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(Original Research)

Sustainable Waste Management and Environmental Pollution Control Through Catalytic Pyrolysis by Transforming Waste Thermocol into Alternative Fuels

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ABSTRACT

Expanded polystyrene (EPS), known as Thermocol, is a significant environmental concern due to its non-biodegradability and improper disposal, contributing to plastic pollution. Conventional recycling methods are often ineffective, needing a sustainable approach to convert this waste into valuable hydrocarbons. Catalytic pyrolysis offers a promising solution by breaking down waste thermocol into liquid fuels, reducing plastic accumulation while creating alternative energy sources. This study employs a biogas-fired reactor, an eco-friendly heating system, to enhance catalytic pyrolysis using Rice Husk Ash Catalyst (RHC) and Zeolite Catalyst (ZeC). A dual air and water-cooled condenser efficiently separated low and high boiling hydrocarbons. As the high boiling hydrocarbon yield in liquid formation is higher so it was detailly analyzed. The waste thermocol oil (WTCO) was analyzed using Gas Chromatography-Mass Spectrometry (GC-MS), Nuclear Magnetic Resonance (NMR) and elemental analysis to determine its chemical composition and physical properties. The important innovation lies in employing a biogas-fired reactor, reducing carbon emissions and promoting green energy utilization. RHC reduced the degradation temperature and processing duration, achieving a higher oil yield of 76% with no carbon residue. Which in turn producing a balanced hydrocarbons like pentane, benzene and toluene, which predominantly contains higher aliphatic hydrocarbons. In contrast, ZeC enhanced higher cracking activity, generating more gases yield of 51% rather than oil yield and predominantly contains higher aromatic hydrocarbons. WTCO derived from both catalysts exhibited similar to diesel properties, such as high calorific value and optimal density. These findings highlight that catalyst selection enables tailored hydrocarbon production from waste thermocol advancing sustainable waste management, pollution control and green fuel development, aligning with global environmental conservation efforts.

INTRODUCTION

Thermocol, is widely used because of its versatility, lightweight nature and cost-effectiveness. It serves as a key material in packaging, insulation and buoyant aid for fishermen. However, improper disposal poses significant environmental challenges and contributes to land, air and water pollution. The open burning of thermocol releases hazardous gases, such as carbon monoxide (CO), carbon dioxide (CO_2), styrene vapors and highly toxic dioxins and furans. Removing these dioxins from water is challenging, as studied by researchers such as **Barisci et al. 2023.** Since thermocol cannot be reused or recycled, addressing its environmental impact is essential. To address these environmental concerns, pyrolysis has emerged as a sustainable solution for converting waste thermocol into valuable liquid hydrocarbons that can be blended with conventional fuels. Various thermal, catalytic, co-pyrolysis and liquefaction techniques have been explored to enhance the thermocol degradation and optimize hydrocarbon production. **Nisar et al. 2023** investigated thermal and catalytic pyrolysis using nickel oxide (NiO) as a catalyst and optimized the process at 370°C under oxygen-free conditions. The chemical composition of the pyrolysis oil was analyzed by Thermogravimetric Analysis (TGA) and Gas Chromatography-Mass Spectroscopy (GC-MS). Similarly, **Mohapatra et al. 2021** explored the co-pyrolysis of thermocol with sugarcane bagasse and identified the peak oil yields at 400°C. Elemental and proximate analyses confirmed high volatile matter and carbon contents, making thermocol a suitable feedstock for pyrolysis. **Ahmad et al. 2020** employed a liquefaction approach using ethanol as a solvent and optimized the conditions at 350°C to achieve high oil yields, with GC-MS analysis identifying the aromatic compounds, alkenes and alkyl groups in the resulting oil. **Raguraman et al. 2021** demonstrated the co-pyrolysis of thermocol with neem de-oiled cake and waste polythene in a 1:2 ratio, producing pyrolysis oil blended with diesel and tested in diesel engines, resulting in reduced emissions and improved efficiency. **Onuh et al. 2020** utilized fly ash as a sustainable catalyst for municipal plastic waste pyrolysis and conducted thermal behavior analysis through thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) to determine the decomposition temperatures, weight loss patterns and glass transition properties.

Authors	**Yield**	**Temperature / Time**	**Reactions**	**Significance**
Nisar et al. 2023, Polystyrene waste with Nickel Oxide catalyst	5% catalyst, 84.68% oil yield	370°C / 70 minutes	Catalytic pyrolysis of plastic waste reduces activation energy and enhances oil quality.	Oil rich in fuel-range hydrocarbons like ethylbenzene, similar to diesel, gasoline and kerosene.
Mohapatra et al. 2021, Sugarcane Bagasse (SB) and Thermocol Waste (TW)	43% (SB) at 500°C, 66.75% (SB:TW = 1:3) at 550°C	400–600°C / 60–90 minutes	Co-pyrolysis method	Oils blended and used for running IC engines.
Ahmad et al.2020, Polystyrene with ethanol as solvent	84.7 wt% oil yield	290–370°C / 15 to 75 minutes	Thermal liquefaction using ethanol	GC–MS showed aromatics, alkenes, alkyls; effective oil conversion.
Raguraman et al. 2021, Neem deoiled cake and waste polystyrene	73% oil yield	550°C / 30 minutes to 2 hours	Co-pyrolysis approach	Converts agricultural and plastic waste into alternative fuels.
Onuh et al. 2020, Municipal Plastic Waste (MPW) with fly ash catalyst	87% (PP), 85% (HDPE)	500°C	Catalytic pyrolysis	Produced plastic fuel showed good engine performance and acceptable emissions in CI engine tests.

Researchers have employed various advanced analytical techniques to characterize waste thermocol and pyrolysis oils. TGA and DSC are widely used to study thermal stability, decomposition stages and heat flow characteristics, whereas GC-MS plays a pivotal role in identifying aromatic and aliphatic hydrocarbons in pyrolysis oil. Fourier Transform Infrared Spectroscopy (FTIR) provides insights into the molecular structures and functional groups, whereas Nuclear Magnetic Resonance (NMR) spectroscopy helps analyze the molecular arrangement and atomic geometry of hydrocarbons. Energy-dispersive X-ray spectroscopy (EDX) and Scanning Electron Microscopy (SEM) offer detailed insights into the surface morphology and elemental composition of the catalysts and degradation residues. These studies collectively confirm that pyrolysis, enhanced by thermal and catalytic approaches, is an effective method for converting waste thermocols into valuable hydrocarbons. The integration of EDX, SEM, elemental analysis, GC-MS and NMR ensures comprehensive physical and chemical characterization, helps to optimize pyrolysis conditions, improves catalyst efficiency and maximizes hydrocarbon yields.

The novelty of this study lies in the strategic use of RHC as a cost-effective and sustainable catalyst for the pyrolytic degradation of waste thermocol into fuel-grade hydrocarbons. Unlike The novelty of this study lies in the strategic application of RHC as a cost-effective and sustainable catalyst for the pyrolytic degradation of waste thermocol into fuel-grade hydrocarbons. Unlike conventional synthetic catalysts such as zeolites or metal oxides, RHC is an abundantly available agricultural byproduct that requires minimal processing, thereby significantly lowering both material costs and environmental impact. While both RHC and ZeC exhibit catalytic activity, RHC offers distinct advantages, including high silica content, favorable surface area and inherent porosity that contribute to enhanced cracking efficiency. These characteristics position RHC not only as a low-cost alternative but also as a technically promising catalyst for thermocol-to-fuel conversion. Furthermore, the use of RHC supports circular economy principles by transforming biomass waste into valuable resources, while reducing reliance on energy-intensive synthetic catalysts. These combined benefits distinguish the present study from earlier works and underscore its contribution to the development of more sustainable fuel production technologies.

Despite these advancements, certain challenges persist. Many existing studies continue to depend on electricity, LPG or other fossil fuels as heating sources for pyrolysis, which, although effective, generate carbon emissions and compromise the sustainability of the process. Moreover, the focus of prior research has largely remained on synthetic catalysts like zeolites, which, despite their high efficiency, are costly and environmentally burdensome. The potential of natural catalysts such as RHC remains relatively underexplored. As a renewable and eco-friendly alternative, RHC holds the potential to significantly enhance the environmental and economic sustainability of pyrolysis without sacrificing performance. Future research should therefore prioritize the development and optimization of bio-based catalysts, improve energy efficiency and explore renewable heating sources such as biogas to pave the way for a truly sustainable thermochemical waste management approach.

2. MATERIALS AND METHODS

2.1. Material

In this study, waste thermocols were collected from a nearby waste collection site. Rice fly ash was sourced from a rice production facility near a rice mill, whereas zeolite served as a feed additive for fish on aquaculture farms.

2.2. Characterization of Waste Thermocol

FTIR spectroscopy provides further insights into the molecular structure of waste thermocols. Fig. 1 shows the FTIR spectrum peaks observed in the waste for the thermocol, along with an explanation of each peak.

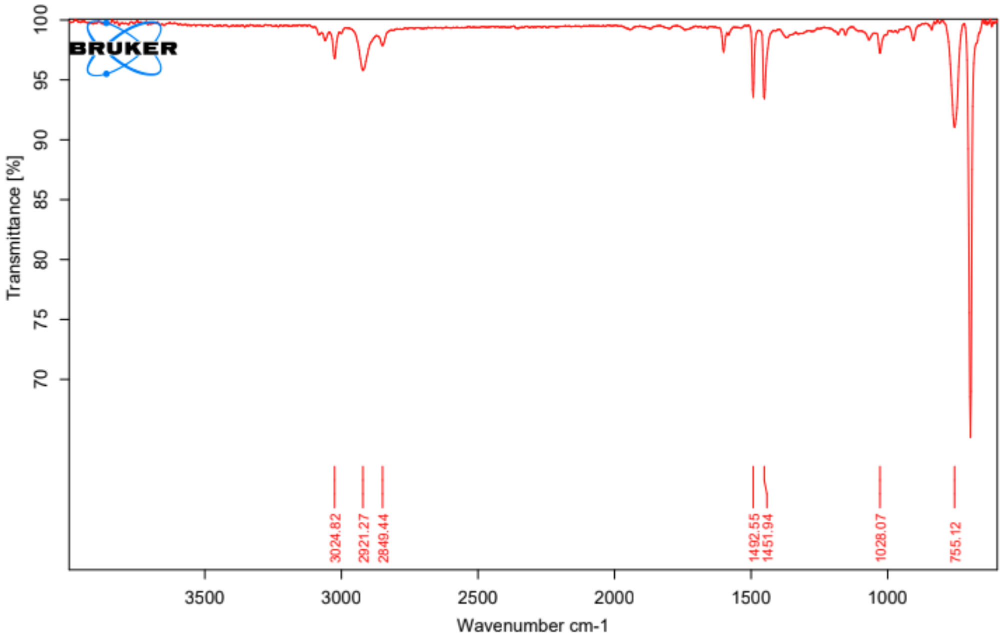

Fig. 1: FTIR Spectra of Waste Thermocol.

The peaks in the 3000–3100 cm^{-1} region, such as 3062.92 cm^{-1}, are attributed to the C-H stretching vibrations of aromatic rings, while the peaks near 2918.27 and 2849.14 cm^{-1} represent the aliphatic C-H stretching of CH_2 and CH_3 groups in the polymer backbone. The characteristic C=C stretching vibrations of the benzene ring are observed at 1492.95 and 1445.85 cm^{-1}, confirming the aromatic nature of polystyrene. Additionally, peaks at 1260.07 and 1126.07 cm^{-1} correspond to C-H in-plane and out-of-plane bending vibrations of the aromatic structure. The strong absorption at 725.12 cm^{-1} indicates C-H out-of-plane bending, a definitive feature of mono-substituted benzene rings in polystyrene. These results confirm that thermocol plastic is primarily composed of polystyrene, with distinct peaks that highlight its aromatic and aliphatic functional groups. The spectrum clearly identifies the structure of the material, with a combination of aromatic stretching and bending vibrations serving as important indicators of the expanded polystyrene.

2.3. Characterization of Rice Husk Catalyst (RHC) and Zeolite Catalyst (ZeC)

The EDX spectroscopy analysis of RHC Fig. 2, reveals high concentrations of silicon (Si), aluminum (Al) and oxygen (O), which are the primary components of RHC. The EDX spectra indicate the presence of various elements, including carbon (C), oxygen (O), sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), chromium (Cr), manganese (Mn), copper (Cu) and zinc (Zn). The intensity of the peaks, measured in counts, reflects the relative abundance of these elements. Silicon exhibits the highest peak, confirming its dominance, as RHC contain approximately 15–20% silica by weight.

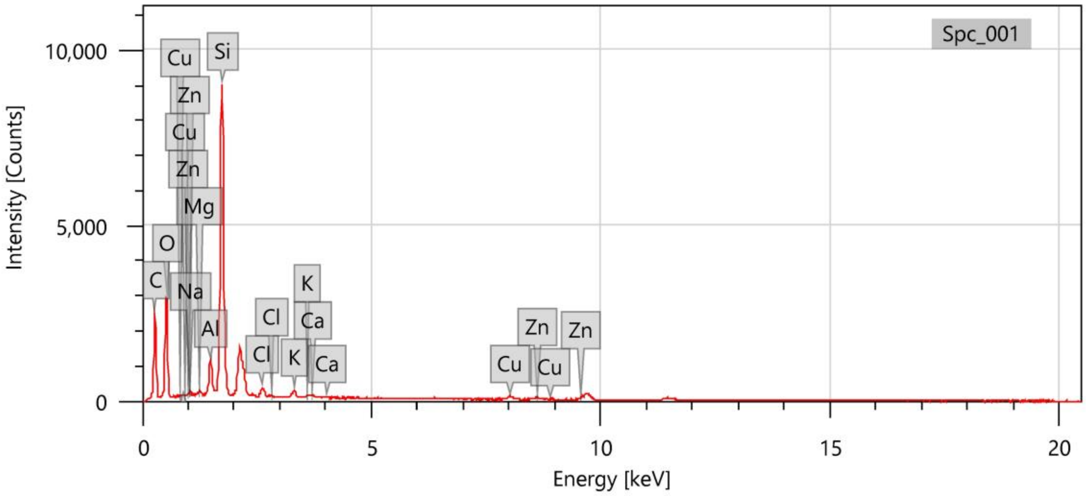

Fig. 2: EDX spectrum of the RHC.

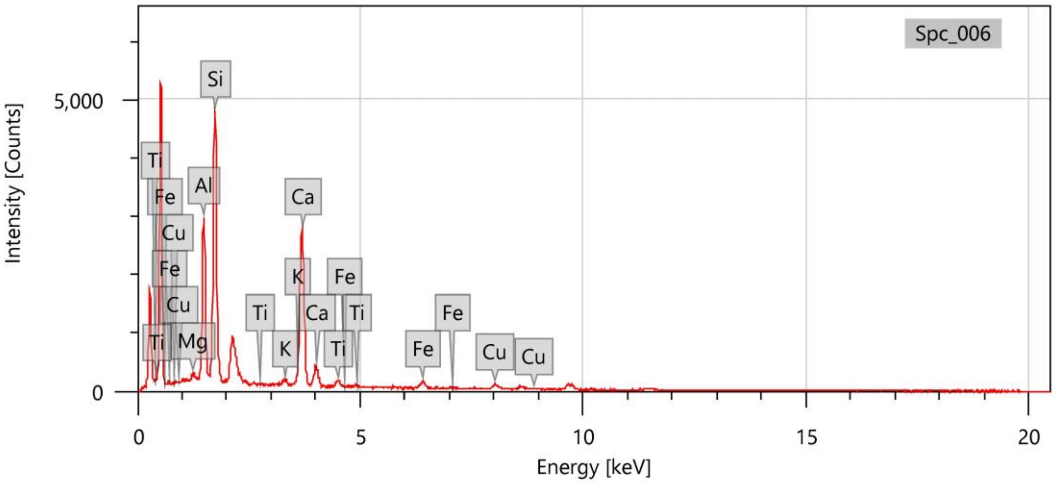

Fig. 3: EDX spectrum of the ZeC.

In the cracking process, Si and Al are crucial because of their porous structure, similar to zeolites, which are aluminosilicate minerals that are widely used in catalytic applications. **Cocchi et al. 2020** highlights the effectiveness of coal fly ash as a catalyst because, of its high silica (SiO_2) and alumina (Al_2O_3) content, which enhances the pyrolysis of plastic and biomass. This study aligns with sustainable energy efforts, demonstrating how coal fly ash optimizes the yield and quality of thermally decomposed oils.

The EDX spectrum of ZeC , Fig. 3, highlights key elements, including Si, Al, Ca, Cu, Zn, Cl and K, which are essential for catalytic activity in the degradation of thermocol (polystyrene). The Si and Al structures provides active acidic sites, making ZeC effective for breaking long polymer chains into smaller hydrocarbon molecules. The aluminum content (~20–25%) enhances acidity and, promotes polymer chain cracking. Calcium (Ca) acts as an exchangeable cation, improving the thermal stability of ZeC and participating in redox reactions that destabilize the polymer chains. The presence of Cu (~0.5–1.5%) and Zn (~0.2–1.0%) accelerates oxidative degradation by facilitating electron transfer, leading to faster polymer breakdown into gaseous products. Chlorine (~0.1–0.5%) aids in dechlorination reactions, while potassium (~0.5–2.0%) contributes to the conversion of short-chain polymers into smaller hydrocarbons. The combination of these elements enhances the catalytic efficiency of ZeC. Its porous nature provides active sites for polymer protonation, making the chains more susceptible to cracking. The redox activity of Cu and Zn significantly accelerated thermocol degradation and increased the gas production rates. Thus, ZeC is a highly effective catalyst for polymer decomposition, particularly for gas-phase reactions.

2.4. Experimental Procedure

Figure 4 illustrates the setup of a biogas-fired waste plastic oil extraction plant, specifically designed for the pyrolytic degradation of waste thermocol using biogas as the primary heat source. At the heart of the system is a cylindrical stainless-steel reactor with a diameter of 1300 mm, engineered to enable the catalytic cracking process. Positioned directly beneath the reactor is a biogas burner that provides the necessary heat, offering an environmentally sustainable alternative to conventional fossil fuels. To minimize heat loss and maintain optimal thermal conditions, the reactor is enclosed within a thin cylindrical metal shell, with glass wool insulation packed between the layers.

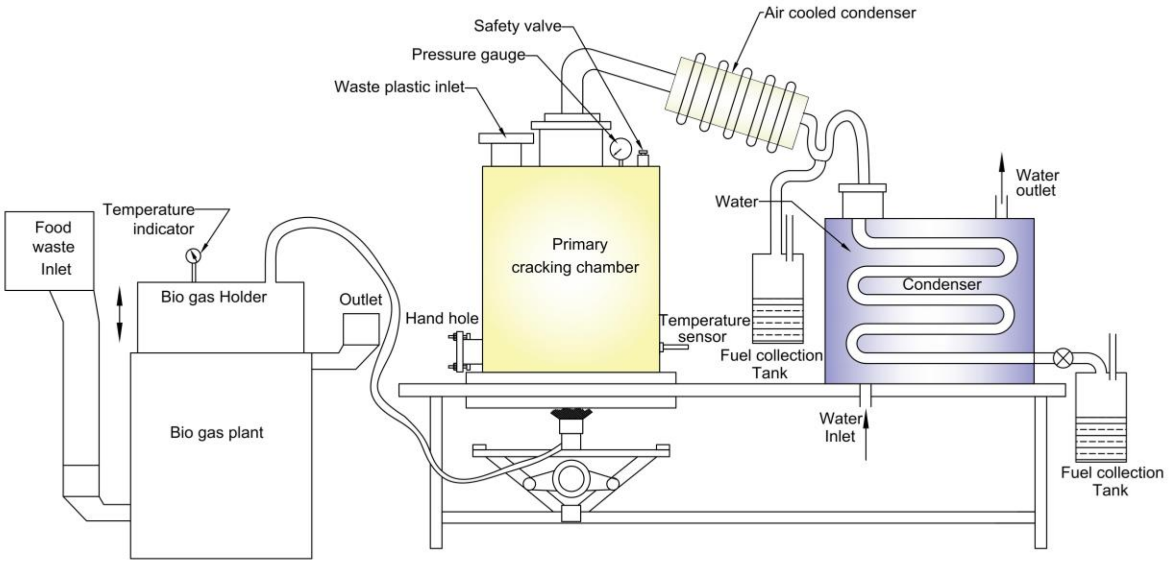

Fig. 4: Biogas-fired waste plastic oil extraction plant.

The top of the reactor is equipped with essential components for safe and efficient operation, including a safety valve rated to withstand pressures up to 500 kg/m², a pressure gauge, an airtight stopcock for feeding in the waste thermocol and an outlet to direct vaporized products toward the condensation system. At the bottom of the reactor, a hand hole fitted with an airtight stopcock allows for the removal of residual solid materials after the reaction. A temperature sensor is also installed at the base of the reactor to monitor and regulate internal temperatures throughout the process.

The condensation system operates in two stages. The first stage is an air-cooled condenser made of stainless steel, measuring 1500 mm in length with a pipe diameter of 20 mm. It condenses high-boiling hydrocarbon vapors into a diesel-like liquid. The second stage is a water-cooled condenser, consisting of a stainless-steel coil (1800 mm in length and 20 mm in diameter) housed within a water jacket measuring 300 mm in diameter and 500 mm in height. Water is circulated through the jacket from a bottom inlet to a top outlet to efficiently cool and condense the remaining low-boiling vapors into a petrol-like liquid.

The condensed hydrocarbon products are collected separately in two stainless-steel fuel tanks based on their boiling point. The high-boiling fraction, obtained from the air-cooled condenser, exhibits diesel-like properties, while the low-boiling fraction from the water-cooled condenser resembles petrol. Both fractions were stored in separate tanks. For this study, only the high-boiling oil collected from the air-cooled condenser was subjected to further physical and chemical analysis.

2.5. Analysing the physical and chemical characteristics of WTCOs

By analyzing the physical properties of the WTCOs collected from the air-cooled condenser and diesel, our methodology adhered to recognized standards for fuel testing, such as determining the density by IS-1448-P16, specific gravity by IS-1448-P-32 and kinematic viscosity by IS-1448-P25. The fire and flash points were determined using P-36, whereas the pour points were determined using IP-16. The gross calorific value was calculated based on the IS1448. The Centralized Instrumentation and Service Laboratory (CISL) within the Faculty of Science Physics Department captured SEM images and EDX analysis using a JEOL-JSM-IT 200. A Bruker Advance NMR spectrometer operating at 400 MHz was used to obtain ^{1}H and ^{13}C NMR spectra. The Department of Mining Engineering Research Lab at Annamalai University performed elemental analysis on CHNS, a model of various macrocubes made by Elementar Excellence in Elements.

3. RESULTS AND DISCUSSIONS

3.1. Degradation of Waste Thermocol

The Fig.5, illustrates the influence of different catalysts on the conversion of waste thermocol (polystyrene) into valuable products such as oil and gas through the degradation process of waste thermocol (polystyrene). The waste thermocol obtained from electronic packaging was processed by cutting it into uniform cubes of approximately 1 to 3 cm³ using ashablades. This physical preparation ensured consistent feedstock size for uniform thermal degradation. A precisely weighed quantity of this shredded thermocol was mixed with two different catalysts RHC and ZeC. A small quantity of water was lightly sprayed onto the mixture to prevent the airborne dispersion of the finely powdered catalyst and to enhance adhesion between the waste thermocol and catalyst. The mixture was then air-dried to remove residual moisture before pyrolysis.

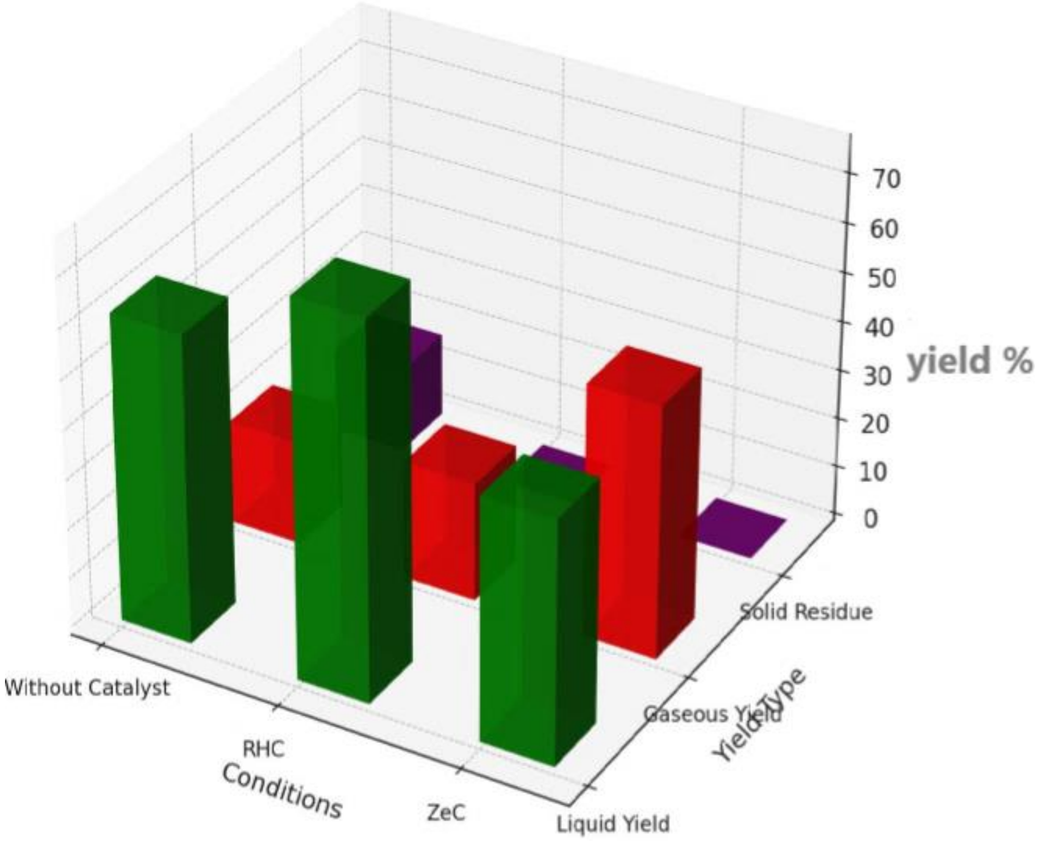

Fig. 5: Degradation of waste thermocol with and without catalysts.

The degradation were conducted under three conditions: thermal degradation without catalyst, catalytic degradation with RHC and ZeC. Biogas was used as the heating medium to ensure a low-emission, renewable energy source for the reaction. The degradation profiles and product yields varied distinctly under each condition. In thermal degradation without any catalyst or mixer of catatlyst and plastic (catalyst to polymer ratio = 0), oil formation began at 224°C and ceased at 410°C, with a total reaction time of 100 minutes. This condition produced 62% gained liquid (G_L), 21% gained gas (Gg) and 17% gained solid residue (Gs). Although capable of yielding usable oil, this method proved to be energy-intensive and inefficient due to extended reaction time and higher temperatures. Prior studies by **Nisar et al. (2019)** corroborated these findings by reporting an 82% liquid yield at similar temperatures, further highlighting the potential for catalytic enhancement.

With the use of RHC (cat/pol ratio = 0.1), the degradation process became more efficient, initiating at 190°C and completing at 370°C within 80 minutes. The G_L significantly increased to 76%, Gg was 24% and no solid residue remained. This improvement in catalytic performance is attributed to the high concentrations of SiO_2 (34.48%), CaO (36.50%) and Al_2O_3 (17.56%) in RHC, which actively participated in depolymerization and cracking reactions. Additionally, the CaO component reacted with water during heating to form $Ca(OH)_2$, which helped stabilize acidic intermediates and improve the final fuel quality. Park et al. 2019 reported 86%–99% liquid product and high gas yields in two-stage pyrolysis using a fluidized bed reactor.

In contrast, ZeC (cat/pol ratio = 0.1) demonstrated even faster degradation, with oil formation beginning at 170°C and ceasing at 320°C within 60 minutes. However, the $G_L$was reduced to 49%, while Gg increased to 51%. This is due to the high oxygen content (29.35%) and the presence of redox-active elements such as Cu and Zn in ZeC, which promote oxidative reactions over selective cracking. These elements facilitated secondary reactions and enhanced gas formation through redox pathways. Studies Kumar et al. 2020 studied the various catalysts used to convert plastic into oil and how polymer-to-catalyst ratios affect degradation products' yields and compositions.

The chemical mechanisms underlying these degradation processes differ significantly between the two catalysts

- Degradation with RHC catalyst

RHC contains a high proportion of SiO_2 and CaO, which actively participate in cracking the polystyrene chains into smaller hydrocarbons and gaseous products. The catalytic activity enhances depolymerization and secondary cracking reactions

$$(C_8H_8)_n \rightarrow \text{Small Hydrocarbons } (C_5H_{12}, C_6H_6, C_7H_8) + \text{Gases } (CH_4, H_2, CO, CO_2)$$

Additionally, CaO present in RHC reacts with moisture to form calcium hydroxide, which may also contribute to stabilization of acidic pyrolysis products:

$$CaO + H_2O \rightarrow Ca(OH)_2$$

This reaction reduces acidity and neutralizes unwanted by-products, improving the fuel properties of the resulting oil.

- Degradation with ZeC Catalyst

ZeC, rich in Al and Si in a crystalline framework, provide acidic active sites that promote oxidation and reforming reactions, favouring gas formation over liquid hydrocarbons.

Overall Reaction

$$(C_8H_8)_n \rightarrow CO_2 + CO + H_2 + C_1\text{–}C_4 \text{ Hydrocarbons}$$

In the presence of strong acidic and redox-active components like Cu and Zn found in ZeC, the polystyrene undergoes oxidative degradation rather than selective cracking.

Product yields were calculated as follows: The measurements were made in a similar manner for the uncatalytic reaction, reaction using cat/pol = 0.1. The measurements for degradation of waste thermocol were made in a similar manner.

The gains of solid, liquid and gaseous products are denoted as G_S, G_L and G_g, respectively. Let the weights of solid material remaining in the reactor after the reaction as W_P Let the weight of catalyst be W_c.

Weight of solid product $(W_S) = W_P - W_c$

Let the weight of liquid be W_L . The values of W_P, W_C, W_S and W_L are expressed in g

Weight of polymer taken =1 kg = 1000 g

$$G_S = \frac{W_s}{1000} \times 100 \qquad (\%)$$

$$G_L = \frac{W_L}{1000} \times 100 \qquad (\%)$$

$$G_g = (100 - G_s - G_L) \qquad (\%)$$

The values of Gs, G_L,and Gg were determined as part of the analysis and these calculations confirmed that the choice of catalyst plays a critical role in influencing product distribution, reaction temperature and overall energy efficiency. RHC is more suitable for maximizing liquid fuel production, while ZeC favors gas generation. The redox activity and porosity of ZeC make it effective for producing syngas, while RHC's balanced composition supports stable oil generation with minimal energy consumption. These findings underscore the importance of tailoring catalysts based on desired end products and provide valuable insights for advancing waste-to-energy technologies.

3.2. Evaluating RHC as a Function of Catalyst

The SEM images and EDX spectra of RCH, both before and after the degradation process, as shown in Figure 6, confirm its catalytic role in the pyrolytic degradation of waste thermocol. The catalyst exhibits physical changes during the reaction while largely maintaining its chemical composition, underscoring its active involvement in the process. SEM analysis of the RCH catalyst prior to degradation reveals a highly porous and irregular surface structure. This morphology is ideal for catalysis, as the increased surface area enhances contact between the catalyst and the polymer, thereby improving the efficiency of polymer chain breakdown. The initially porous and irregular structure of the catalyst becomes smoother and more compact, indicating substantial interaction with the thermocol during the reaction. The reduced porosity and surface definition suggest that the catalyst has actively participated in the adsorption and subsequent breakdown of polymer chains. Similar structural transitions are observed in the SEM images of RHC, which also displays a highly porous surface before degradation and a smoother, less porous morphology afterward further confirming its catalytic activity.

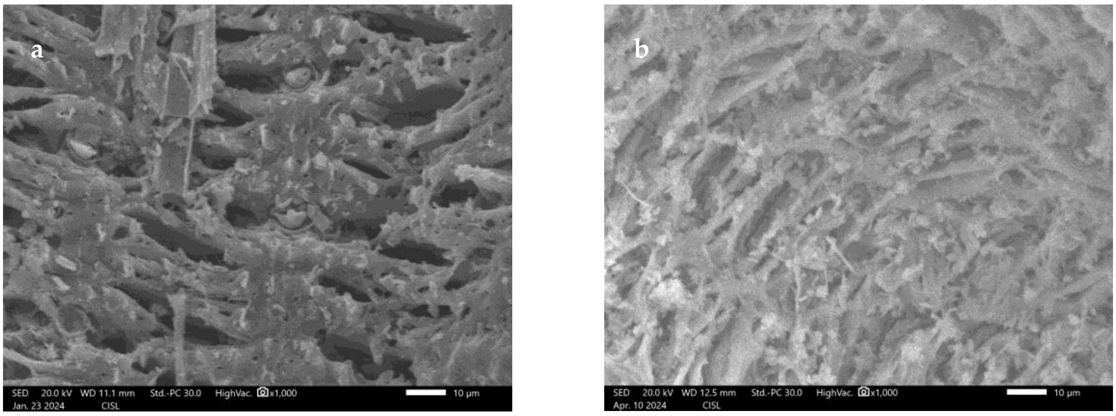

Fig. 6: SEM Analysis of RHC a) Before the degradation of RHC, b) After degradation of RHC cat/pol ratio=0.1.

These morphological alterations may be attributed in part to catalyst deactivation, wherein active sites become blocked by residues from the degradation process. Notably, changes in the catalyst's structure were especially pronounced at a catalyst-to-polymer (cat/pol) ratio of 0.1, highlighting the influence of catalyst loading on structural modifications. Similar findings were reported by **Premkumar et al. (2024),** who conducted SEM and EDX analyses of lignite fly ash and observed comparable morphological changes post-degradation across different cat/pol ratios.

- **SEM Analysis of ZeC**

The SEM image of ZeC Fig. 7, shows a highly porous and rough surface texture, which is characteristic of zeolite structures. ZeC's porous aluminosilicate structure with high surface area (300–800 m^2/g) enables efficient diffusion and interaction with thermocol. SEM shows a rough, porous surface with spherical aggregates. Zeolites are effective catalysts their micropores and mesopores, allowing polymer molecules to diffuse into their internal structure and interact with active sites more efficiently.

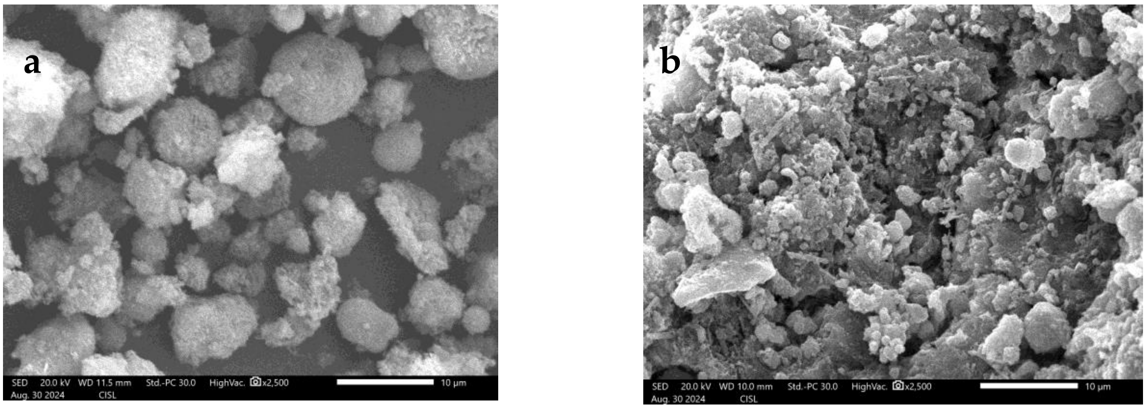

Fig. 7: SEM Analysis of ZeC a) Before the degradation of ZeC, b) After degradation of ZeC cat/pol ratio=0.1.

The silicon-aluminum framework of zeolites forms acidic sites that serve as proton donors during thermocol degradation. These acid sites weaken the carbon-carbon bonds in the polystyrene structure, initiating the polymer breakdown. This porous structure facilitates the diffusion of large thermocol molecules, thereby promoting their conversion into smaller hydrocarbons. As a result, degradation is more efficient, producing gaseous or liquid products depending on the reaction conditions. Zeolite's high surface area ensures maximum exposure of catalytic sites, enhancing their efficiency. Consequently, zeolite serves as an excellent catalyst for cracking polymer waste, including thermocols into valuable hydrocarbons.

- ***EDX Spectra of RHC***

The EDX spectrum Fig. 8, shows the elemental composition of RHC before and after degradation.

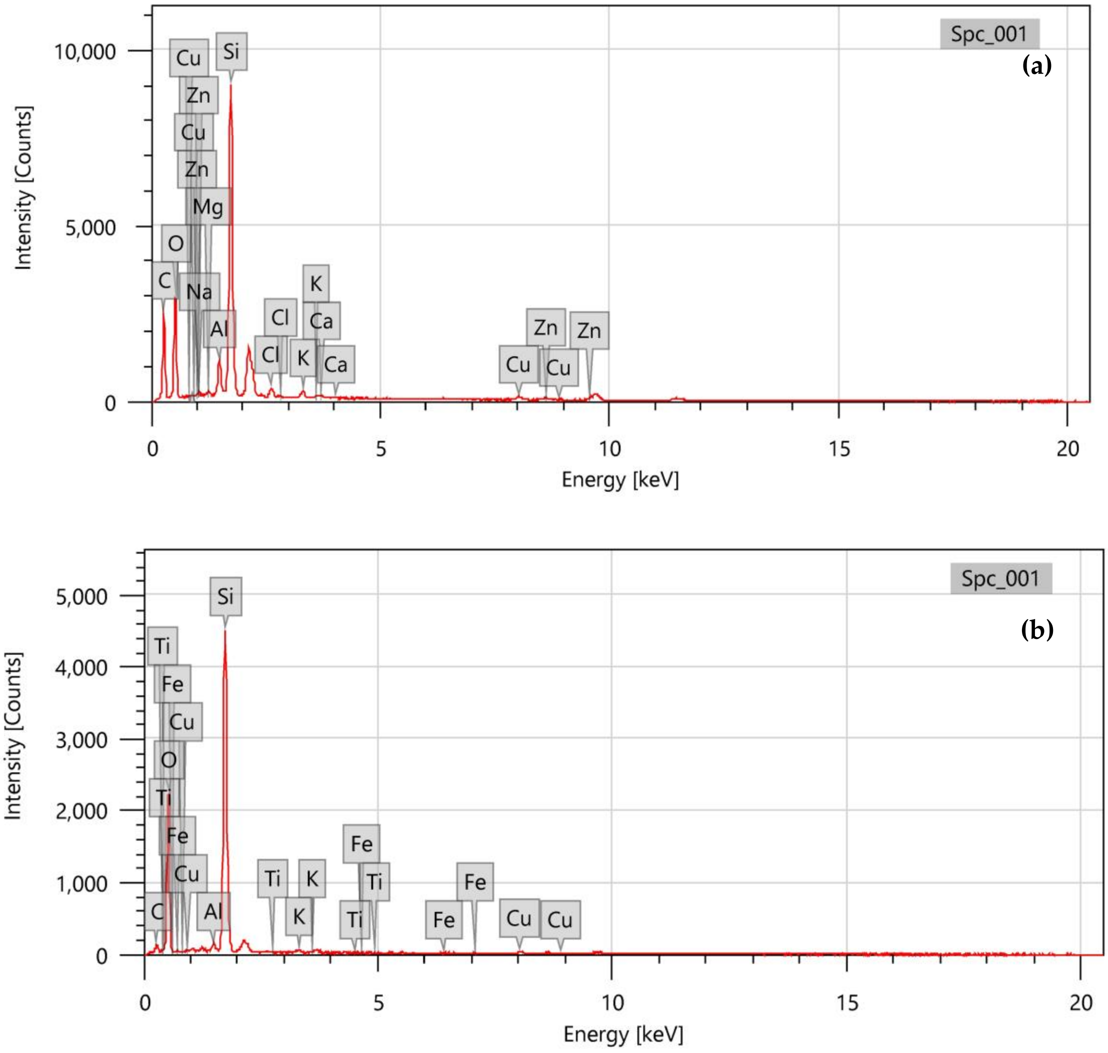

Fig. 8: EDX Analysis of RHC, a) Before the degradation of RCH, b) After the degradation of RCH, cat/pol ratio=0.1.

EDX analysis of the RHC catalyst before and after degradation reveals significant changes in elemental composition, further confirming its active role in the thermocol degradation process. EDX analysis reveals increased carbon (~12%) and altered oxygen (~10%) levels post-degradation, suggesting adsorption of degradation products. High silica content (~70–80%) offers thermal stability, while SEM-EDX results confirm RHC's catalytic role in lowering degradation temperature and energy barriers. Before degradation, the catalyst primarily consisted of silica (SiO_2) along with other mineral oxides naturally present in RHC. . After degradation, the chemical composition of RHC exhibited notable variations, indicating active participation in the degradation process. Initially, the catalyst consisted primarily of silica (SiO_2: ~70–80%) and other mineral oxides derived from the RHC. After degradation, the spectra revealed changes in the elemental intensities, suggesting the incorporation of polymer fragments or the presence of degradation residues.

The smoother and less porous surface indicates interactions with the degradation by-products that may block the active sites. Important elements identified in the EDX spectra included silicon (Si: ~75%), carbon (C: ~12%) and oxygen (O: ~10%). The high silica content contributes to the thermal stability, ensuring that the catalyst has high degradation temperatures. The silica component reduces the degradation temperature and lowers the energy barrier for the thermocol breakdown. Carbon and silicon interactions during combustion further aid in the transformation of molecules into simpler compounds, thereby reducing solid residues. SEM and EDX analyses confirmed significant post-degradation changes on the catalyst surface, suggesting physical adsorption or chemical interactions with the degradation products. This results in a more efficient breakdown of waste thermocol into liquid hydrocarbons, minimizing residual solid and gas formation. According to **Emmanuel et al. 2021,** coal fly ash (CFA) contains SiO_2 (~50–60%), further supporting its catalytic role in polymer degradation.

- ***EDX Spectra of ZeC Before and After Thermocol Degradation***

The EDX spectra of ZeC Fig. 9, before and after the thermocol degradation provided clear evidence of its catalytic effectiveness. EDX reveals key catalytic elements (Si, Al, Mg, K, Ca, Zn). Post-degradation, increased Fe, Cu and Ti levels suggest active redox and cracking roles. A reduced Si peak indicates structural changes. These features confirm ZeC's effectiveness in acid-catalyzed and redox-driven thermocol degradation. Post-degradation EDX of ZeC shows increased Fe (3–7%), Cu (1–2%) and Ti (1–3%), indicating their active role in the degradation process. These metals act as redox sites, aiding in electron transfer and reducing activation energy for polymer breakdown. Ti enhances catalyst stability and supports secondary cracking. The changes confirm chemical interaction between ZeC and thermocol, highlighting its efficient catalytic performance in plastic waste degradation.

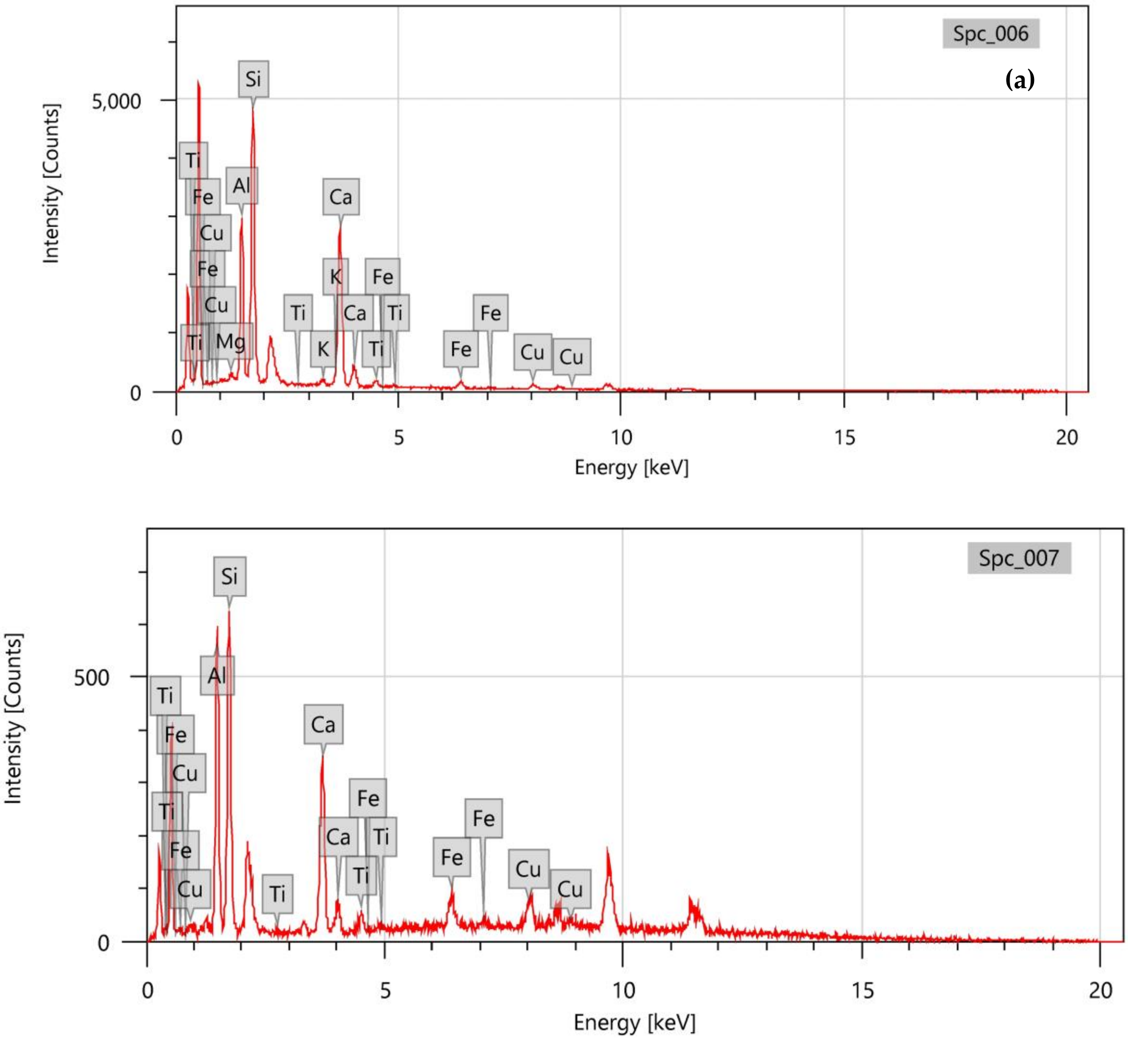

Fig. 9: EDX Analysis of RHC, a) Before the degradation of RCH, b) After the degradation of RCH, cat/pol ratio=0.1.

The catalytic efficiency of ZeC, as evidenced by changes in the elemental composition and peak intensities, highlights its suitability for polymer waste management, particularly for degrading thermocol as a sustainable fuel alternative.

3.3. Comparison of physical properties of WTCOs from air-cooled condenser and diesel

The Fig.10, illustrates the physical properties of WTCOs derived from RHC and ZeC catalysts compared with diesel, demonstrating their potential use in IC engines. The density of RHC-derived WTCO (8.12 g/dL) is slightly lower than diesel (8.2 g/dL), enhancing fuel atomization, while ZeC-derived WTCO (8.24 g/dL) is marginally higher, indicating slightly reduced injection efficiency. The kinematic viscosity of RHC-derived WTCO (1.96 mm²/s) is lower than diesel (2.5 mm²/s), promoting better atomization and combustion efficiency, whereas ZeC-derived WTCO (2.7 mm²/s) may slightly hinder atomization. The flashpoint and fire point values for RHC-derived WTCO (59°C and 70°C) indicate improved safety over diesel (43°C and 62°C), whereas ZeC-derived WTCO shows high flash point 82°C and fire point 90°C due to its rich aromatic content, confirmed by CHNS analysis with a carbon-to-hydrogen ratio of 8.14, GC-MS showing the presence of high-boiling aromatic compounds and NMR indicating an aromatic hydrogen ratio of 0.48. Its higher calorific value of 43 MJ/kg and thermal stability make it safer and more energy-dense than diesel. The calorific value of RHC-derived WTCO (42.8 MJ/kg) exceeds diesel (42.3 MJ/kg), whereas ZeC-derived WTCO (43 MJ/kg) suggests a higher energy release. The cetane number of RHC-derived WTCO (50) matches that of diesel, whereas ZeC-derived WTCO (51) improves ignition quality.

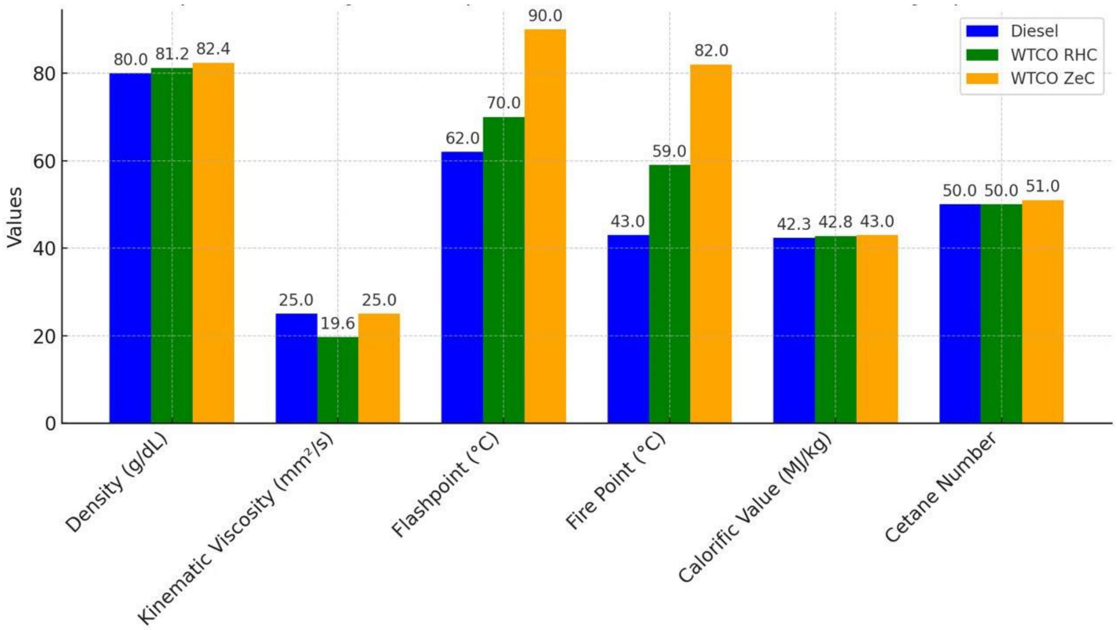

Fig. 10: Comparison of physical properties of WTCOs and Deisel

RHC-derived WTCO, with lower density, viscosity and balanced hydrocarbon composition, supports efficient combustion and reduced emissions, whereas ZeC-derived WTCO, with higher viscosity and aromatic content, may increase soot but enhance ignition quality.

3.4. Chemical Analysis of WTCO

The chemical analysis of the WTCOs was carried out by elemental analysis, GC-MS and NMR Spectrum.

- ***Elemental Analysis of WTCO Using RHC and ZeC Catalysts***

Elemental analysis of WTCO determined the weight percentages of carbon (C), hydrogen (H) and oxygen (O) in the samples, as shown in Table 1. Hydrocarbons typically consist mainly of C and H, with combined weight percentages approaching 100%. The carbon-to-hydrogen (C/H) ratio varied according to the compound type. Aliphatic compounds generally have a C/H ratio below 6, while aromatic compounds exhibit significantly higher ratios, such as benzene (12) and toluene (10.5).

Table 1: Elemental Analysis of WTCO using RHC and ZeC.

Sl. No.	Parameter	WTCO used RHC	WTCO used ZeC
1	C	85	86.3
2	H	11.1	10.6
3	C+H	96.1	96.9
4	C/H ratio	7.65	8.14

The WTCO obtained using RHC contained 85.0% C, 11.1% H and 3.9% H. The higher oxygen content in RHC-derived WTCO suggests a greater presence of alcohols. The C/H ratio was 7.65 indicates the presence of both aliphatic and aromatic compounds. The WTCO obtained using ZeC contained 86.3% C, 10.6% H and 3.1% O. The C/H ratio is 8.14, confirming a higher proportion of aromatic compounds. The higher carbon content aligns with the expected dominance of aromatic hydrocarbons, because aromatic compounds generally have higher carbon ratios than aliphatic hydrocarbons. A higher C/H ratio in ZeC-derived WTCO indicates a greater aromatic content, making it more prone to soot formation. In contrast, RHC-derived WTCO has a balanced composition, making it more suitable for combustion applications. These findings align with those of **Boubacar Laougé et al. (2019),** who reported similar C/H ratios in pyrolysis oils derived from aromatic-rich feedstocks, thereby confirming the presence of large aromatic hydrocarbons in ZeC-based WTCO. These results indicate that ZeC catalysis enhances aromatic hydrocarbon production, whereas RHC promotes a mix of aliphatic and aromatic hydrocarbons, improving fuel quality and combustion efficiency.

- ***Analysis of the WTCO degradation using RHC Catalyst by GC-MS***

The GC-MS analysis of the WTCO produced using RHC as a catalyst revealed the presence of many aliphatic and aromatic compounds. In contrast, WTCO produced using the ZeC catalyst exhibited a greater concentration of aromatic compounds. The major compounds identified in RHC obtained WTCO, are shown in

Fig.11. Although both catalysts, ZeC and RHC, produced oils with similar aromatic compounds, there was a significant difference in the amount and variety of aliphatic compounds produced by each catalyst. More aliphatic compounds were produced when RHC was used as the catalyst than when ZeC was used.

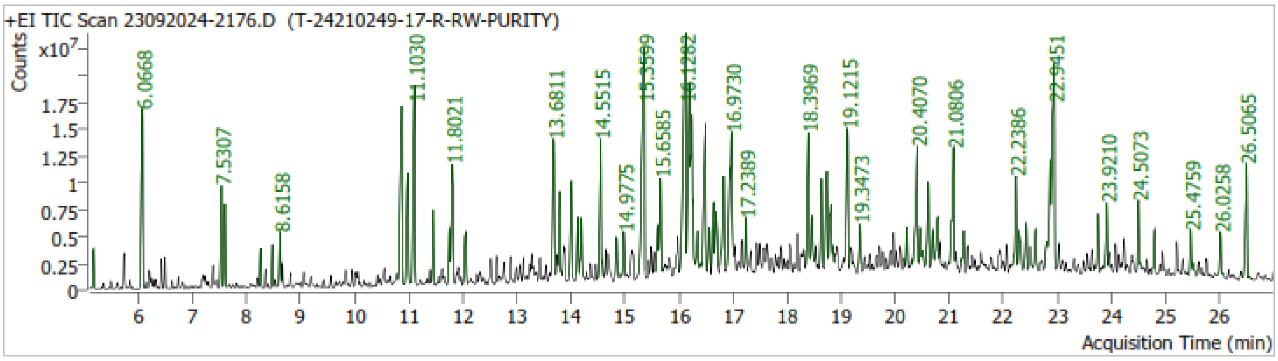

Fig. 11: GC-MS Spectrum of WTCO utilizing RHC as a catalyst.

Considering the higher abundance of aliphatic compounds in the RHC-catalysed process, RHC may possess a different catalytic mechanism that contributes to high-density polyethylene (HDPE) degradation in thermocols. The GC-MS results identified for RHC produces WTCO rich in long-chain aliphatic hydrocarbons, indicating its effectiveness in degrading aliphatic components such as HDPE. Aromatic compounds are present but in lower proportions. **Budsaereechai et al. 2019** also reported the formation of long-chain aliphatic hydrocarbons during the degradation of mixed plastics, particularly when HDPE was used as the catalyst.

The results indicate that the mixture of PS and HDPE is mainly formed from thermocol, wherein the aromatic property is introduced by the PS. In contrast, its aliphatic property is that of HDPE. In breaking down the thermocol with either RHC or ZeC, although both succeeded in breaking the thermocol, RHC appeared to be favourable for the hydrolysis conversion of HDPE because the WTCO yield was better than those of the other mixes. Regarding degradation in gaseous by-products, with the help of HDPE via ZeC degradant, its volume is higher than that in the cases of degradation utilizing RHC. Due to the strong acidic sites, ZeC sites are more likely to prefer cracking reactions, which form smaller gas molecules rather than larger aliphatic chains. The high gas yields obtained with ZeC could be because acidic catalysts favor the formation of smaller molecules. These differences in catalytic characteristics clearly indicate that the two catalysts are different. RHC produces more aliphatic compounds, which are typical for HDPE degradation and ZeC produces more gases due to more aggressive cracking. In thermocol degradation, the choice of catalyst can lead to substantial differences in the product distribution. Thus, RHC yields a liquid with better aromatic and aliphatic balance. GC-MS analysis of the WTCO from ZeC contains a higher concentration of aromatic compounds, including benzene derivatives and styrene-related structures, due to ZeC's strong acidic sites that favor the breakdown of polystyrene's aromatic backbone. The presence of aliphatic compounds in ZeC-derived WTCO is minimal. This indicates a clear difference in product distribution between catalystswhile ZeC promotes the formation of aromatic hydrocarbons, RHC favors the production of aliphatic compounds. Additionally, various alkenes, alcohols and esters were also identified in the oil. Some of the major chemical constituents found in the WTCO are illustrated in Fig 12.

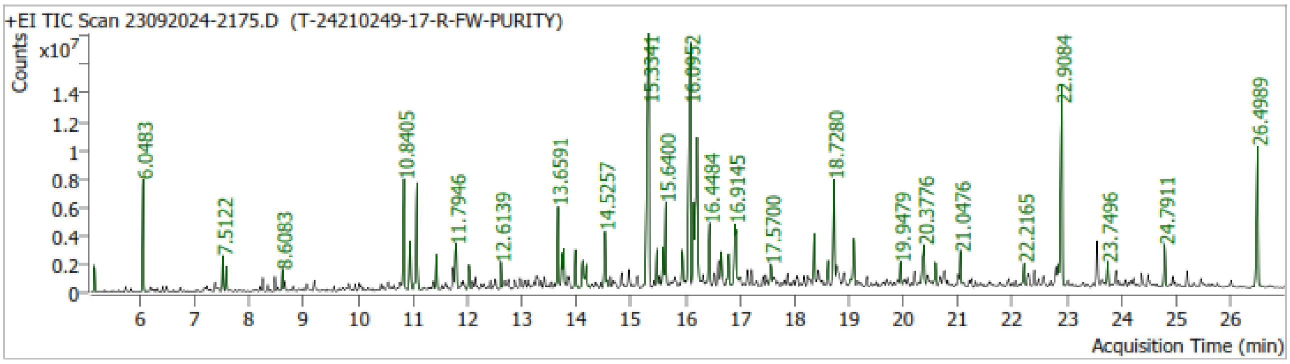

Fig. 12: GC-MS Spectrum of WTCO utilizing ZeC as a catalyst.

The dominance of aromatic compounds in the WTCO indicates that the thermocol used in this study mainly comprised polystyrene (PS). PS, which is a polymer with phenyl groups, has aromatic content. **Selvaganapathy et al. 2020** reported that aromatic hydrocarbons were detected in liquid fuels using PS waste GC-MS. The aromatic compounds identified from the degradation of PS were benzene (1-methylethyl), alpha-methyl Styrene, 1,2-diphenylcyclopropane and bis-benzene compounds. Despite the large amounts of aromatic compounds, there were also large amounts of aliphatic hydrocarbons. The thermocol likely contained a large amount of polyethylene, particularly HDPE, because large amounts of aliphatic compounds were present in the oil. Aromatic and aliphatic hydrocarbons are present and ZeC is used as a catalyst for pyrolysis. GC-MS analysis of the WTCO produced using RHC and ZeC catalysts will provide insight into the differences between these materials. RHC efficiently degrades HDPE; however, RHC catalyzes more aliphatic hydrocarbons, whereas ZeC favors aromatic hydrocarbons because PS is in the thermocol.

- ***NMR Spectra Analysis of WTCO Using RHC and ZeC Catalysts***

^{1}H NMR Spectra Analysis

A method for analyzing the chemical environment of hydrogen atoms or protons, in organic compounds is known as ^{1}H NMR spectroscopy. Different types of hydrogen atoms absorb energy at different chemical shifts, which are expressed in parts per million (ppm). Therefore, in a molecule such as CH_3CH_2Cl, the methyl group, with hydrogen atoms experiences a lower chemical shift than the methylene group and the relative size of the peaks in the spectrum represents the amount of each type of hydrogen. A 3:2 ratio is appropriate in this case.

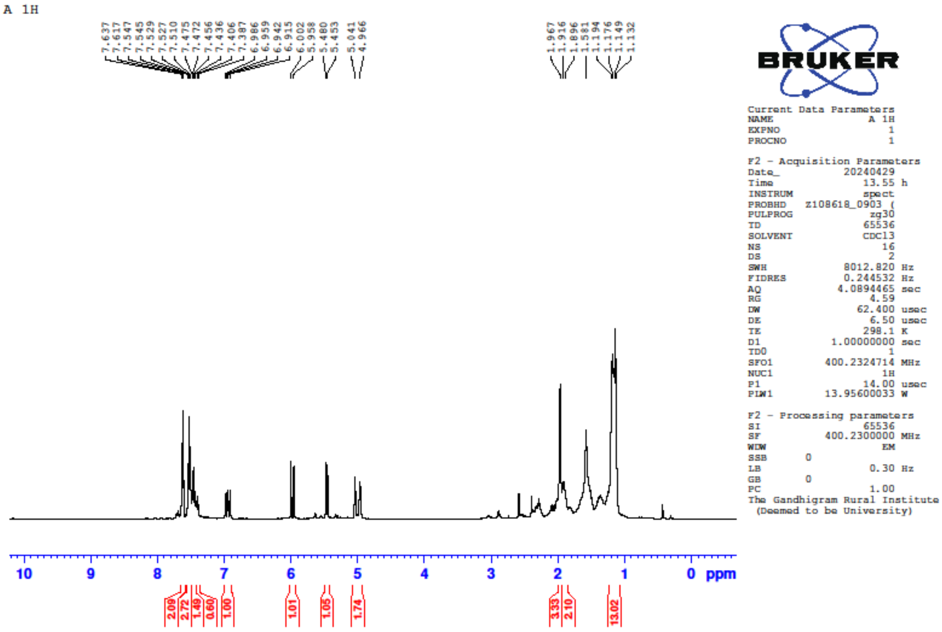

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Plate 1: ^{1}H NMR WTCO used RHC

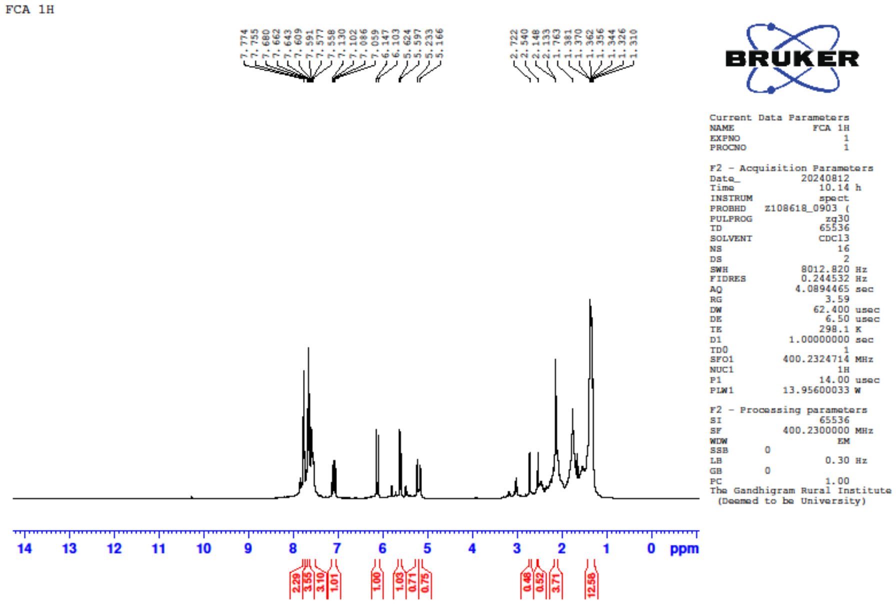

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Plate 2: ^{1}H NMR WTCO used Ze C

Aromatic hydrogens were attached to the aromatic carbons and exhibited chemical shifts that were more significant than those at 7 ppm. Nonaromatic hydrogens have chemical shifts between 0 and 6 ppm in aliphatic compounds. A compound containing aromatic hydrogens naturally contains aromatic hydrogens and the ratio of aromatic hydrogens to nonaromatic hydrogens provides information about the structure of the compound. 1,3-diphenyl propane, a standard thermocol degradation product, had a ratio of 1.67. The ratio was zero when no aromatic hydrogen was present in aliphatic compounds. The area under each signal in the ^{1}H NMR spectrum corresponds to the number of hydrogen atoms that contribute to the signal. In other words, for any aromatic compound, the ratio of aromatic hydrogen signals to nonaromatic hydrogen signals provides a quantitative measure of the relative amount of each type of hydrogen. Because of the absence of aromatic hydrogens in the purely aliphatic compounds, this ratio was zero. Plate 2 shows the ^{1}H NMR spectrum of WTCO obtained from the degradation of the thermocol using ZeC as the catalyst. Aromatic hydrogens were responsible for signals with chemical shifts more significant than 7 ppm, whereas nonaromatic hydrogens were responsible for signals between 0 and 6 ppm. The ratio of aromatic hydrogen signals to nonaromatic hydrogen signals in this spectrum is 0.48, which indicates that the WTCO obtained using ZeC contains a relatively higher proportion of aromatic compounds. According to Plate 1, the ^{1}H NMR spectrum of WTCO obtained using RHC as a catalyst has a different ratio 0.31 between aromatic and nonaromatic hydrogens. In comparison to WTCO produced with

Zeolite, RHC produced WTCO, which contained a lower proportion of aromatic compounds. This comparison shows that, the WTCO produced using ZeC as a catalyst contains a more significant proportion of aromatic compounds than the WTCO produced using RHC as a catalyst. According to GC-MS analysis, ZeC promoted the formation of more aromatic compounds during thermocol degradation. In contrast, RHC favors the formation of nonaromatic compounds (aliphatic compounds). The difference in the thermal degradation process highlights their distinct catalytic characteristics.

^{1}H NMR analysis of pyrolytic oils reveals hydrogen percentages of aromatic, olefinic and aliphatic compounds. CPO and WTCPO exhibit the highest aromatic protons (8.5–6.5 ppm) according to Pradhan et al 2020.

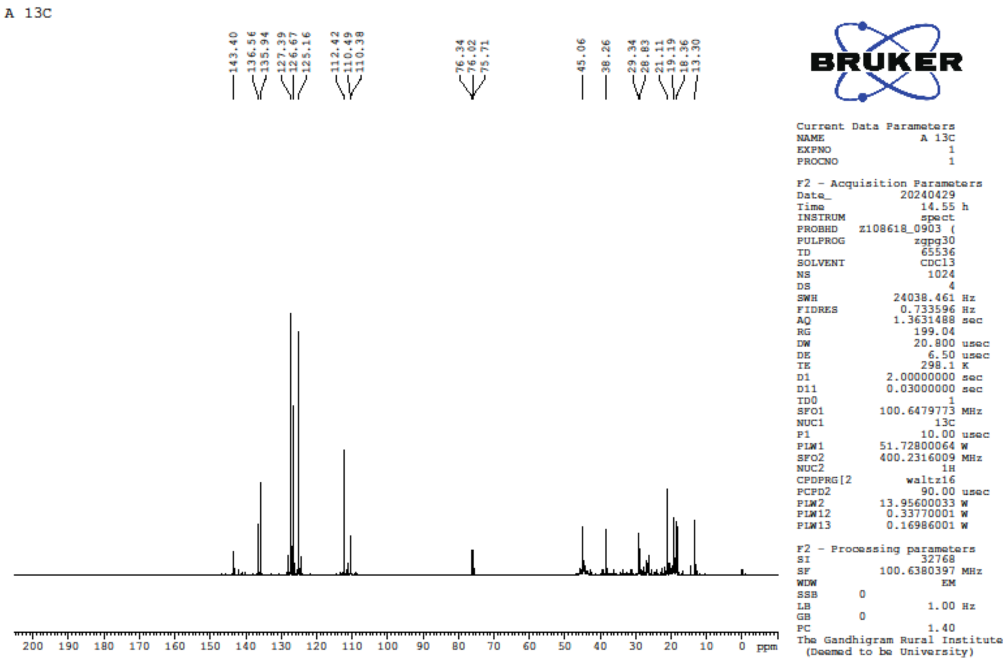

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Plate. 3: ^{13}C NMR WTCO used RHC

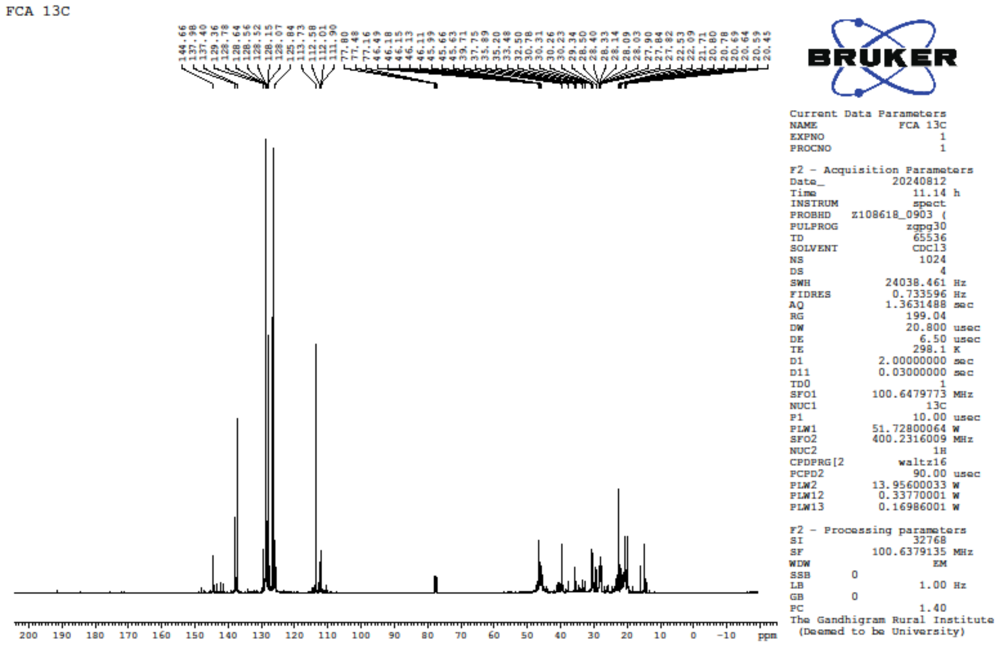

Plate. 4: ^{13}C NMR WTCO used Ze C

For NMR spectroscopy to be practical, the nucleus must have spin. Unlike 12C, the most common carbon isotope, 13C, which account for approximately 1% of carbon isotopes, has a spin of 1/2 and is used in ^{13}C NMR experiments. The chemical shifts of 13C were determined by the chemical environment in which the carbon atoms were located. The chemical shifts of aromatic carbons range between 120 and 150 ppm, those of olefinic carbons (found in alkenes) were 110 - 140 ppm and those of saturated aliphatic carbons (found in alkanes) were below 60 ppm. The plate 3, ^{13}C NMR spectrum of WTCO obtained using RHC showed both aromatic and aliphatic signals. The presence of aromatic and aliphatic compounds in WTCO corresponds to previous findings that RHC promotes the production of a mixture of hydrocarbons. The plate 4, ^{13}C NMR spectrum of WTCO obtained using ZeC as the catalyst also showed aromatic and aliphatic signals. ZeC promoted the production of more aromatic compounds during thermocol degradation, as evidenced by the presence of aromatic carbons in this spectrum. The ^{13}C NMR spectra of RHC and ZeC demonstrated that both catalyzed the formation of aromatic and aliphatic hydrocarbons. However, zeolite contains a higher proportion of aromatic carbons than other catalysts do. The results of these analyses confirmed the differences between the two materials in terms of their catalytic properties, as determined by ^{1}H NMR and GC-MS analyses.

4. DISCUSSION

4.1. Comparative Analysis of Chemical Composition in Diesel and WTCOs using NMR and GC-MS Techniques

The table:2 chemical analysis of Diesel, WTCO RHC and WTCO ZeC revealed differences in aliphatic and aromatic contents. ^{1}H & ^{13}C NMR and GC-MS were used to study their compositions. Diesel, which is predominantly aliphatic (0.5–2.5 ppm in ^{1}H NMR), ensures high stability and efficient combustion. The WTCO RHC, with an aromatic-to-aliphatic hydrogen ratio of 0.31, supports balanced combustion, whereas the WTCO ZeC (ratio 0.48), which is rich in aromatics, may increase soot formation. GC-MS confirmed the stability of diesel (hexadecane, octane), RHC’s aliphatic-alcohol mix of WTCO RHC and aromatic dominance. WTCO RHC shows potential for IC engine combustion, while the high aromatic content of WTCO ZeC may pose challenges.

Table 2: Comparison of various techniques used analyzed WTCO (RHC & ZeC)

Fuels	Findings (NMR)	Aromatic to Aliphatic Ratio	GC-MS Findings	Notable Compounds	Combustion Implications
Diesel	Aliphatic dominant (0.5–2.5 ppm)	Low	Long-chain alkanes	Hexadecane, Octane	Efficient combustion, low soot
WTCO RHC	Balanced aromatic-aliphatic signals	0.31	Aliphatic hydrocarbons and alcohols	Toluene, Pentane, Ethanol	Good combustion, moderate emissions
WTCO ZeC	Aromatic dominant (>6.5 ppm)	0.48	Rich in aromatic compounds	Benzene, Ethylbenzene, Toluene	High emissions, potential soot formation

This study presents a sustainable approach for managing non-recyclable waste thermocol by converting it into hydrocarbon fuels through a catalytic pyrolysis, significantly reducing environmental impact. The process eliminates open burning, thereby preventing the release of toxic pollutants like styrene vapors, carbon monoxide, dioxins and furans. Conducted in an oxygen-free environment, pyrolysis minimizes harmful emissions and the use of biogas as a renewable heat source enhances carbon neutrality. Economically, the process is viable due to the use of RHC, an agricultural waste, as a low-cost, reusable catalyst. The production cost of WTCO is estimated at ₹30–₹40 per litre well below conventional diesel prices offering substantial cost savings. The resulting fuel exhibits high brake thermal efficiency and lower emissions, making it commercially attractive. By valorizing both thermocol and biomass waste, the study aligns with circular economy principles and supports UN Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), demonstrating potential for scalable, decentralized waste-to-fuel solutions.

5. CONCLUSIONS

This work shows the potential of the catalytic pyrolysis as a sustainable method for converting waste thermocol into liquid hydrocarbon, significantly contributing to waste management and pollution reduction. The waste thermocol thermally decomposes between 224 and 410°C, yielding 62% liquid, 21% gas and 17% solid residue in 100 min. Using RHC as a catalyst the degradation process initiated and ceased between the temperature of 190–370°C and the processing time ceased at 80 min, increasing the liquid yield of 76%. Whereas ZeC further lowers the processing temperature in between 170–320°C. The entire degradation process completed at 60 mins, by producing lesser oil yield of 49% and higher yield of 51% of gaseous product. RHC promoted the formation of pentane, benzene and toluene, while ZeC increased gas production through oxidation. GC-MS and NMR analyses confirmed that RHC-derived WTCO contained both aliphatic and aromatic compounds, enhancing combustion efficiency, whereas ZeC-derived WTCO was aromatic-rich, favoring gas recovery. Both WTCO samples exhibit diesel-like properties, with calorific values of 42.8–43 MJ/kg and cetane numbers of 50–51, making them potential alternative technologies and environmental conservation.

To facilitate industrial-scale implementation, further research is essential in several key areas. First, the longevity, recyclability and potential deactivation of catalysts such as RHC and ZeC over multiple pyrolysis cycles need thorough evaluation to ensure long-term operational stability. Additionally, the impact of varying thermocol waste types differing in composition and quality on pyrolysis efficiency and fuel yield should be studied to maintain consistent fuel performance.

Comprehensive engine testing is also crucial. This should include combustion analysis, emissions profiling and durability testing using both WTCO blends and pure WTCO to assess compatibility with conventional diesel engines. Furthermore, process optimization is needed, focusing on continuous reactor design, effective heat recovery and seamless integration of biogas heating systems to enhance energy efficiency and scalability.

Environmental impact assessments through life cycle assessment (LCA) and techno-economic analysis (TEA) are necessary to quantify sustainability and economic feasibility. Incorporating in-situ monitoring tools such as thermogravimetric analysis (TGA) with real-time gas analysis could provide valuable insights into degradation kinetics and improve catalyst development. Catalyst modification through doping or composite formulations may enhance selectivity toward targeted fuel fractions. Addressing these areas will strengthen the role of this technology in circular economy models and sustainable energy systems.

6. PATENTS

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

Author Contributions: For research articles with multiple authors, include a brief paragraph outlining each author's contributions using the following format: "Conceptualization, V. Elangkathir.; methodology, V. Elangkathir.;.; validation, V. Elangkathir; investigation, P. Premkumar resources; writing—original draft preparation, V. Elangkathir.;.; writing—review and editing, C.G. Sarvanan.; visualization, S.Kumaravel.; supervision, P. Premkumar .;.; project administration, P. Premkumar. .; funding acquisition,. All authors have read and agreed to the published version of the manuscript." A." Authorship should be restricted to individuals who have made significant contributions to the research.

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Institutional Review Board Statement: "Not applicable."

Informed Consent Statement: "Not applicable."

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Conflicts of Interest: I, on behalf of all the authors of the manuscript titled Sustainable Waste Management and Environmental Pollution Control Through Catalytic Pyrolysis by Transforming waste thermocol into Alternative Fuels, hereby declare that there are no conflicts of interest related to this research work.

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