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Functional Group Identification and Fuel Property Assessment of Tire Pyrolysis Oil Blended with Mahua Biodiesel

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Abstract

The growing demand for sustainable energy and the environmental impact of fossil fuels necessitate alternative fuel. This study investigates the potential of a blend of Waste Tire Pyrolysis Oil (WTPO) and non-edible Mahua Biodiesel as a renewable diesel substitute. TPO offers high energy content but lacks from high viscosity and emissions, while Mahua biodiesel provides better combustion properties and environmental benefits. A 10% TPO and 90% Mahua biodiesel blend (TPO10B90) by wt% was prepared and analyzed for its physicochemical properties and chemical composition using FTIR spectroscopy. The blend demonstrated improved calorific value (41.76 MJ/kg), flash point (62°C), fire point (76°C), and kinematic viscosity (3.74 cSt), all within acceptable ASTM standards. FTIR results confirmed the presence of functional groups from both biodiesel and pyrolytic compounds, validating their compatibility. The findings suggest that the TPO10B90 blend offers a viable, cleaner-burning, and more sustainable fuel alternative for diesel engines, contributing to both waste tire management and renewable energy development.

Keywords

Tyre Pyrolysis Oil (TPO), Mahua Biodiesel, FTIR Spectroscopy, TPO-Biodiesel Blend (TPO10B90).

1. Introduction

The rapid rise in global energy demand and concerns over climate change have intensified the need for alternative, sustainable, and renewable fuels capable of reducing dependence on fossil resources. Waste-to-energy technologies have gained significant attention for their dual benefits of resource recovery and waste minimization. Among various waste-derived fuels, tire pyrolysis oil (TPO) has emerged as a promising candidate due to its high energy content and the ability to convert end-of-life tires (ELTs) into usable liquid fuel through thermochemical decomposition (Williams, 2013)(Kar, 2011). Globally, millions of waste tires are discarded annually, posing severe environmental challenges because of their non-biodegradable nature and complex polymer structure. Pyrolysis offers an environmentally responsible solution by converting waste tires into valuable products—solid char, non-condensable gases, and TPO (Quek and Balasubramanian, 2013).

1.1 Objectives

- To extract oil by pyrolysis of waste tire.
- To analyze the physiochemical properties of Tire Pyrolysis Oil (TPO) and Mahua Biodiesel blend.
- To identify and characterize the functional groups and chemical composition of TPO and Mahua Biodiesel Blend by using Fourier Transform Infrared (FTIR) Spectroscopy.

2. Literature Review

TPO is a complex mixture of hydrocarbons containing aliphatic chains, aromatic rings, polyaromatic structures, and small quantities of oxygenated compounds, giving it a heating value comparable to conventional diesel fuel (Frigo *et al.*, 2014) (Banar *et al.*, 2012). Despite these advantages, direct use of TPO in diesel engines is limited. Its high viscosity, elevated sulfur content, poor volatility, and unstable combustion behavior hinder its suitability as a standalone fuel (Murugan, Ramaswamy and Nagarajan, 2008). Additionally, the presence of diverse functional groups such as carbonyl, alkene, aromatic, and heteroatomic structures can adversely affect storage stability and ignition quality (Stankovikj *et al.*, 2017). Therefore, blending TPO with a compatible, oxygen-rich biofuel is considered an effective strategy for improving its physicochemical and combustion characteristics. Mahua (Madhuca indica) biodiesel, produced from a widely available non-edible feedstock in South Asia, has shown great potential as a renewable and eco-friendly biofuel. Mahua oil contains long-chain triglycerides that can be transesterified into fatty acid methyl esters (FAMEs) possessing favorable fuel properties such as higher oxygen content, improved lubricity, lower sulfur levels, and cleaner combustion (Raheman and Ghadge, 2007). Compared to diesel, Mahua biodiesel typically exhibits a higher flash point and reduced emissions of particulate matter and unburnt hydrocarbons, although its viscosity and heating value are slightly less favorable (Nabi, Rahman and Akhter, 2009).

The blending of TPO with Mahua biodiesel presents a promising approach to addressing the limitations of each fuel. The oxygenated nature of biodiesel enhances combustion efficiency, improves ignition quality, and reduces smoke and particulate emissions associated with TPO (Sahoo and Das, 2009). Conversely, the high energy content and aromatic constituents of TPO can compensate for the lower calorific value of biodiesel, resulting in a more balanced and energetically viable fuel blend (Prakash *et al.*, 2019). Such blends may offer synergistic improvements, including reduced viscosity, improved volatility, enhanced atomization, and better fuel stability compared to pure TPO (Ahmad *et al.*, 2023). A clear understanding of the molecular structure and functional groups present in TPO, Mahua biodiesel, and their blends is essential for predicting compatibility, reaction pathways, combustibility, and storage behavior. Fourier Transform Infrared Spectroscopy (FTIR) has proven to be a powerful tool for characterizing functional groups in hydrocarbon fuels and biodiesel (Knothe, 2006) (Sharma *et al.*, 2019). Additionally, fuel property evaluation including density, kinematic viscosity, flash point, pour point, calorific value, and Cetane index is critical for assessing blend performance and ensuring compliance with fuel standards.

Therefore, this study aims to provide a comprehensive functional group identification and fuel property assessment of tire pyrolysis oil blended with Mahua biodiesel. The outcomes of this research are expected to enhance the understanding of waste-derived and renewable fuel interactions, offering valuable insights for future applications of TPO–biodiesel blends in diesel engine and combustion systems.

3. Methodology

The overall research involved the production of Waste Tire Pyrolysis Oil, the preparation of a blend with Mahua Biodiesel, and the comprehensive characterization of the resulting fuel. The production of the TPO was carried out using a pyrolysis setup. The schematic diagram of the WTPO production process is represented in Figure 1: Schematic Diagram. The entire sequence, from waste collection to fuel blending, is illustrated in the process flow chart, Figure 2 Flow Chart.

The pyrolysis setup used for generating the Waste Tire Pyrolysis Oil included several key components:

- **Reactor:** Used for the thermal decomposition of the shredded waste tires.

- **Condenser:** Used to cool and condense the hydrocarbon vapors produced from the reactor into liquid pyrolysis oil.
- **Valve:** Used for regulating the gas flow.
- **Burner:** Provided the heat required for the pyrolysis reaction.
- **Tripod:** Used to support the reactor and burner setup.
- **Inert Gas:** Nitrogen or another inert gas was used to ensure an oxygen-free atmosphere for pyrolysis.
- **LPG Gas:** The gas source for the burner.
- **Laboratory Drying Oven:** Used for preparing samples or drying components.

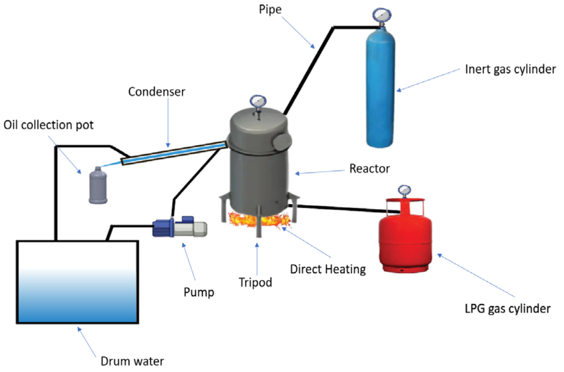

Figure 1: Schematic Diagram.

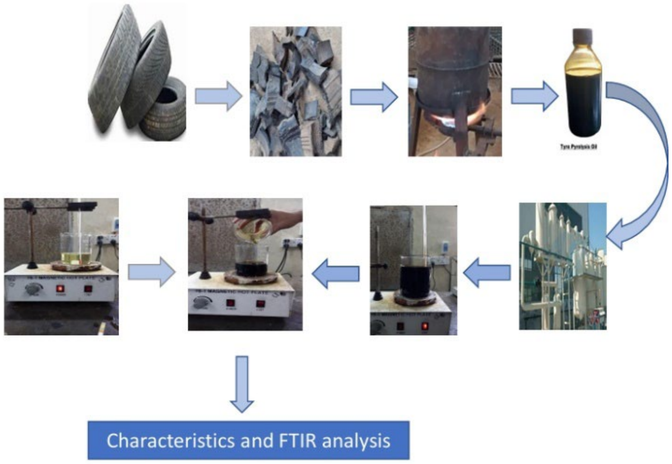

Figure 2: Process Flow Chart for WTPO and Mahua Oil Blend Production.

The flow chart in Figure 3 depicts the process of transforming waste tires into an eco-friendly fuel blend that includes TPO and Mahua oil. The process begins by collecting the waste tires, which are then shredded into smaller pieces to aid in pyrolysis. The shredded tires are then put through pyrolysis, which can be defined as the thermal decomposition in the absence of oxygen; this process yields TPO. The raw TPO is collected and subsequently purified to upgrade its fuel properties. TPO is then blended with Mahua oil to improve its performance parameters and decrease emissions.

(a) (b) (c)

Figure 3: (a) Calorific value measurement using bomb calorimeter. (b) Pensky-Martens closed cup tester. (c) Rotational viscometer.

The blend sample, designated TPO10B90, was prepared by combining 10% Waste Tire Pyrolysis Oil (TPO10) and 90% Mahua Biodiesel (B90) by weight which is shown in Figure 4. A weight-based blending approach was employed. Specifically, 10.08 grams of TPO and 90.53 grams of Mahua biodiesel were measured using a digital precision balance and stored in separate beakers. The Mahua biodiesel was placed on a magnetic stirrer hot plate. Its temperature was gradually raised and maintained between 50°C and 60°C to reduce viscosity without degrading fuel properties, and stirring was initiated to generate a uniform vortex. The pre-measured TPO was introduced slowly, dropwise, into the heated and stirring Mahua biodiesel to ensure controlled mixing and mitigate thermal shocks or phase separation. The mixture was allowed to stir at the controlled temperature for a specified period until a consistent and homogeneous blend was achieved.

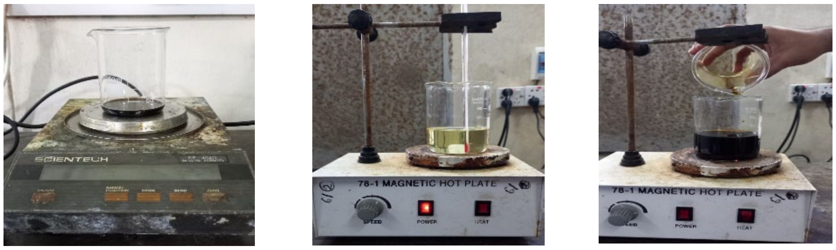

Figure 4: Preparation of TPO10B90 blend sample.

The physicochemical properties of the fuels were characterized following established ASTM standards to assess their quality as a potential alternative fuel. The calorific value or heat energy content, a critical parameter directly affecting engine performance, was determined using a VSI Microprocessor Fully Automated Digital Bomb Calorimeter as shown in Figure 3. For safety and handling assessment, the flash point and fire point were measured using a Pensky-Martens closed cup tester illustrated in Figure 3. The kinematic viscosity, which is crucial for proper fuel injection and atomization in compression-ignition (CI) engines, was measured using a rotational viscometer depicted in Figure 3.3(c). Finally, density measurements were recorded, and Fourier-transform infrared (FTIR) spectroscopy was performed to identify and compare the functional groups present in the fuel samples, providing insights into their chemical composition and verifying the compatibility of TPO and Mahua Biodiesel.

4. Data Collection and Analysis

4.1 Calorific Value Analysis

In this study, the calorific values of Tire Pyrolysis Oil (TPO)**,** Mahua Biodiesel (B100), and their blend (TPO10B90) were measured using a VSI Microprocessor Fully Automated Digital Bomb Calorimeter, which ensures precise and consistent results under controlled conditions. Below Table 1 shows the data for calorific value test (TPO) and Table 2 shows for TPO10B90.

Table 1: Data for calorific value test. (TPO)

Weight of the pyro-oil, m(gm)	0.69
Length of nichrome wire, L(cm)	5
Length of cotton wire, I(cm)	10
The pressure of the oxygen inside the bomb, P(atm)	30
Volume of distilled water, V(ml)	2000
The energy equivalent of the calorimeter (considering consideration) under standardization, W (cal/°C)	2426
Initial temperature (°C)	27.604
Temperature rise δT (°C)	2.972

Higher calorific value = $[(\delta T * W) - e_1 - e_2 - e_3]\ /m$ ....(1)

$= [(2.972*2426) - 23.9 - 13.9 - 17.5]\ /0.69$ cal/gm

$= 10362.865$ cal/gm

$= 43.37$ MJ/kg

Therefore, the higher calorific value of the recovered pyro-oil is 43.37 MJ/kg.

Table 2: Data for calorific value test. (TPO10B90)

Weight of the pyro-oil, m(gm)	0.70
Length of nichrome wire, L(cm)	5
Length of cotton wire, I(cm)	10
The pressure of the oxygen inside the bomb, P(atm)	30
Volume of distilled water, V(ml)	2000
The energy equivalent of the calorimeter (considering consideration) under standardization, W (cal/°C)	2426
Initial temperature (°C)	27.834
Temperature rise δT (°C)	2.892

Higher calorific value = $[(\delta T * W) - e_1 - e_2 - e_{3]}\ /m$………. (2)

$= [(2.892*2426) - 23.9 - 13.9 - 17.5]\ /0.70$ cal/gm

$= 10362.865$ cal/gm

$= 41.76$ MJ/kg

Therefore, the higher calorific value of the TPO10B90 sample is 41.76 MJ/kg

4.2 Flash and Fire Points

Flash and fire points reflect the volatility and safety of handling fuels. These were determined using standard apparatus. The flash point refers to the minimum temperature at which the vapor of a volatile substance ignites in the presence of an ignition source. In contrast, the fire point is the lowest temperature at which the vapors sustain combustion even after the ignition source is removed. The measured flash and fire point values are summarized in Table 3.

Table 3: Flash and Fire Points

Fuel Type	Flash Point(°C)	Fire Point(°C)
TPO	44	65
B100	>100	>100
TPO10B90	62	76

4.3 Viscosity Analysis

Viscosity affects atomization and fuel injection in engines. Dynamic viscosity was measured using a rotational viscometer. Below table 4 shows the dynamic viscosity values.

Table 4: Dynamic Viscosity

Fuel Type	Dynamic Viscosity(cP)	Kinematic Viscosity(cSt)
TPO	2.5	2.77
B100	2.34	2.73
TPO10B90	3.3	3.74

4.4 Density Analysis

Density plays a vital role in determining the energy per unit volume of the fuel. It was measured using the gravimetric method. Table 5 represents the density of fuel samples.

Table 5: Density of Fuel Samples

Fuel Type	Density(kg/m^3)
TPO	903
B100	856
TPO10B90	883

4.5 Summary of Fuel Properties

Table 6 summarizes all tested fuel properties and compared with ASTM value.

Table 6: Summary of All Tested Properties

Property	TPO	B100	TPO10B90	Standard Biodiesel (ASTM D6751) (Wang *et al.*, 2016)	Standard Diesel (ASTM D975) (Azad *et al.*, 2016)
Calorific Value	43.37	39	41.76	39.3-39.8	45.3-46.7
Flash Point(°C)	44	>100	62	100-170	60-80
Fire Point (°C)	65	>100	76	-	-
Dynamic Viscosity (cP)	2.5	2.34	3.3	1.67-5.5	1.04-3.36
Kinematic Viscosity(cSt)	2.77	2.73	3.74	1.9-6.0	1.3-4.1
Density(kg/m^3)	903	856	883	860-900	800-820

5. Results and Discussion

5.1 Calorific Value

Comparison of the calorific value is shown below in Figure 5. The calorific value of a fuel is a direct indication of its energy potential. ASTM Diesel stands out with the highest value, making it the most energy-dense fuel tested. TPO follows closely, highlighting its viability as an alternative energy source despite being derived from waste materials. Mohua Biodiesel, on the other hand, shows a lower calorific value due to oxygen presence which dilutes energy-rich hydrocarbons. Blending TPO with biodiesel in TPO10B90 yields a compromise fuel with a satisfactory energy output.

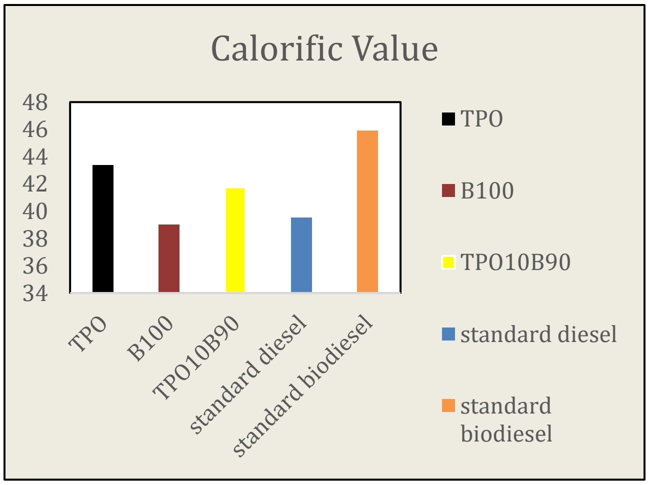

Figure 5. Comparison of the Calorific value among TPO, B100, TPO10B90, ASTM Biodiesel and ASTM Diesel.

5.2 Flash Point

The flash point values are given below in Figure 6. TPO exhibits the lowest flash point, suggesting it ignites easily and poses handling risks. ASTM Diesel is more stable but not as safe as biodiesels. Mohua Biodiesel and ASTM Biodiesel show flash points over 100°C, indicating excellent resistance to ignition under normal conditions. The TPO10B90 blend significantly improves flash point over pure TPO, thus increasing safety during storage and transportation. This improvement makes the blend more suitable for commercial and industrial useThe study clearly shows that adding biodiesel enhances the flash point of TPO.

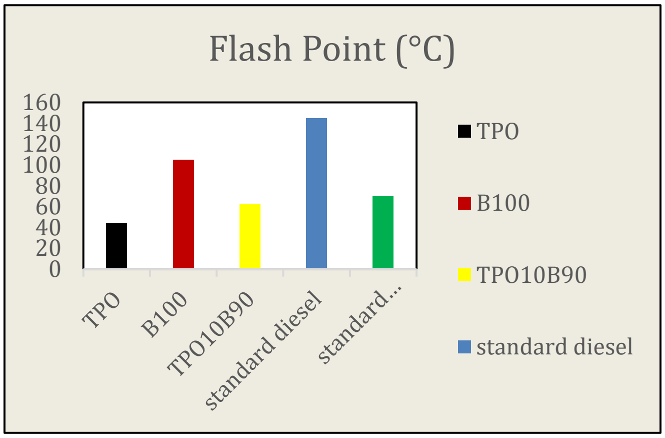

Figure 6: Comparison of the Flash point among TPO, B100, TPO10B90, ASTM Biodiesel and ASTM Diesel.

5.3 Fire Point

The flash point and fire point values are given below in Figure 7. ASTM Diesel and biodiesels like Mohua and ASTM variants show significantly higher fire points, reflecting better thermal stability and consistent ignition behavior. The TPO10B90 blend increases the fire point over TPO, showing its enhanced combustion control. High fire points are crucial for engine safety, particularly under continuous high-load operations. The improvement seen in TPO10B90 also contributes to reducing accidental ignition risks. This shows that TPO-based blends can be engineered to meet safety standards. The combination of fuels with high and low fire points offers design flexibility for cleaner and safer energy use.

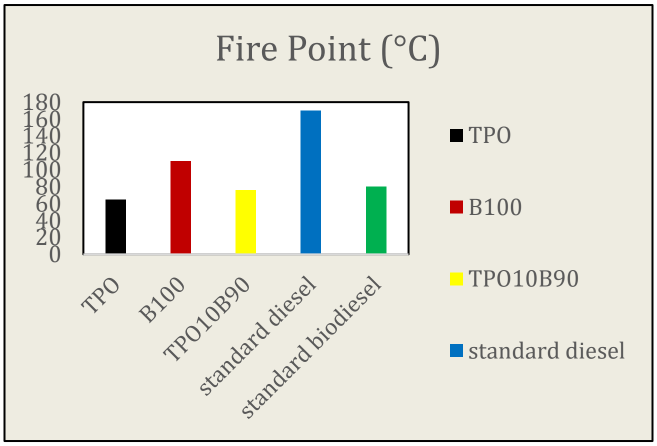

Figure 7: Comparison of the Fire point among TPO, B100, TPO10B90, ASTM Biodiesel and ASTM Diesel.

5.4 Density

The values of density are given below in Figure 8. Mohua and ASTM Biodiesel have lower densities and better align with biodiesel standards. TPO10B90 shows an optimized density that supports improved spray and combustion characteristics. Lower densities, like that of ASTM Diesel, enable better atomization and more complete burning. Managing fuel density is critical in ensuring energy efficiency and minimizing soot formation. When TPO is blended with biodiesel, density decreases, allowing better engine performance. Blending serves as a useful strategy to balance energy potential and practical usability.

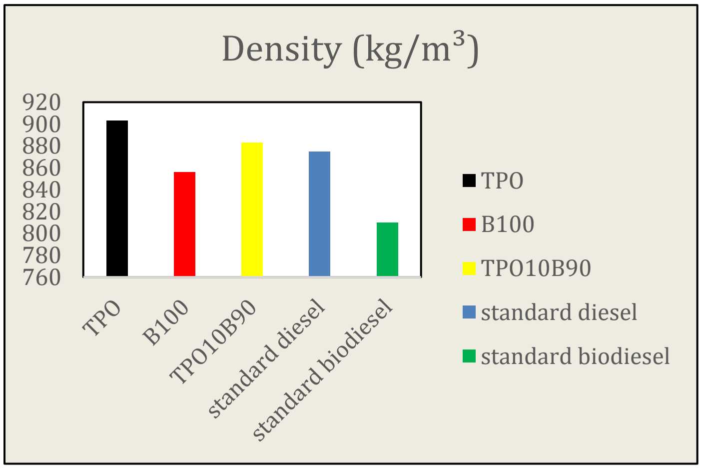

Figure 8: Comparison of the Density among TPO, B100, TPO10B90, ASTM Biodiesel and ASTM Diesel.

5.5 Viscosity

The flash point and fire point values are given below in Figure 9 TPO s higher viscosity may challenge fuel flow but helps in lubrication. Mohua Biodiesel presents moderate viscosity, offering better protection to engine parts. The TPO10B90 blend shows an elevated but ASTM-compliant viscosity, making it feasible for engine use. While high viscosity may cause deposits, it also reduces wear in pumps and injectors.Viscosity needs to be carefully controlled in blended fuels to ensure smooth engine operation. It is a balancing act between lubricity and combustion efficiency. Well-managed viscosity in blended fuels like TPO10B90 allows for practical use in diesel engines.

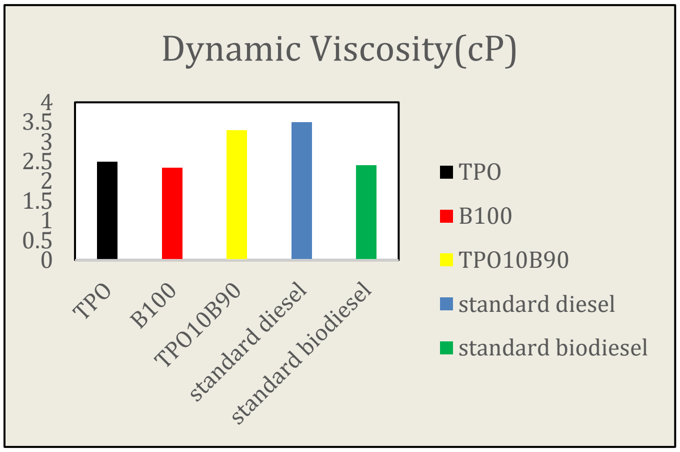

Figure 9. Comparison of the Viscosity among TPO, B100, TPO10B90, ASTM Biodiesel and ASTM Diesel.

5.6 FTIR Absorbance Spectrum Analysis

Figure 10 displays the FTIR absorbance spectra of TPO samples from three different runs, demonstrating consistent peak patterns and indicating reproducibility in the chemical composition across the tests. Also, Table 7 shows possible compounds for FTIR Absorbance test.

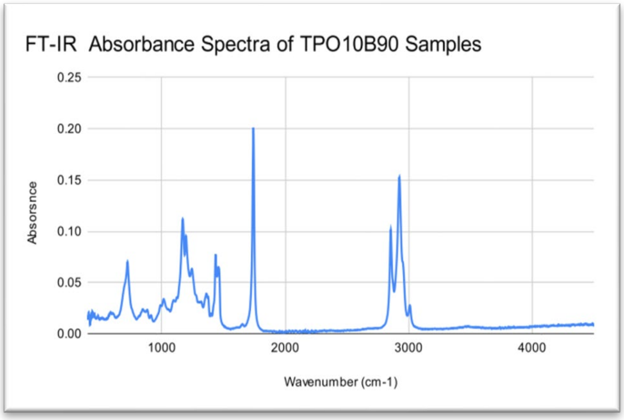

Figure 10: FT-IR Absorbance Spectra of TPO10B90 Samples.

Table 7: Possible compounds for FTIR Absorbance test

Wavenumber (cm⁻¹)	Functional Group	Possible Compounds
~3050–3000	=C–H stretch	Aromatic hydrocarbons, alkenes
~2950–2850	C–H stretch	Alkanes, long-chain hydrocarbons
~1740–1700	C=O stretch	Esters (from biodiesel), ketones
~1600–1500	C=C stretch	Benzene ring compounds, aromatic content from TPO
~1465–1375	CH_2/CH_3 bending	Methyl, methylene compounds
~1250–1050	C–O stretch	Fatty acid methyl esters (biodiesel component)
~900–700	=C–H bending	Substituted benzene derivatives

- The strong absorbance near 3050–3000 cm^{-1} suggests the presence of aromatic C–H bonds, a typical signature of aromatic hydrocarbons found in tyre pyrolysis oil.
- Peaks around 2950–2850 cm^{-1} confirm the presence of aliphatic C–H stretching vibrations, indicating long-chain alkanes present in both TPO and biodiesel.
- The C=O stretch (1740–1700 cm^{-1}) is a strong indicator of ester bonds, confirming the presence of methyl esters from transesterified Mahua oil.
- Peaks near 1600–1500 cm^{-1} correspond to C=C stretching in aromatic rings, reinforcing the presence of aromatic compounds from tyre degradation.
- The region 1250–1050 cm^{-1} corresponds to C–O stretches, confirming the presence of FAME in the biodiesel portion of the blend.
- Lastly, bands between 900–700 cm^{-1} indicate out-of-plane bending of =C–H bonds, usually associated with substituted aromatic rings, common in degraded tyre products.

The absorbance spectrum confirms that the blend retains key molecular characteristics of both components**:** the aromatic and hydrocarbon richness of TPO**,** and the ester-based, oxygenated structure of Mahua biodiesel**.** This combination supports the hybrid nature of the fuel and its potential in CI engine applications.

5.7 FTIR Transmittance Spectrum Analysis

Figure 11 presents the FTIR transmittance spectra of TPO from three separate runs, illustrating a high level of consistency in the detected functional groups throughout the samples. Also, Table 8 shows possible compounds for FTIR Transmittance test.

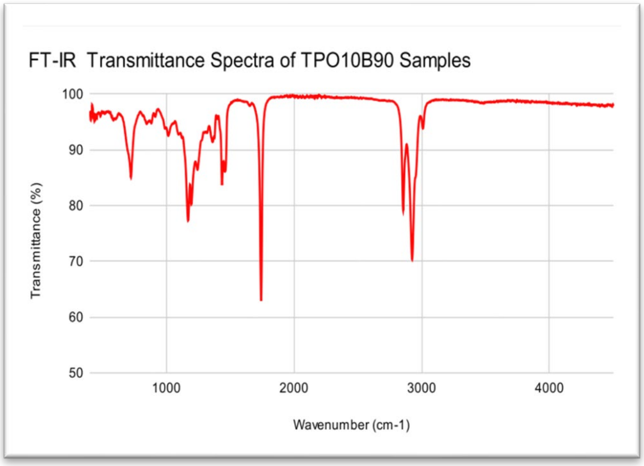

Figure 11: FT-IR transmittance Spectra of TPO10B90 Samples.

Table 8: Possible compounds for FTIR Transmittance test

Wavenumber (cm^{-1})	Functional Group	Possible compounds
~3050–3000	=C–H stretch	Aromatic rings, alkenes
~2950–2850	$–CH_3$, $–CH_2–$ stretch	Alkanes
~1740–1700	C=O stretch	ketones
~1600–1500	C=C stretch	Aromatic compounds
~1465–1375	CH_2, CH_3 bending	Methyl, methylene groups
~1250–1050	C–O stretch	Esters, ethers
~900–700	Aromatic C–H bending	Substituted aromatic rings

- The transmittance dip near 3050–3000 cm^{-1} again confirms aromatic C–H stretching, consistent with the presence of polyaromatic hydrocarbons from the tire pyrolysis oil.

- The bands near 2950–2850 cm^{-1} are attributed to aliphatic C–H stretching, a typical feature of long hydrocarbon chains present in both fuel components.
- The C=O stretching region (~1740–1700 cm^{-1}) shows clear evidence of carbonyl functionalities, supporting the presence of esters (Mahua methyl esters) and possibly ketones.
- A pronounced dip in the 1600–1500 cm^{-1} region again reflects the aromatic C=C bond**,** validating the aromatic nature of the tire pyrolysis component.
- The C–O stretching vibrations (~1250–1050 cm^{-1}) are associated with ether and ester groups, commonly found in biodiesel molecules.
- The ~900–700 cm^{-1} range shows aromatic C–H out-of-plane bending, typical for substituted benzene derivatives, suggesting degradation products from tires.

The transmittance spectrum supports the findings of the absorbance mode, confirming that the blend comprises both aromatic-rich fractions from TPO and oxygenated ester functionalities from Mahua biodiesel**.** These overlapping signatures validate the compatibility and presence of both components in the final blend, which is crucial for understanding its combustion characteristics.

6. Conclusion

This research successfully explored the feasibility of using a TPO and Mahua biodiesel blend as an alternative fuel in diesel engines. The TPO10B90 blend demonstrated balanced fuel properties, combining the high energy potential of pyrolysis oil with the combustion stability of Mahua biodiesel. Experimental data revealed that the blend exhibited improved safety (higher flash and fire points), optimal viscosity and density, and an acceptable calorific value, indicating efficient energy release. FTIR analysis confirmed the chemical compatibility of the two fuels, showing the coexistence of esters, hydrocarbons, and aromatic compounds.

- A TPO10B90 blend (10% TPO, 90% Mahua biodiesel) was prepared using controlled thermal mixing.
- The blend exhibited favorable properties all values met ASTM fuel standards.
- FTIR analysis revealed key functional groups from both TPO and biodiesel (C=O, C–O, and aromatic C–H), indicating strong molecular interaction and blend stability.
- Blending significantly improved the flash/fire points and viscosity of TPO, reducing volatility.
- The fuel blend supports waste reduction, reduces reliance on fossil fuel, and utilizes non-edible renewable resources, offering a low-cost energy alternative.
- The promising results suggest the TPO10B90 blend can be further tested for engine performance, emission characteristics.

7. Future Work

- Perform engine performance and emission tests with TPO and biodiesel blends.
  Conducting performance and emission analysis with different TPO-biodiesel blends will help determine their suitability for diesel engines in terms of power output, fuel consumption, and pollutant levels. This can validate the practical application of these blends as an alternative to conventional fuels.
- Investigate the effect of nano-additives.
  Nano-additives (like metal oxide nanoparticles) can enhance combustion efficiency and reduce emissions when added to fuel. Studying their effect on TPO-biodiesel blends could lead to improved engine performance, better fuel properties, and lower environmental impact.

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Biographies

Md. Shawon Rahaman, a graduate of the Chittagong University of Engineering and Technology (CUET). He is passionate about biofuels and renewable energy, and he actively working in these fields to contribute to sustainable energy solutions. During his university years, he was involved in sports and various extracurricular activities, which helped him build strong teamwork and leadership skills. His goal is to continue growing in the renewable energy sector and make a meaningful impact through innovation and sustainable solutions.

Lulu Gawhar completed her B.Sc. in Mechanical Engineering from the Chittagong University of Engineering and Technology (CUET), Bangladesh, and is currently pursuing her M.Sc. in Mechanical Engineering at the same institution. Her research interests lie in biofuels, alternative energy sources, and renewable energy technologies such as solar and wind power. She has conducted research on the pyrolysis of oil derived from waste tyres, with a particular focus on FTIR-based functional group analysis and fuel property evaluation. Her academic journey reflects a strong commitment to sustainable energy development and innovative engineering solutions.

Marwa Asgar Tanha is a Mechanical Engineering researcher currently pursuing her M.Sc. at the Chittagong University of Engineering and Technology (CUET), where she also completed her B.Sc. Her specialization centers on sustainable energy and thermal systems, highlighted by her work in renewable energy technologies and the application of Thermoelectric Generators (TEGs) for converting waste heat into usable electricity. Additionally, she has significant experience in process simulation, particularly using Aspen Plus for the recycling of used engine oil, positioning her as a promising expert in both resource management and innovative energy conversion techniques.