refining/blending.
- HDPE oil (1000 kg/m³) is still heavier but more manageable than LDPE oil.

4.5.4 Implications

- Mixed oil is the most practical candidate due to its diesel-like density.
- HDPE oil is acceptable but may need slight adjustment.
- LDPE oil requires upgrading (distillation or cracking) before use as a fuel substitute.

4.6 Net Calorific Value:

The calorific value of a fuel is the total amount of heat released when a unit mass of the fuel is completely burned. It is a critical indicator of the fuel's energy efficiency and suitability for practical applications, such as in power generation, heating, and as an alternative to fossil fuels like diesel and petrol.

4.6.1 Experimental Data

LDPE oil:

We know,

$$CV = (m_{water} \times c \times \Delta T) / m_{oil}$$

Where,

m_{water} =Mass of water,
c= Specific heat of water,
ΔT= Temperature rise of water,
m_{oil} = Mass of oil burned ,



Fig 4.10:Temperature Gun

SL No	m_{water} (kg)	c (kJ/kg℃)	T_1 ˚C	T_2 ˚C	ΔT (T_2- T_1) ˚C	m_{oil} (kg)	CV kJ/kg
1	0.1	4.18	29.5	55.3	25.8	0.005	2156.88
2	0.1	4.18	29.9	60.0	30.1	0.005	2516.36
3	0.1	4.18	30.0	58.3	28.3	0.005	2365.88

Table 4.8: Experimental data of Calorific value of LDPE pyrolysis oil

Final Result: CV= (2156.88+2516.36+2365.88)/3= 2346.37 kJ/kg

HDPE oil:

We know,

$$CV = (m_{water} \times c \times \Delta T) / m_{oil}$$

Where,

m_{water} =Mass of water,

c= Specific heat of water,

ΔT= Temperature rise of water,

m_{oil} = Mass of oil burned ,

SL No	m_{water} (kg)	c (kJ/kg℃)	T_1 ˚C	T_2 ˚C	ΔT (T_2- T_1) ˚C	m_{oil} (kg)	CV kJ/kg
1	0.1	4.18	29.8	59.6	29.8	0.005	2491.28
2	0.1	4.18	30.0	64.0	34.0	0.005	2842.40
3	0.1	4.18	30.5	66.1	35.6	0.005	2976.16

Table 4.9: Experimental data of Calorific value of HDPE pyrolysis oil

Final Result: CV= (2491.28+2842.40+2976.16)/3= 2769.94 kJ/kg

Mixed Plastic oil:

We know,

$$CV = (m_{water} \times c \times \Delta T) / m_{oil}$$

Where,

m_{water} =Mass of water,

c= Specific heat of water,

ΔT= Temperature rise of water,

m_{oil} = Mass of oil burned ,

SL No	m_{water} (kg)	c (kJ/kg℃)	T_1 ˚C	T_2 ˚C	ΔT (T_2- T_1) ˚C	m_{oil} (kg)	CV kJ/kg
1	0.1	4.18	29.5	62.8	33.3	0.005	2783.88
2	0.1	4.18	30.0	65.2	35.5	0.005	2967.80
3	0.1	4.18	29.0	64.0	35.0	0.005	2926.00

Table 4.10: Experimental data of Calorific value of Mixed pyrolysis oil

Final Result: CV= (2783.88+2967.80+2926.00)/3= 2892.56 kJ/kg

4.6.2 Comparative Discussion

LDPE Oil (2346.37 kJ/kg)

- Lowest calorific value among the three.
- Indicates less energy release per kilogram of oil.
- May be due to higher presence of lighter hydrocarbons or incomplete carbonization during pyrolysis.
- Less efficient as a direct fuel substitute.

HDPE Oil (2769.94 kJ/kg)

- About 18% higher CV than LDPE oil.
- Presence of longer carbon chains in HDPE may contribute to better combustion properties.
- Offers higher energy yield, but other fuel properties (e.g., flash point) must be considered for safety.

Mixed Plastic Oil (2892.56 kJ/kg)

- Highest CV among all samples, ~23% higher than LDPE and ~4% higher than HDPE.
- Likely due to the balanced combination of LDPE and HDPE degradation products.
- Indicates the best energy efficiency, making it the most promising alternative fuel candidate.

4.6.3 Comparison with Conventional Fuels

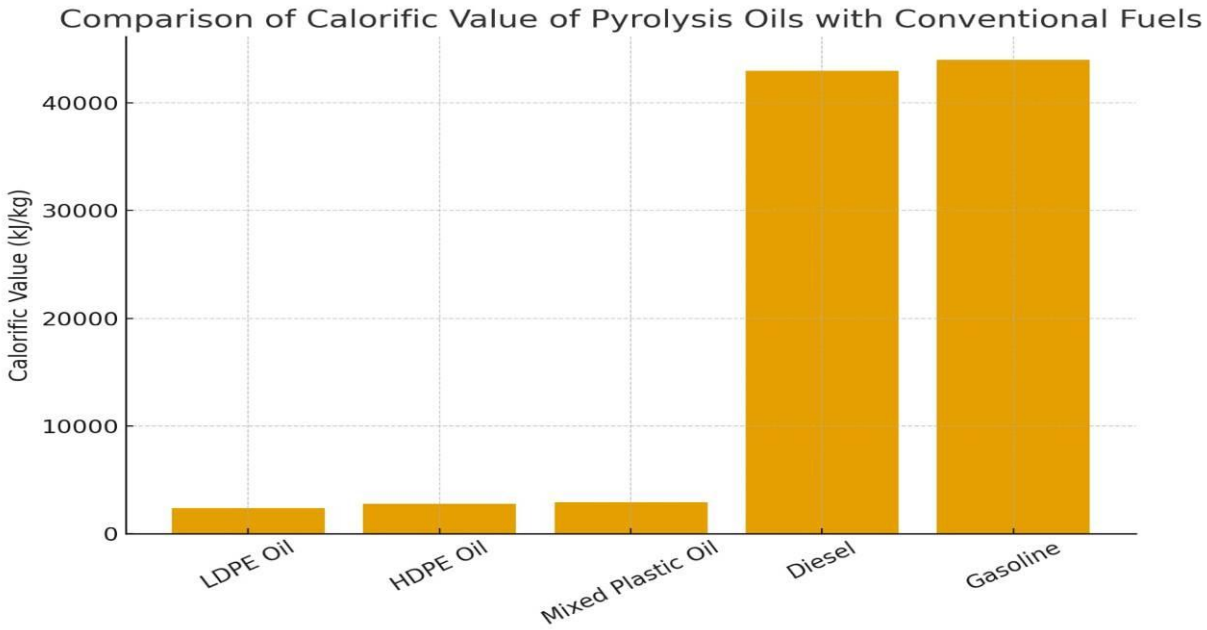


Fig 4.11: Comparison of Calorific Value of Pyrolysis oil with conventional fuels

- Diesel fuel: ~43,000 kJ/kg
- Gasoline: ~44,000 kJ/kg
- Pyrolysis oils (this study): ~2300–2900 kJ/kg

The method we used to measure calorific value burning a small amount of oil to heat water and then calculating from the temperature rise is simple and effective for a quick estimate, but it does have its limitations. A big issue is that not all the heat from the burning fuel goes into the water; some is lost to the surroundings, the container or through radiation. Sometimes the fuel doesn't burn completely, especially with complex oils like those from plastic pyrolysis, which means less energy is released than expected. Volatile parts of the fuel can also evaporate before they burn, further lowering the results. On top of that, the method assumes water's heat capacity is constant, even though it changes slightly with temperature. Another limitation is that it doesn't account for the hidden heat in the water vapor formed during combustion, so what's measured is closer to the net calorific value rather than the true gross value. Finally, because the experiment uses small quantities, even tiny measurement errors in mass or temperature can have a big impact. All of these factors mean the value we get in the lab will almost always be lower than the real energy content of the fuel.

Chapter 5
Conclusion

5.1 Conclusion

This study investigated the qualitative properties of pyrolysis oils derived from LDPE, HDPE, and mixed plastic waste (LDPE, HDPE, PP, PS) through controlled thermal decomposition. The experimental results and analytical findings (FTIR, calorific value, flash point, viscosity, pH, and density tests) provide several important conclusions.

1. Fuel-like Hydrocarbon Composition
All tested plastics produced hydrocarbon-rich oils containing alkanes, alkenes, and aromatics. FTIR analysis confirmed strong similarities with conventional fuels, though variations were observed in the levels of unsaturated and oxygenated compounds.

2. Energy Potential
Mixed plastic oil demonstrated the highest calorific value (2892.56 kJ/kg), followed by HDPE oil (2769.94 kJ/kg) and LDPE oil (2346.37 kJ/kg). Although all values were lower than diesel and gasoline, mixed plastic oil showed the best potential as an alternative energy source.

3. Safety and Stability
Flash point analysis revealed that LDPE and mixed oils (~52–57 °C) are safer for storage and handling compared to HDPE oil (~38 °C), which is highly volatile. However, unsaturated and oxygenated groups present in all oils indicate risks of instability, polymerization, and corrosion during storage.

4. Environmental Implication
Pyrolysis successfully diverts plastic waste from landfills, reducing environmental pollution and offering a pathway for circular economy integration. Although refinement is necessary, the process demonstrates real potential as a sustainable waste-to-energy solution.

Overall, the research establishes that mixed plastic pyrolysis oil is the most promising candidate for future fuel development, while HDPE and LDPE oils require additional upgrading or blending for practical use.

5.2 Limitations of the Study

While this study provides valuable insights into the qualitative analysis of pyrolysis oils derived from LDPE, HDPE, and mixed plastics, certain limitations should be acknowledged.

1. Laboratory Scale Constraints
The experiments were carried out on a small batch pyrolysis setup.Large-scale performance, continuous operation, and industrial applicability were not tested.

2. Limited Polymer Scope

Only LDPE, HDPE, PP, and PS (in mixtures) were considered.Other common plastics such as PVC and PET were excluded due to challenges with chlorine and oxygenated by-products.

3. Incomplete Fuel Property Testing
While FTIR, calorific value, flash point, viscosity, density, and pH were measured, advanced fuel specifications such as cetane number, pour point, distillation range, sulfur content, and emission profiles were not analyzed.

4. Stability and Storage Analysis
Long-term storage stability (oxidation, polymerization, gum formation) was not evaluated. Corrosion tests on metallic and polymeric materials were not performed.

5. Economic and Environmental Assessments
The study did not include a techno-economic analysis or life-cycle assessment (LCA) to evaluate cost feasibility, CO_2 reduction potential, or scalability.

5.3 Future Scope of Research

- **Comprehensive Feedstock Study**

  Expand analysis to include other plastics (PET, PVC, multilayer packaging) to better represent real-world mixed waste streams.

- **Catalytic Pyrolysis**

  Explore the use of catalysts (e.g., zeolites, silica-alumina, metal oxides) to enhance selectivity toward high-value fuel fractions and reduce unwanted by-products.

- **Co-Pyrolysis**

  Investigate co-pyrolysis with biomass or other organic wastes to improve oil stability, reduce aromatic dominance (especially in PS oils), and enhance environmental sustainability.

- **Quantitative & Property Analysis**

  Perform quantitative GC–MS, proximate and ultimate analyses, and standard fuel testing (calorific value, viscosity, flash point, pour point, emissions) to assess suitability as transportation fuels.

- **Process Optimization & Scale-Up**

  Optimize parameters such as temperature, residence time, and heating rate for maximum yield and desired product composition.

  Conduct pilot-scale studies to assess economic feasibility, energy efficiency, and emission control systems.

- **Life Cycle & Environmental Assessment**

  Evaluate the overall environmental benefits and carbon footprint of plastic-to-oil pyrolysis compared to landfilling, incineration, or recycling.

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