STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 3, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Catalytic Pyrolysis of Polymer Composites

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Abstract

The increasing accumulation of polymer-based waste, including polymer composites, is causing degradation of environment and hence becoming a big issue. In the present paper, the researchers have taken up the question and tried to find the solution in the form of catalytic pyrolysis which can be opted as potential substitute. By the application of catalytic pyrolysis, it is getting checked and analysed that whether application will lead to transformation of waste polymer composites. For the present research we have adopted methods to recycle the plastic waste like Pyrolysis and Gasification. In the paper Pyrolysis of Waste plastic has been through Flow Chart. In the results and discussion section of the paper, it is being shown that the pyrolysis process yields fuel oil which has properties similar to diesel. We have taken readings with catalyst such as Zinc oxide (ZnO), Sodium carbonate (Na2CO3) and Calcium carbonate (CaCO3). By comparing all yield reading we concluded, ZnO is more effective. The liquid fuels obtained exhibit properties comparable to conventional petroleum-based fuels. Additionally, the gaseous products, primarily consisting of syngas, can be further processed into value-added chemicals or used as a fuel source. The solid char, a carbon-rich residue, can be utilized in various applications, including activated carbon production, soil amendment, and as a fuel source. This research will add value to scientific community.

Keywords: Polymer composites, waste valorization, liquid fuels, char, environmental impact, catalytic pyrolysis

INTRODUCTION

The increasing accumulation of polymer-based waste, particularly polymer composites, has become a pressing global environmental concern. These materials, often discarded after their intended use, contribute to pollution and resource depletion. To address this issue, catalytic pyrolysis has emerged as a promising technology for the sustainable valorization of polymer composites. [1-2] Pyrolysis, a thermal decomposition process, involves the breakdown of complex polymeric structures into simpler molecules through the application of heat in the absence of oxygen. [3-5] By incorporating catalysts into the pyrolysis process, it is possible to enhance the efficiency of the reaction, increase product yields, and improve the quality of the resulting products.[6] Catalytic pyrolysis offers a sustainable pathway for converting waste polymer composites into valuable resources, such as liquid fuels, gases, and solid char. [7]

Polymer Composites: A Focus on Sustainability

Polymer composites, which combine the properties of polymers with reinforcing materials like fibers or fillers, have found widespread applications in various industries due to their superior mechanical and thermal properties. [8,9] However, the disposal of these materials poses significant environmental challenges. Catalytic

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Received Date: December 16, 2024
Accepted Date: February 05, 2025
Published Date: April 29, 2025

Citation: Girish N. Desai, Jagadish H. Patil, Pratima Khandelwal, Sudhindra Narayan Jalwadi, Sudhanva M Desai Catalytic Pyrolysis of Polymer Composites. Journal of Polymer & Composites. 2025; 13(Special Issue 3): S379–S389p.

pyrolysis provides a potential solution by breaking down the complex polymer matrix and releasing valuable components.[10]

By investigating the influence of various parameters, such as temperature, heating rate, and catalyst type, researchers can optimize the pyrolysis process to maximize the yield of desired products. The resulting liquid fuels can be refined and blended with conventional fuels to reduce dependence on fossil fuels. Gaseous products, such as syngas, can be used as feedstocks for the production of chemicals or as a fuel source. Solid char can be utilized as a carbon source for various applications, including activated carbon production and soil amendment.

Polymer Composites: A Growing Environmental Challenge

Polymer composites, comprising a matrix polymer reinforced with fibers or fillers, have revolutionized various industries due to their enhanced properties.[11] However, the widespread use and subsequent disposal of these materials pose significant environmental concerns. As polymer composites reach the end of their lifecycle, they contribute to the growing problem of plastic waste.[12]

The diverse range of polymer composites, incorporating various polymers and fillers, presents challenges in their recycling and disposal. Traditional recycling methods often prove inadequate for these complex materials. [13] Consequently, these composites often end up in landfills or are incinerated, leading to environmental pollution and resource depletion. The increasing accumulation of polymer composite waste necessitates the development of sustainable solutions for their management. Catalytic pyrolysis, a thermal decomposition process, offers a promising approach to convert these waste materials into valuable products. [14] By breaking down the complex polymer matrix and reinforcing fillers, pyrolysis can yield a range of valuable products, including liquid fuels, gases, and solid char. [15] These products can be further processed and utilized in various industries, contributing to a circular economy.[16]

Pyrolysis of waste plastic holds promise as a viable technology for converting plastic waste into valuable fuels, contributing to both waste management and energy sustainability goals. Continued research and innovation in this field are crucial for realizing its full potential as a sustainable solution in the global effort towards a cleaner environment and energy independence. [17]

One of the main challenges in the thermal degradation of polymer composites is their complex structure, which includes reinforcing materials like fibers and fillers. These composites do not break down easily using traditional recycling methods, leading to issues with waste accumulation and disposal.[18] Without a catalyst, pyrolysis requires higher temperatures to initiate degradation, making the process energy-intensive. Additionally, selecting the right process conditions, such as temperature, heating rate, and residence time, is crucial for maximizing product yield. The presence of different polymers and additives further complicates the recycling process, often requiring tailored catalytic solutions.[19]

METHODOLOGY

There are many methods to recycle the plastic waste like,

1. Pyrolysis
2. Gasification

We have used pyrolysis method as shown in Figure 1 to produce the fuel oil which is value added product.

EXPERIMENTAL PROCEDURE

Material Preparation

Collect and sort the waste plastic, ensuring it is clean and free from contaminants such as milk, curd. Before shred it should be dried by sunlight or fan. Shred the plastic into small pieces or granules for better heat transfer and pyrolysis efficiency and measure 1 Kg of waste plastic cover for Experiment shown in Figure 2.

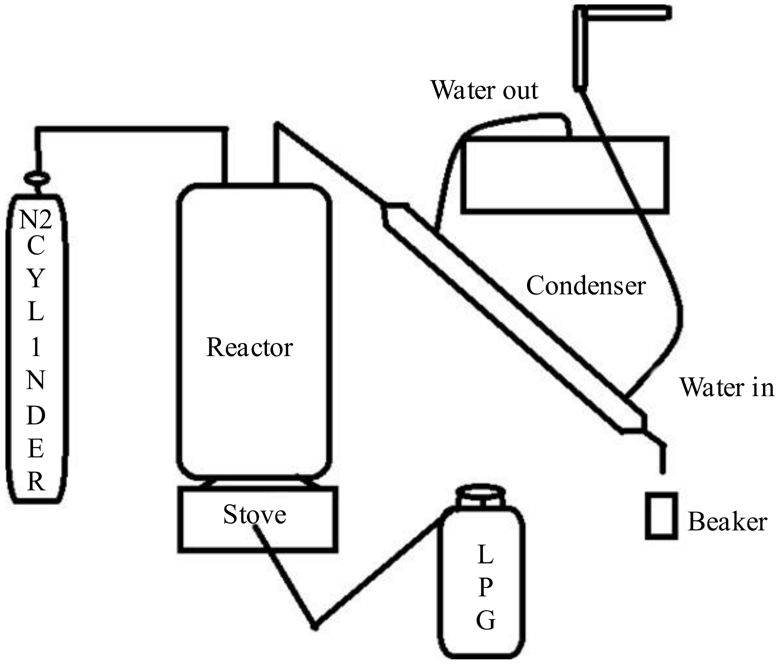

Figure1. Flow chart of pyrolysis of waste plastic.

Equipment Setup

Set up a pyrolysis reactor capacity of 35 liters and made of mild steel. It should reach high temperatures in the absence of oxygen. Connect the reactor to a heating source, such as LPG gas Stove. Install a condenser to collect and condense the pyrolysis vapors. Connect the Nitrogen gas Cylinder to the Reactor shown in Figure 1.

Experimental Parameters

Determine the desired pyrolysis temperature range based on the characteristics of the waste plastic and catalyst being used. Typical temperatures range from 200°C to 400°C. Determine the residence time or reaction time, which is the duration for which the plastic waste is subjected to the pyrolysis conditions. This can vary depending on the reactor design and process requirements.

Pyrolysis Process

Load the prepared waste plastic into the pyrolysis reactor, ensure it, where plastic cover is mixed with catalyst or without catalyst. Purge the reactor with an inert gas, such as nitrogen, to remove any residual oxygen and create an oxygen-free environment. Begin heating the reactor to the desired pyrolysis temperature and measure the temperature by Pistol thermometer for every 15minutes. Collect the pyrolysis vapors and direct them to the condenser or cooling system to condense them into liquid or gaseous products shown in Figure 3Separate The Condensed Products Into Desired Product Such As Fuel Oil. This Process Takes 3-4 Hours.

Product Analysis

Analyze the collected liquid oil for their composition, calorific value, and other relevant properties. Conduct further testing and characterization of the obtained fuel products to assess their quality and potential applications.

Data Collection and Analysis

Record and analyze data related to the pyrolysis process, including temperature profiles, yields of different products, and time shown in Figure 3 and 4. Compare the results with the desired objectives and evaluate the efficiency and effectiveness of the pyrolysis process.

Figure 2. Shredded plastic cover

Figure 3. Reactor closed.

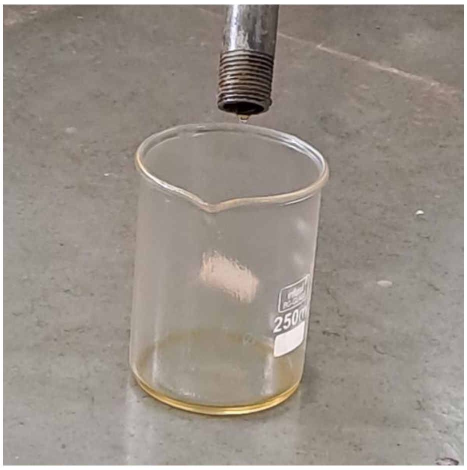

Figure 4. Oil flow.

To address these challenges, specific criteria were used to select polymers and catalysts for the study. Waste plastic composites were chosen as the feedstock, ensuring they were clean and free from contaminants. The study tested three catalysts—Zinc oxide (ZnO), Sodium carbonate (Na_2CO_3), and Calcium carbonate ($CaCO_3$)—to determine their effectiveness in enhancing pyrolysis efficiency and improving product yield. ZnO and Na_2CO_3 demonstrated significantly higher catalytic activity, reducing the reaction temperature and increasing fuel oil yield, whereas $CaCO_3$ was less effective in promoting polymer breakdown.

RESULTS AND DISCUSSION

The pyrolysis process yields fuel oil which has properties similar to diesel. The physical and chemical properties(Figure8) of pyrolysis oil are analyzed. In this process, we have taken readings with catalyst and with catalyst such as Zinc oxide (ZnO), Sodium carbonate (Na_2CO_3) and Calcium carbonate ($CaCO_3$). By comparing all yield reading we concluded, ZnO is more effective. The results obtained are tabulated as below.

1. Physical properties of pyrolysis oil without catalyst
2. Temperature and yield of all catalyst
3. Time and yield for all catalyst
4. Catalysts and Yield
5. Chemical properties of pyrolysis oil
6. Graph of Temperature versus Yield
7. Graph of Time versus

In this process, we got 443 ml of pyrolyzed oil and by firing 2ml of pyrolyzed oil, we concluded that it is flammable and burned for 2-3 minutes.

Table 1 indicates Physical properties of pyrolysis oil without catalyst whereas Figure 5. Amount of oil collected in ml with and without catalysts. Fig6. represents Graph of Temperature versus Yield.

Table1. Physical properties of pyrolysis oil without catalyst.

Physical properties	Pyrolytic oil	Diesel
Density (Kg/m^3), 30°C	933.2	820 - 860
Kinematic Viscosity at 40	6.30	3 - 5
Flash Point °C	39	≥ 55
Pour Point °C	-8	-40 to -1
Gross Calorific Value (MJ/Kg)	38.98	42 - 44

The physical properties of pyrolytic oil are in the range of standard diesel

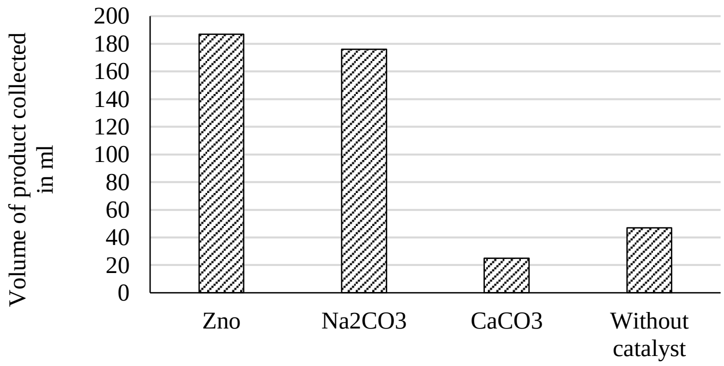

Figure 5. Amount of oil collected in ml with and without catalysts.

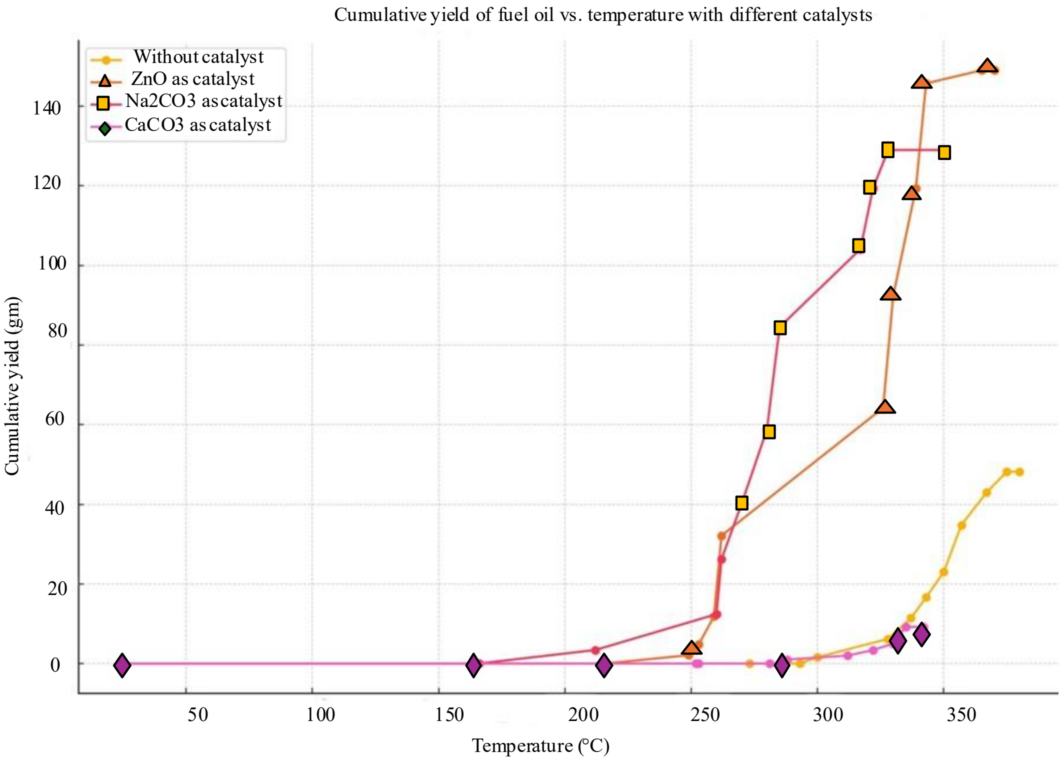

Figure 6. Graph of temperature versus yield.

GRAPH ANALYSIS AND INFERENCES

The graph shows the cumulative yield of fuel oil as a function of temperature for different catalytic conditions (ZnO, Na_2CO_3, $CaCO_3$) and without a catalyst. Each curve represents the cumulative yield in grams across increasing temperature ranges, highlighting how different catalysts affect the overall process.

Without Catalyst

The cumulative yield without a catalyst is meagre, with a maximum yield of 48.2 g at 380°C. The yield increases only after 300°C, showing that higher temperatures are required to initiate the reaction without a catalyst.

ZnO as Catalyst

ZnO significantly enhances the yield, particularly between 250°C and 370°C. The cumulative yield rapidly increases from 2.1 g at 249°C to 149.03 g at 370°C, indicating that ZnO is highly effective within this temperature range.

Na_2CO_3 as Catalyst

Na_2CO_3 also shows a marked increase in yield starting around 250°C, reaching 129 g at 350°C. The catalyst is effective over a broader range of temperatures, making it a strong option for maximizing yield.

$CaCO_3$ as Catalyst

$CaCO_3$ is less effective, with minimal cumulative yield observed across the temperature range. A maximum cumulative yield of 9.2 g is achieved at 335°C, showing that $CaCO_3$ is the least efficient of the catalysts tested.

INFERENCES

Efficiency of Catalysts

ZnO and Na_2CO_3 significantly lower the activation energy required for the reaction, allowing for higher yields at lower temperatures than the catalyst-free process. $CaCO_3$, however, shows limited catalytic activity under the same conditions.

Melting Point of Plastics

Catalysts like ZnO and Na_2CO_3 will likely reduce the plastic feedstock's melting point, enabling decomposition and fuel oil production at lower temperatures. Without a catalyst, higher temperatures are needed to achieve similar results.

Yield of Fuel Oil

The use of ZnO and Na_2CO_3 results in substantially higher fuel oil yields, demonstrating these catalysts' effectiveness in breaking down plastics more efficiently. In contrast, the absence of a catalyst or the use of $CaCO_3$ leads to significantly lower yields.

Advantages and Disadvantages of Using Catalysts Advantages

Higher yields: Catalysts, especially ZnO and Na_2CO_3, greatly enhance the yield of fuel oil, making the process more efficient.

Lower operating temperatures: Catalysts enable the reaction to occur at lower temperatures, reducing energy costs.

Disadvantages

Cost: Catalysts can be expensive and may need to be replaced periodically.

Selective activity: Not all catalysts are equally effective, as seen with $CaCO_3$, which provides minimal yield improvement.

The production of fuel oil from waste plastics through pyrolysis and catalytic processes has garnered significant attention due to its potential to mitigate environmental issues associated with plastic waste. The cumulative yield data presented in the table 1 illustrates the impact of temperature and catalyst type on the efficiency of fuel oil production. Without any catalyst, the cumulative yield remains negligible across various temperatures, highlighting the limitations of thermal degradation alone. In contrast, the introduction of catalysts such as ZnO, Na_2CO_3, and $CaCO_3$ significantly enhances the yield, demonstrating the crucial role of catalytic processes in optimizing fuel production from plastics.

The data indicates that ZnO and Na_2CO_3 are particularly effective, with ZnO achieving a peak cumulative yield of 149.03 g at 365°C, while Na_2CO_3 reaches a maximum of 129 g at 328°C. This suggests that ZnO facilitates the breakdown of long-chain polymers and promotes the formation of liquid hydrocarbons, which are essential for fuel oil production. The Na_2CO_3 catalyst exhibits a broader effective temperature range, maintaining substantial yields even at lower temperatures compared to ZnO. This characteristic may offer operational advantages, such as reduced energy consumption and improved process sustainability.

Conversely, the $CaCO_3$ catalyst demonstrates limited effectiveness, yielding only 9.2 g at 342°C. This indicates that not all catalysts are equally beneficial, emphasizing the need for careful selection based on the specific waste plastic feedstock and desired product characteristics. The findings align with existing literature that underscores the advantages of catalytic pyrolysis, which increases yield and enhances the quality of the produced fuel oil by minimizing the formation of undesirable by-products. Moreover, the thermal degradation of plastics has been shown to produce fuels with properties comparable to conventional fossil fuels, making them viable alternatives for energy generation. Studies have reported that the calorific value of pyrolysis oil derived from waste plastics can be comparable to that of diesel, thus supporting its potential application in diesel engines and other energy systems. The integration of catalytic processes in pyrolysis addresses the challenges of plastic waste disposal. It contributes to developing sustainable energy solutions, aligning with the principles of a circular economy.

The experimental data demonstrates that catalysts, particularly ZnO and Na_2CO_3, significantly enhance the cumulative yield of fuel oil from waste plastics, underscoring the importance of optimizing process conditions to achieve efficient and sustainable energy recovery from plastic waste.

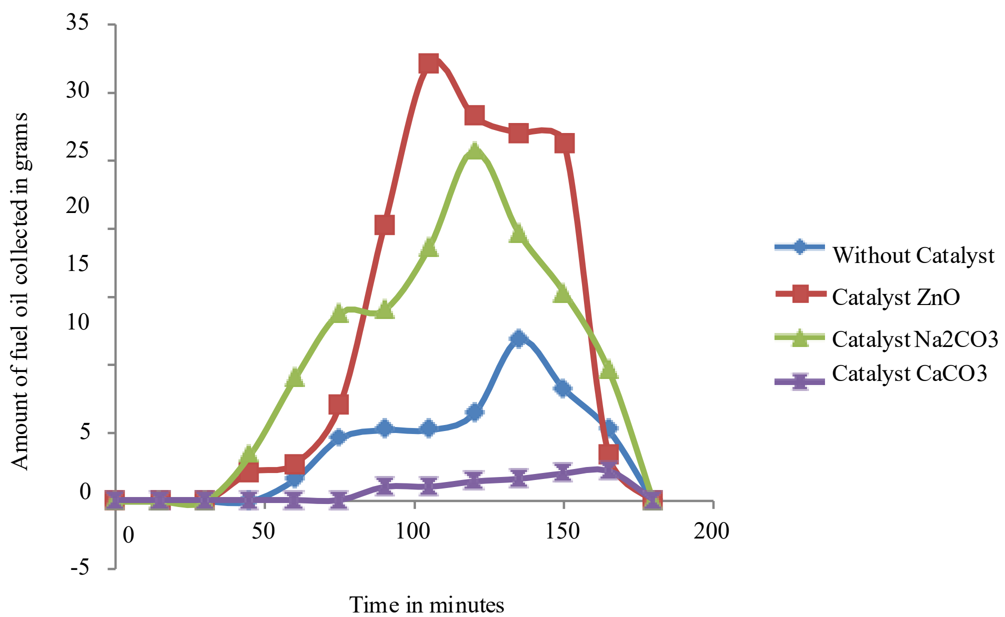

Figure 7. Graph of time versus yield.

Above graph shows that temperature increases mean while yield increases reaches maximum and decreases and reaches zero showing no condensate is collected.

Above graph(Figure 7) shows that time increases mean while yield increases reaches maximum and decreases and reaches zero showing no condensate is collected showing completion of reaction.

In catalytic conversion processes like converting waste plastic, the yield of the desired product (in this case, likely a liquid or gaseous fuel) is influenced by the catalyst used. Probable explanation, why different catalysts result in different yields, based on the data is

Role of Catalysts

Catalysts are substances that accelerate chemical reactions without being consumed themselves. They lower the activation energy required for the reaction to proceed, making it easier for reactants to transform into products. In the context of waste plastic conversion, catalysts can help break down the complex hydrocarbon chains in plastics into simpler molecules such as liquid fuels or gases.

Effect on Yield

The yield of the desired product (measured in ml in this case) depends on how effectively the catalyst promotes the breakdown of plastic molecules into the desired products. Higher yields indicate that the catalyst is more effective at converting the plastic into usable products (liquid or gas).

Interpreting the Data

ZnO (Zinc Oxide) and Na2CO3 (Sodium Carbonate) have higher yields (188ml and 178ml respectively) compared to CaCO3 (Calcium Carbonate) and Without Catalyst (25ml and 60ml respectively). This suggests that ZnO and Na2CO3 are more effective catalysts for the conversion of waste plastic into the desired products than CaCO3 or the absence of a catalyst.

Reasons for Variation

Different catalysts have different properties that affect their ability to interact with and break down plastics. Factors such as surface area, acidity/basicity, and specific catalytic properties can influence their effectiveness. ZnO and Na2CO3 might provide active sites or chemical environments that enhance the cleavage of plastic bonds, leading to higher yields. CaCO3 might have less favorable catalytic properties for this specific reaction, resulting in a lower yield. Without any catalyst, the reaction proceeds at a slower rate with fewer molecules being converted into the desired products, hence the lowest yield among the tested conditions.[20]

In summary, the varying yields in catalytic conversion of waste plastic are primarily due to the differences in catalytic activity and effectiveness of the catalysts used. Catalysts like ZnO and Na2CO3 are more efficient at promoting the breakdown of plastics into usable products compared to CaCO3 or no catalyst at all.[21] This underscores the importance of catalyst selection in optimizing the efficiency and yield of chemical processes such as waste plastic conversion.

1. *2914 cm^{-1}:* This peak is due to the asymmetric stretching vibration of the CH2 group in polyethylene.
2. *2847 cm^{-1}:* This peak is due to the symmetric stretching vibration of the CH2 group in polyethylene.
3. *1714 cm^{-1}:* This peak is due to the C=O stretching vibration in aldehydes, ketones, carboxylic acids, and esters.
4. *1470 cm^{-1}*: This peak is due to the scissoring vibration of the CH2 group in polyethylene.
5. *1380 cm^{-1}:* This peak is due to the CH3 bending vibration in polyethylene.
6. *1150 cm^{-1}*: This peak is due to the C-O stretching vibration in alcohols, ethers, carboxylic acids, and esters.
7. *970 cm^{-1}:* This peak is due to the C=C stretching vibration in alkenes.

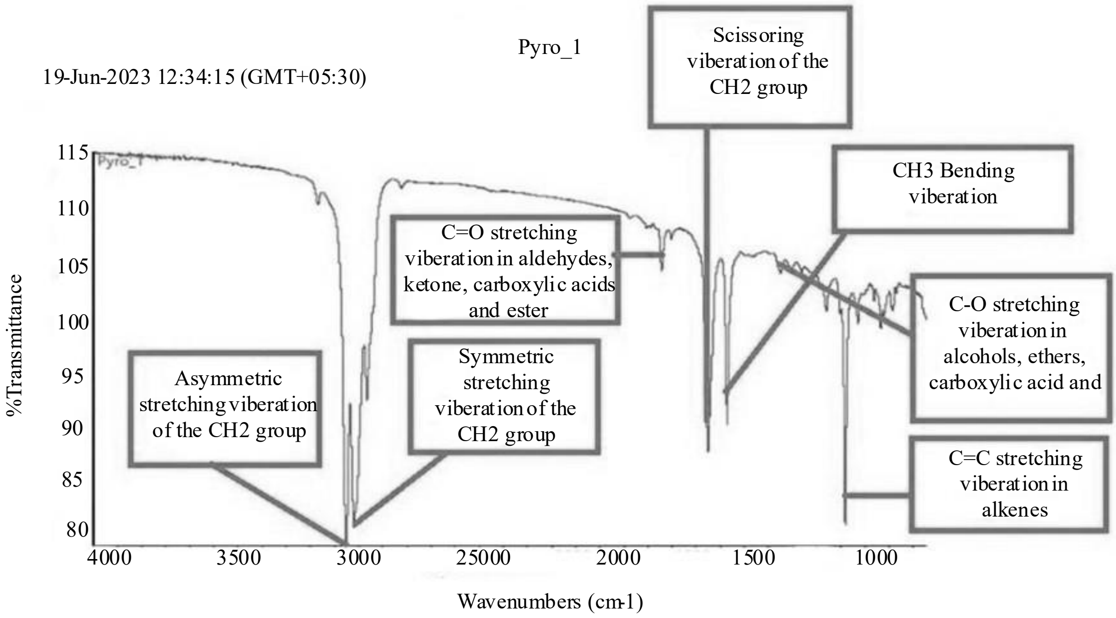

Figure 8. Chemical properties of pyrolysis oil graph.

A key outcome of the pyrolysis process was the recovery of valuable monomers and chemicals that can contribute to polymer recycling. The study found that the process yielded fuel oil with properties comparable to diesel, making it a viable alternative energy source. In addition, gaseous products such as syngas can be further processed into value-added chemicals or used directly as a fuel source.[22] The solid char produced can be utilized in various applications, including activated carbon production, soil amendment, and as an alternative fuel. These outputs highlight the potential for converting plastic waste into useful resources.[23]

CONCLUSION

This study contributes significantly to the circular economy and waste valorization by transforming non-recyclable polymer composites into valuable products. Instead of allowing plastic waste to accumulate in landfills or be incinerated, this approach recovers energy and valuable materials, reducing environmental pollution. By producing alternative fuels and high-value chemicals, the process supports sustainability efforts and decreases dependence on fossil fuels. The ability to recycle waste plastics into usable products aligns with the principles of a circular economy, promoting resource efficiency and long-term environmental benefits. The pyrolysis of waste plastic offers a promising solution for the management of plastic waste generated from milk packaging or milk-related products. This process not only helps in resource recovery and waste management but also addresses environmental concerns associated with plastic waste. The conversion of waste plastic into fuel through pyrolysis contributes to the reduction of environmental pollution by diverting plastic from landfills or incineration. It provides an opportunity to recover energy from a waste stream that would otherwise contribute to the depletion of natural resources. By producing fuel from waste plastic, it also offers an alternative to fossil fuels, thereby promoting sustainability and reducing greenhouse gas emissions. Furthermore, pyrolysis of waste plastic creates economic value by transforming a discarded resource into a useful product. It highlights the potential for a circular economy approach where waste materials can be converted into valuable resources, promoting a more sustainable and efficient use of resources. However, it is important to note that the implementation of pyrolysis technology for waste plastic requires careful consideration of various factors such as process efficiency, economic viability, and environmental impact assessment. Further research and development are needed to optimize the pyrolysis process, explore different feedstock compositions, and evaluate the potential emissions and environmental implications associated with this method. We have used three catalyst and one without for pyrolysis process. By comparing all yield readings, ZnO is more effective. In this, including all experiment we got 443ml of fuel oil.

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ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

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