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Microwave-Assisted Pyrolysis of Waste Lubricating Engine Oil for Recovery of Diesel-Like Alternative Fuel

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Abstract: *Every year, approximately 24 million metric tonnes of waste lubricating engine oil is produced worldwide, posing a serious threat to both environmental sustainability and resource management. This study explores microwave-assisted pyrolysis (MAP) as an energy-efficient technique to reclaim diesel-equivalent fuel from discarded automotive lubricating oil. The experimental setup utilised a modified household microwave oven operating at 2.45 GHz with 1000 W power output, employing carbon rods as susceptors within the reaction vessel and nitrogen gas to establish an oxygen-free environment. Vapours generated during pyrolysis were condensed using a water-cooled condenser unit. Distillate collection began at an initial boiling point of approximately 110–150°C, while the primary thermal cracking reactions occurred within the 280–350°C range. The fuel recovered demonstrated density values of 0.843–0.862 g/cc, gross calorific values of approximately 10,600–10,750 kcal/kg, and flash/fire points surpassing those of commercial diesel, signifying safer storage characteristics. The estimated production cost was around Rs. 50 per litre, representing a 35–45% reduction compared to retail diesel prices. These findings validate microwave-heated pyrolysis as a sustainable and economically viable pathway for converting waste oil into commercially useful energy products.*

Keywords: Microwave pyrolysis, waste lubricating oil, diesel-like fuel, hydrocarbon recovery, thermal cracking, energy recovery, circular economy

I. INTRODUCTION

Lubricating oils play a critical role in the functioning of modern mechanical systems by minimising friction, transferring heat, preventing corrosion, and trapping contaminants. During use in internal combustion engines, these oils undergo irreversible chemical changes due to oxidation, thermal breakdown, and contamination from fuel residues, metallic wear particles, soot, and moisture. Roughly half of the oil in active service gets consumed during the combustion process, while the remaining portion turns into waste oil that necessitates safe and responsible disposal [1].

Worldwide lubricant consumption stands at nearly 40 million metric tonnes annually, with more than 60% eventually becoming waste oil — an estimated 24 million metric tonnes each year. A troubling reality is that fewer than 45% of the waste oil generated is properly collected for treatment; the rest is illegally discarded, leading to severe ecological consequences [2]. Even a single litre of improperly disposed waste oil can render up to one million litres of groundwater unfit for use. Traditional incineration of waste oil releases hazardous atmospheric pollutants such as CO, NOx, SO2, dioxins, and furans.

Pyrolysis — the thermochemical breakdown of organic material in an oxygen-deficient environment — presents an appealing alternative, transforming waste oil into usable liquid hydrocarbon fuel, flammable gases, and solid char while keeping toxic emissions to a minimum. Among pyrolysis techniques, microwave-assisted pyrolysis (MAP) stands out due to its volumetric energy deposition, fast response time, selective heating capability, and a reported energy ratio of approximately 8 [3, 7].

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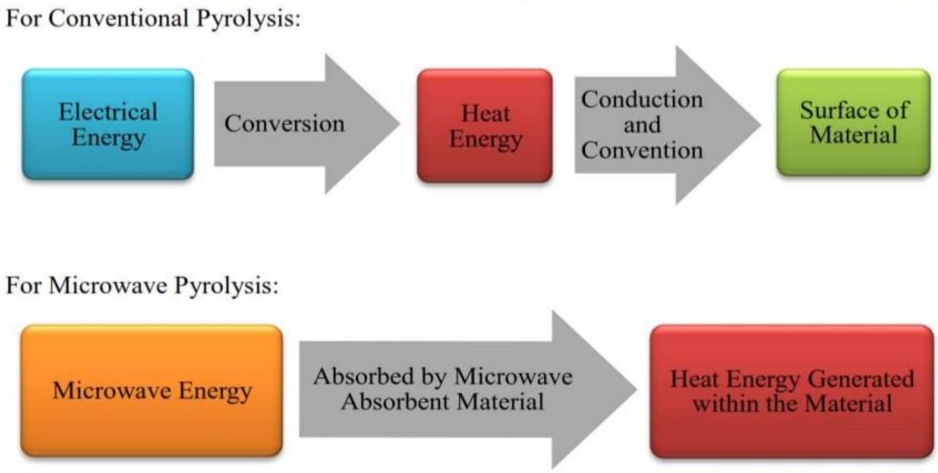

Fig. 1: Comparison of conventional vs. microwave pyrolysis heating mechanisms

This research investigates MAP applied to waste automotive lubricating oil with carbon rods acting as microwave susceptors under a nitrogen blanket, analyses the properties of the recovered fuel, and evaluates the economic feasibility of the process.

II. LITERATURE REVIEW

Al-Omari [9] demonstrated the calorific suitability of waste lubricating oil as an auxiliary fuel source. Fuentes et al. [2] provided quantitative data on global waste oil generation and studied the kinetics of pyrolytic decomposition. Thostenson and Chou [4] laid the theoretical groundwork for microwave-based processing, highlighting key benefits such as selective, rapid, and volumetric heating characteristics.

Demirbas et al. at Dicle University, Turkey reported a pyrolysis oil yield of 88 wt% from waste engine oil through MAP, achieving 90% energy recovery, low sulphur and PAH content, and a positive energy ratio of 8. A continuous 5 kW system processed waste oil at 5 kg/h with a net energy output of 179,390 kJ/h. Lam et al. [5, 7] at the University of Cambridge presented microwave pyrolysis as an innovative recycling route, reporting liquid yields of 80–90 wt% with product quality broadly comparable to fuels derived from fresh oil.

Manasomboonphan et al. [10] in Bangkok examined batch pyrolysis at temperatures between 200–500°C under vacuum conditions, with the highest liquid yield (exceeding 50 wt%) achieved at 350°C. Arpa and Yumrutas [8] engineered a pyrolytic distillation system that recovered diesel-like fuel (DLF) and gasoline-like fuel (GLF) from waste oil, demonstrating engine performance on par with commercial diesel. Selukar et al. explored catalytic pyrolysis employing zeolite catalysts to reduce oil viscosity and improve overall fuel quality.

III. APPARATUS AND EXPERIMENTAL SETUP

The MAP setup consisted of the following components: (1) a modified domestic microwave oven (2.45 GHz, 1000 W output, 1.6 kW input); (2) a 1000 mL five-necked glass reaction kettle sealed using plaster of Paris; (3) a high-purity nitrogen gas supply (>99.5%) for maintaining an inert atmosphere and sweeping vapours; (4) a rotary vacuum pump providing 0.9 bar vacuum; (5) a glass water-cooled condenser; (6) calibrated collection flasks; (7) a K-type thermocouple digital thermometer with a range of 0–1200°C; (8) carbon rods functioning as microwave susceptors; and (9) ceramic pieces to act as nucleation sites.

Carbon rods exhibit a high dielectric loss factor, enabling strong coupling with the 2.45 GHz microwave field. They heat up quickly and transfer energy to the surrounding oil via conduction and radiation. Since waste oil itself is a non-polar hydrocarbon mixture with limited microwave coupling, carbon rods serve as essential intermediaries. Ceramic pieces

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prevent superheating events and potentially hazardous pressure surges. The mass ratio of oil to carbon rods was kept at 2:1 throughout the experiments.

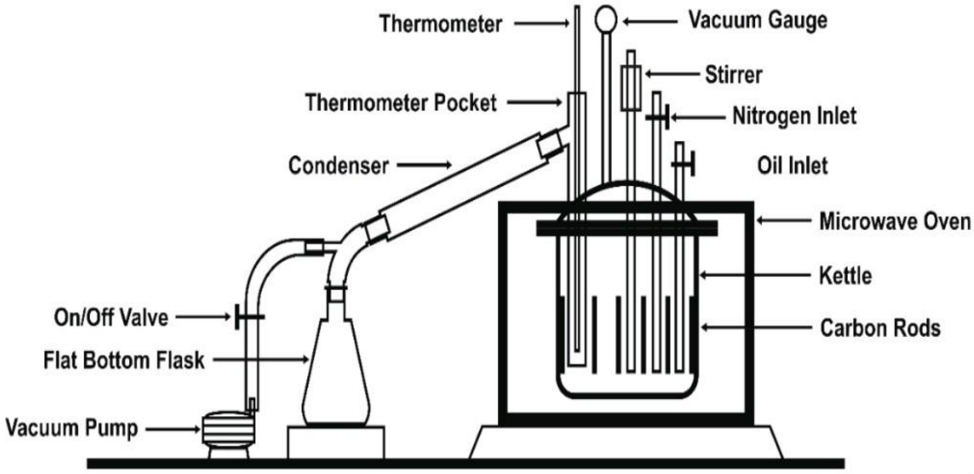

Fig. 2: Schematic diagram of the microwave-assisted pyrolysis experimental setup

IV. EXPERIMENTAL PROCEDURE

Waste lubricating oil was sourced from automotive service workshops, passed through a 200-mesh stainless steel filter, and 750 mL was charged into the reaction kettle per experimental run. Carbon rods and ceramic pieces were added in the specified ratio. The apparatus was then sealed and evacuated to 0.9 bar vacuum, followed by nitrogen purging using three successive evacuation-fill cycles. A steady nitrogen flow of 200–500 mL/min was maintained for 10 minutes prior to the start of heating.

The microwave oven was run at its maximum power setting (1000 W), with continuous temperature monitoring throughout. Heating was carried out in cyclic intervals of 5 minutes on and 2 minutes off to avoid overheating. Initial condensate appeared at 110–150°C (initial boiling point), while substantial liquid production was observed in the 280–350°C range. Heating was stopped once condensate collection ceased. After each run, the system was allowed to cool below 60°C under flowing nitrogen before being disassembled. Results are reported as averages of three replicate runs per experimental condition.

V. RESULTS AND DISCUSSION

A. Fuel Property Analysis

The recovered pyrolysis oil was subjected to standard ASTM fuel property tests and the results were compared against commercial diesel specifications. Table 1 presents a summary of the measured properties.

Property	Unit	Diesel Std.	Sample 1	Sample 2
Flash Point	°C	52–96	208	212
Fire Point	°C	60–110	215	228
Kin. Viscosity	cSt	2–6	70.64	73.6
Density @25°C	g/cc	0.820–0.826	0.843	0.862
Gross Cal. Value	kcal/kg	~10,700	10,599	10,747

Table 1: Fuel properties of pyrolysis oil vs. commercial diesel

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B. Discussion

Flash and Fire Points: The flash points of both samples (208–212°C) and fire points (215–228°C) substantially exceed the commercial diesel specification (52–96°C flash; 60–110°C fire), demonstrating markedly superior storage safety. These elevated values indicate a higher proportion of heavier hydrocarbon fractions in the recovered pyrolysis oil compared to conventional diesel.

Viscosity: The kinematic viscosity of the pyrolysis oil (70.64–73.6 cSt at 25°C) is considerably higher than the diesel standard (2–6 cSt at 40°C), which is attributed to incomplete cracking of longer hydrocarbon chains. This limitation can be addressed by blending with commercial diesel or by catalytic upgrading using zeolite to bring viscosity within acceptable limits for compression ignition engines.

Density: At 0.843–0.862 g/cc, the pyrolysis oil density is marginally above the diesel range (0.820–0.826 g/cc), likely due to the presence of heavier hydrocarbons and aromatic compounds. The difference is small enough to allow blending without materially affecting fuel system calibration.

Gross Calorific Value: Ranging from 10,599 to 10,747 kcal/kg, the recovered pyrolysis oil retains roughly 99% of the energy content of commercial diesel, confirming excellent energy recovery from the waste feedstock.

VI. ECONOMIC ANALYSIS

Using a 1.6 kW microwave oven operating at an 80% load factor and an electricity tariff of Rs. 8 per kWh, the electrical energy cost works out to Rs. 10.24 per hour. With waste oil feedstock priced at Rs. 40 per 1.3 kg, the overall production cost is estimated at approximately Rs. 50 per litre. This compares favourably with retail diesel prices of Rs. 80–90 per litre, translating to a cost saving of 35–45%. The economic advantage is further amplified when waste oil feedstock is procured at little or no cost through partnerships with automotive service centres.

VII. CONCLUSION

This investigation has demonstrated that microwave-assisted pyrolysis of waste lubricating engine oil is technically achievable, economically attractive, and environmentally preferable to conventional disposal approaches. The principal outcomes are: (i) bulk liquid production occurred in the 280–350°C range with an initial boiling point of 110–150°C; (ii) gross calorific value (approximately 10,600–10,750 kcal/kg) is nearly equivalent to that of commercial diesel; (iii) flash and fire points exceeded diesel standards, indicating safer fuel handling; (iv) production cost of approximately Rs. 50 per litre represents a 35–45% reduction compared to retail diesel; and (v) operation under a closed inert atmosphere effectively minimises toxic emissions and the risk of groundwater contamination. Prospective research directions include engine performance testing with the recovered fuel, catalytic treatment for viscosity reduction, development of a continuous reactor design, and a comprehensive lifecycle assessment of the process.

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