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Pyrolysis of Polyvinyl Chloride, Polypropylene, and Polystyrene: Current Research and Future Outlook †

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Abstract: Plastic waste increased worldwide due to the steady rise in plastic consumption. Several strategies were developed to mitigate plastic waste. Among these methods, pyrolysis is a promising technology for converting plastic waste into valuable products. This paper discusses the latest advancements in the pyrolysis of three common types of plastic waste: polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS). The challenges associated with the pyrolysis of these plastics are highlighted, and an outlook on the future of research on pyrolysis is given. Overall, this review provides valuable insights into the current state of research on the pyrolysis of PVC, PP, and PS. This has implications for advancing pyrolysis technology to contribute to a more sustainable and circular economy.

Keywords: pyrolysis; polyvinyl chloride; polypropylene; polystyrene

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1. Introduction

Plastic consumption continues to increase worldwide and has caused a surge in plastic waste globally. Because plastics are made from long-chain hydrocarbons, they are non-biodegradable, thus making their disposal a significant environmental concern. Typically, solid wastes such as plastics are being disposed through sanitary landfills or are incinerated. However, both have negative impacts in the environment for they generate toxic emissions in the form of leachates and VOCs. This has led to the adoption of alternative modes of waste management strategies, but none of them provides a comprehensive solution to the growing plastic waste problem.

Among the technologies being considered for plastic waste management is using pyrolysis. Pyrolysis is a thermochemical process that decomposes organic feedstocks such as plastic waste in the absence of oxygen, producing a range of products such as biochar, bio-oil, and syngas. It is a promising technology to generate valuable materials out of waste plastics. For example, biochar can be used as a soil amendment material. Bio-oil may contain valuable products that can be further purified for the production of chemicals. Meanwhile, biogas or syngas can be used as an alternative fuel for electricity generation.

There are different types of pyrolysis depending on the temperature and the heating rate. Slow pyrolysis occurs at low temperatures (400–700°C) and a slow heating rate (less than 10 °C/min). This process produces biochar as the primary product with a small amount of bio-oil and gas. Because it is done at slow heating rate, this process has high residence time. Meanwhile, fast pyrolysis occurs at higher temperatures (500–800 °C) and a high heating rate (greater than 100 °C/s). This produces bio-oil as the primary product and a small amount of biochar and gas. This process typically has low residence time and produces high yield of valuable bio-oil. Lastly, flash pyrolysis occurs at very high temperatures (greater than 1000 °C) and a very high heating rate (greater than 1000 °C/s). Because of the harsh pyrolysis conditions, it produces a high yield of gas as the primary product and a small amount of bio-oil and biochar.

The efficiency of the pyrolysis process is influenced by several factors, including the plastic type, pyrolysis temperature, heating rate, residence time, use of catalysts, and reactor design. This paper focuses on the latest advancements in the pyrolysis of polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS).

2. Pyrolysis of Different Plastics

The type of plastic used is a significant factor that affects the pyrolysis process. The main types of plastic are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyurethane (PU). These plastics have different chemical compositions and molecular structures, which affect their pyrolysis behavior. For instance, the pyrolysis of PE and PP at high temperatures (400–600 °C) results in high yields of liquid products (70–80%), while PS and PVC pyrolysis yield mainly gaseous products. PET and PU pyrolysis produce a combination of liquid, gas, and solid products. In this paper, we will focus on the pyrolysis of PVC, PP, and PS.

2.1. Polyvinyl Chloride

PVC is an excellent choice of material for construction materials such as electrical insulations and pipings because of its resistance to fire and other environmental factors. When mixed with several additives, the use of PVC can be extended to other products such as in packaging, medical devices, automotive interiors, credit cards, and synthetic leather. PVC contains very high levels of chlorine. Upon heating, it releases dangerously high levels of chlorinated compounds that are toxic to human beings upon inhalation. When released in the atmosphere and upon the action of UV light from the sun, these chlorinated compounds can break down to form chlorine-free radicals that can participate in the atmospheric destruction of ozone. Because of these concerns, studies on the pyrolysis of PVC are not very common and are only usually done for comparative analysis with other plastics.

Tang et al. [1] found that the structural breakdown of PVC started at around 240 °C and ends at about 530 °C. A maximum decline in the initial weight loss (66%) has been observed to occur between 250 °C and 380 °C. When pyrolysis is conducted at 380 °C, minimal chlorine release (4%) was observed. When the pyrolysis temperature is increased beyond 380 °C, additional PVC degradation occurred (28.5% of its initial weight) in the temperature range of 385–525 °C. However, this accompanied increased chlorine levels which are undesirable in an HSE point-of-view. Ephraim et al. [2] found that pyrolysis of pure PVC yields 10.3 wt.% char, 30.3 wt.% oil, and 59.2 wt.% gases. 96.9 wt.% of the total chlorine in PVC is released in the gas phase while only 2.9 wt.% and 0.04 wt.% of the total chlorine goes to the oil and char phase respectively.

Özsin and Pütün [3] studied the kinetics of PVC pyrolysis and found that the activation energy of PVC pyrolysis to be in the range of 93.2–263.7 kJ/mol and average activation energy varied between 144.7 and 161.0 kJ/mol depending on the kinetic model used. They also found that the activation energy is highly dependent on conversion degree which indicates that PVC pyrolysis undergoes a very intricate pyrolytic degradation due to different types of reactions involved in the process.

López et al. [4] reported that thermal degradation of PVC takes place by means of "side group elimination." This is a two-stage process—first, the polymer chain is first stripped of molecules or "sidechains" attached to the backbone of the polymer thus leaving an unsaturated chain, and second further degradation of the remaining unsaturated chain. They observed that almost all the chlorine (≈99 wt.%) is lost at a pyrolysis temperature of 300 °C (54.1 wt.% PVC degradation); lower chlorine release is achieved at lower temperatures even at extended pyrolysis time. To deal with the issue of chlorine release, they added calcium carbonate ($CaCO_3$) to PVC to dechlorinate the plastic samples during pyrolysis. The addition of $CaCO_3$ increased the gas generation from 34.0 wt.% to 54.4 wt.% and decreased oil production from 65.2 wt.% to 46.6 wt.%. Accordingly, $CaCO_3$ also acts as a catalyst during the conventional pyrolysis of PVC, thus modifying the product composition by increasing volatile components in the pyrolysis products.

While intuition tells us that it is desirable to pyrolyze all types of plastics, our review showed that this may not be very applicable to PVCs. This has implications in setting up pyrolysis plants because PVC removal from the original plastic mix may be needed prior to feeding the pyrolysis reactors.

2.2. Polypropylene

First synthesized by Phillips Petroleum chemists J. Paul Hogan and Robert Banks, polypropylene emerged to be one of the most produced plastics after polyethylene. PP is a saturated polymer with a linear hydrocarbon chain. Isotactic polypropylene has a higher degree of crystallinity, stiffer, and more resistant to creep than polyethylene or atactic polypropylene. It has a good chemical resistance except for strong oxidizing agents and has a good thermal resistance. Because it has the lowest density among all commodity plastics, it is highly-desired in the production of plastic parts since greater quantities can be manufactured for a given mass of PP compared to other types of plastics. The applications of PP are diverse—plastic hinges, plumbing systems, laboratory containers, home decors, ropes, plastic moldings, packaging, storage boxes, pails, and aircraft and radio parts, among others. Due to its wide applications, plastic wastes made from PP can also be found in large numbers despite its long shelf-life.

Ahmad et al. [5] studied the pyrolysis of polypropylene over a temperature range of 250–400 °C. They achieved 98.66% total conversion; 69.82% is transformed into liquid oils, 28.84% to gaseous products, and the remaining 1.34% was converted to chars at 300 °C. Further increase in temperature resulted in lower total conversion due to coke formation and elevated gas formation. Analysis of the liquid products showed that 50% of the liquid fraction is in the light naphtha range hydrocarbons (C_6–C_{16}) while the remaining oil ranges from C_{13} to C_{16} (33.04%), and C_{17} to C_{20} (24.97%) which corresponds to diesel range hydrocarbons. Pyrolyzed PP liquid oils are richer in paraffinic hydrocarbons (66.55%) relative to olefins and naphthenes which comprise 25.87% and 7.58%, respectively. As such, the liquid oils derived from pyrolyzed PP can be used for diesel engines. In fact, their study showed that the produced oils meet the fuel grade criteria set by ASTM.

In a study by Abbas-Abadi et al. [6], pyrolysis of polypropylene was done with an equilibrium fluid catalytic cracking (FCC) catalyst. They found that the product molecular weight decreases with increasing temperature. At higher temperatures, they observed that the conversion of liquid products directly to aromatics and some gases are favored which occurs via the Diels–Alder reaction, followed by dehydrogenation. The maximum condensed product yield was achieved with a 10% FCC catalyst. In a non-catalyzed reaction using similar conditions, the majority of the products obtained are waxy in nature which is less valuable compared to liquid oils. Adding FCC catalyst to as low as 2% loading shifts the reaction to produce the more valuable liquid fuels. They also showed that agitation rate affects the overall reaction kinetics. In particular, the reactor without a stirrer has very weak radiation heat transfer in high temperatures. The poor thermal conductivity of the polymer increases the residence time of the pyrolysis process, thus requiring larger reactor volumes. This can lead to non-homogeneity of polymer/catalyst mixture and build-up of non-uniform temperature gradient which alters the product composition. The maximum condensed hydrocarbon yield was obtained at 50 rpm. As such, this study showed that pyrolysis of plastics, in particular that of PP, is a complex process that involves inter-relationships between several process parameters.

Aboulkas et al. [7] studied the kinetics of polypropylene pyrolysis using isoconversional methods. They estimated the activation energy to be around 179–183 kJ/mol which is lower compared to HDPE (238–247 kJ/mol) and LDPE (215–221 kJ/mol). This shows that thermodynamically speaking, PP requires lower energy compared to HDPE and LDPE to convert them into pyrolysis products. Furthermore, according to their study, a ''Contracting Cylinder'' model best describes the kinetics of PP pyrolysis as opposed to the ''Contracting Sphere'' model for HDPE and LDPE. The difference in the kinetic mechanisms between PP and polyethylene can have an impact on designing pyrolysis plants.

2.3. Polystyrene

Polystyrene is made of polymerized styrene molecules and is typically used for various applications such as in household items (toys, kitchen utensils, coffee cups, plates, food packaging) and in industrial materials (insulation material, packing material, etc.). Typically used in its foam form, PS has very low bulk density and thus occupies a large volume in municipal solid wastes. Typically, people do not recognize PS as plastic. Thus, during waste segregation, PS is usually thrown as a residual. Because recycling PS is not usually done, pyrolyzing polystyrene is the only alternative before it ends in landfills.

Adnan et al. [8] investigated the pyrolysis of expanded PS waste in a batch reactor. Among the zinc bulk catalysts that they used, the Zn metal catalyst was found to be the best catalyst yielding 96.73% liquid products at 450 °C, 120 min heating time and 1:0.2 feed to catalyst ratio. The liquid products consist of 2.47 wt.% toluene, 1.16 wt.% ethylbenzene, 47.96 wt.% styrene, and 1.90 wt.% α-methylstyrene. They found that the nature of the catalyst used during PS pyrolysis has a deep relation to the activity and selectivity of products. For the case of Zn metal, they found that it has higher activity and selectivity for the production of low molecular weight aromatic hydrocarbons compared to other catalysts that they studied.

Shah et al. [9] used a different catalyst to pyrolyze expanded PS. In their work, the maximum yield of liquid product was achieved using a 15% Mg–Al_2O_3 catalyst (95.47 wt.%) at 450 °C under an optimized polymer: catalyst ratio is at 1:0.3. The optimum reaction time for the conditions is 30 minutes; beyond this temperature, the liquid yield drops. In comparison, non-catalyzed degradation of PS at 500 °C showed increasing liquid yield as the reaction time is increased. Their analysis of the liquid products showed a composition of 56.20 wt.% styrene, 13.10 wt.% benzene, and 8.93 wt.% ethylbenzene as the top three products.

In another work by Adnan et al. [10], the pyrolysis of PS was carried out using several Cu catalysts. In an N_2 atmosphere, about 99.57% of the weight loss attributed to PS degradation occurred from 300.98 °C to 409.85 °C. On the contrary, under an O_2 environment, 100% of the weight changes occurred from 292.50 °C to 407.79 °C. Unlike those of Zn catalysts where the Zn metal yields the maximum liquid products, they found that Cu supported catalysts are more selective towards low molecular weight aromatic hydrocarbons as compared to Cu metal and the supports. The best catalyst is 20% Cu-Al_2O_3 which has moderate activity and high selectivity towards the desirable low molecular weight aromatic hydrocarbons, yielding 60.48% styrene, 10.98% toluene, 9.92% ethylbenzene, and 3.66% methylstyrene.

These studies show the influence of the catalysts used in the composition of the pyrolysis products. In general, PS yields highly-aromatic liquid oils with minimal char and gas production at mild temperatures. This shows that the liquid oils can have the potential to be used as fuels most especially in diesel engines.

3. Research Gaps

Plastic pyrolysis has the potential to address the environmental issues caused by plastic waste at the same time producing valuable products. However, several research gaps limit its full potential. Understanding of the optimization of pyrolysis conditions, product analysis and characterization, effects of feedstock characteristics, proper reactor and catalyst design, environmental impact assessment, and economic viability and scale-up are crucial to the development of plastic pyrolysis technology. These gaps need to be addressed before plastic pyrolysis can be adopted commercially.

3.1. Process Optimization

The pyrolysis of plastics involves heating the feedstock in the absence of oxygen to break down the polymer chains into smaller fragments. Such process is influenced by several process factors, including temperature, heating rate, reactor residence time, and feedstock characteristics, among others. Extensive research had been done to elucidate the effect of these variables on the product yield, product distribution, and product characteristics. However, there is still a need to conduct optimization studies to improve the yield and quality of the pyrolysis products and to lower the operating costs of pyrolysis process.

For example, some studies mention that as higher heating rate increases the yield of liquid products due to the rapid decomposition of the plastic waste. However, some studies reported that a slower heating rate tend to favor the production of higher yields of valuable products like aromatics and olefins. These conflicting studies merit further investigation and optimization to identify the optimal heating rates for each plastic and for different reactor designs.

3.2. Product Characterization

Plastic pyrolysis produces a range of products, including solids (char), liquids (oils and aromatics), and gases, each with varying properties and potential uses. Significant research has been conducted on the yield, distribution, and properties of these products. However, there is still a need to further characterize the products in terms of melting point, molecular weight, chemical structure, chemical stability, and heating value, among others.

Liquid products obtained from plastic pyrolysis are typically a source of valuable products like aromatics and olefins, which can be used as raw materials for the production of various products such as fuels, polymers, and other industrial chemicals. However, different types of plastic feedstock, reaction conditions, and reactor type may produce varying product distributions and yield, affecting the quality of the products. Thus, there is a need to thoroughly investigate how the variations in product composition affects their properties. Moreover, there is a need to develop effective means to separate and purify the components of these products to enhance their value and marketability.

A detailed analysis of the product quality is needed to ascertain the market potential of the pyrolysis products. However, there is currently no consensus on the standard methods to analyze the quality of pyrolysis products. Some researchers used gas chromatography-mass spectrometry (GC-MS), Fourier-transform infrared spectroscopy (FTIR), and nuclear magnetic resonance spectroscopy (NMR) to characterize the pyrolysis products. However, the lack of standardized methodology in pyrolysis product analysis makes it challenging to compare the results across studies, leading to inconsistent findings. Hence, there is a need to develop standardized tools and methods to ensure data consistency and comparability of results.

3.3. Feedstock Selection

As discussed in the previous section, feedstock selection is a critical aspect in plastic pyrolysis. The type of plastic can influence the product yield and quality, product distribution, properties, and even the efficiency of the entire process. Thus, the choice of plastic must be carefully assessed to ensure an optimized process.

Most studies involving plastic pyrolysis focuses on the use of single plastic types. Here, we reported studies on polyvinyl chloride, polypropylene, and polystyrene. However, in the real world, plastic wastes occur as a mixture of different plastic types. The effect of plastic waste composition on the pyrolysis process is not well understood. Therefore, further studies need to be done to explore how feedstock characteristics affect the pyrolysis process and the corresponding product yield and distribution. Additionally, the effect of impurities such as water, oxygen, and metals, among others, on the product quality and yield has not been thoroughly investigated. There is a need to elucidate how these impurities affect the reaction mechanism and the overall efficiency of the process. Understanding how the feedstock characteristics affect the pyrolysis process is crucial in selecting the appropriate catalyst and in reactor design.

3.4. Reactor Design

Like in any chemical process, reactor design is essential in the efficiency of pyrolysis process. The type of reactor directly impacts the yield of the pyrolysis products, as well as the energy requirements, by-product formation, and environmental impact of the process. Therefore, it is necessary to choose the right type of reactor to maximize the benefits of plastic pyrolysis.

The comprehensive understanding of the underlying mechanisms involved in plastic pyrolysis is a pre-requisite to effectively design an efficient pyrolysis reactor. However, our understanding in this area is still limited primarily because of the complexity of the reactions involved during the thermochemical process. More research is needed to understand the reaction mechanism, kinetics, and thermodynamics of the pyrolysis process for these are essential components of reaction engineering and reactor design. Fundamental understanding on the chemistry of the process is required to develop more efficient reactor designs.

There is also limited research in the scale-up of plastic pyrolysis. Most studies in the literature are conducted using laboratory-scale reactors which may be different to industrial-sized reactors. Scale-up of reactors involves understanding on the effect of heat and mass transfer on the kinetics of pyrolysis. Moreover, there is a need to develop effective designs to optimize heat and mass transfer and to effectively control the reaction conditions such as temperature, flow rates, and residence time. Knowledge on the appropriate materials of construction is also needed to ensure that the reactor will be serviceable throughout the plant lifetime. As such, the effect of corrosion and fouling on the reactor performance may also be investigated in the future.

Overall, developing an efficient reactor for plastic pyrolysis is crucial to help address the plastic waste problem and to facilitate the adoption of pyrolysis technology on a larger scale.

3.5. Catalyst Design

Typically, plastic pyrolysis use catalysts to enhance the reaction rate, thus increasing the yield and quality of the products obtained. While there are already several catalysts investigated for this purpose, there remains a need to develop novel catalysts that are more efficient, possesses high selectivity and thermal stability, more sustainable, and of lower cost. Catalysts play a critical role in improving the overall pyrolysis process and in reducing the operational cost.

One of the major challenges in catalyst design is achieving high selectivity for the desired valuable products. Current catalytic pyrolysis processes produce a wide range of products, including unwanted byproducts, which reduces the overall yield and quality of the desired products. Catalysts are also prone to fouling, poisoning, and sintering at high pyrolysis temperatures and long reaction times, leading to deactivation and loss of performance. As such, future researchers should explore new catalysts that are more resistant to catalyst deactivation and can perform over long period of time without regeneration.

Catalysts should also be designed to withstand the harsh reaction conditions inside the pyrolysis reactor. Most catalysts have been tested in laboratory-scale reactors, but studies should also focus on using these catalysts in pilot-scale and industrial-scale reactors where heat transfer and mass transfer effects may be more predominant. Moreover, the cost of the catalyst is the most important consideration when adopting a catalyst for commercial use. Hence, the catalyst should be made from cheap raw materials and have minimal environmental impact for it to be sustainable and economically-feasible.

3.6. Environmental Impact

Plastic pyrolysis has a great potential to reduce our plastic waste and to produce valuable products. However, there is still a need to comprehensively assess its environmental impact since pyrolysis may release harmful emissions (greenhouse gases, particulate matter, volatile organic compounds, toxic compounds, etc.) that may have a significant health and environmental impact. It is also crucial to reduce the production of these emissions by enhancing the efficiency of the process, developing greener catalysts, and optimizing the process. Therefore, there is a need to investigate the environmental impact of pyrolysis to assess its viability compared to other plastic waste management options. Future research may also focus on lifecycle analysis to thoroughly evaluate the environmental and economic benefits and drawbacks of plastic pyrolysis, including the energy consumption, greenhouse gas emissions, and the economic feasibility of the process.

3.7. Economic Viability

Due to the latest advancements in plastic pyrolysis, there is a growing interest in utilizing pyrolysis to manage our increasing production of plastic waste. However, as the technology is gaining maturity, there is a need to investigate the economic viability and technological scalability to maximize its impact. As such, we need to assess the true cost of the pyrolysis process and the actual value of the produced pyrolysis products to determine its profitability. Unfortunately, there is still a lack of systematic studies done on the cost analysis of plastic pyrolysis. Most studies are also limited to small-scale laboratory experiments. Thus, pilot-scale studies should be done to assess the technological viability of the process when scaled up from laboratory setting. Moreover, a market study on the pyrolysis products is needed to ascertain their current demand and prices which are helpful in evaluating the economic feasibility of the pyrolysis process.

4. Future Outlook

The increase of plastic garbage in the environment has sparked research and innovation in waste management systems. Among these, pyrolysis has emerged as a viable solution for addressing the difficulties posed by plastic waste, with a particular focus on polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS). As society explores sustainable alternatives to traditional trash disposal systems, the pyrolysis of these three primary plastic types holds tremendous promise.

Polyvinyl chloride (PVC) is ubiquitous due to its diverse qualities, making it a standard in building, healthcare, and consumer goods. However, PVC’s lifecycle poses considerable environmental concerns, from its hazardous chlorine-based manufacture through its resistance to degradation. Pyrolysis provides a solution to these problems. Innovative pyrolysis techniques may enable the controlled breakdown of PVC into usable components in the future while limiting harmful emissions. Advanced catalysts have the potential to improve the selectivity and efficiency of the pyrolysis process, generating valuable hydrocarbons and chemical intermediates. Researchers want to reduce environmental harm by optimizing pyrolysis conditions, which will reduce the creation of chlorine-containing byproducts. Furthermore, the possibility of circularity in PVC pyrolysis appears interesting. The byproducts could be utilized as feedstock for the manufacture of other materials, effectively closing the loop and lowering the demand for virgin resources. While energy consumption remains a concern, the incorporation of renewable energy sources and creative reactor designs may alleviate this issue, making PVC pyrolysis more energy-efficient and environmentally beneficial.

Polypropylene (PP) is well-known for its lightweight and long-lasting properties, making it a popular material in packaging, textiles, and a variety of consumer products.

Nonetheless, the accumulation of PP trash in landfills and waterways needs environmentally friendly disposal options, making pyrolysis an appealing option. The future of PP pyrolysis is focused on improving pyrolysis technologies to improve product selectivity and yield. Customized catalysts can improve conversion efficiency and result in desirable outputs such as liquid fuels and valuable chemical feedstocks. The manufacture of renewable chemicals and polymers from PP pyrolysis products is an interesting prospect. The pyrolysis oils produced can be used as a sustainable supply of feedstock for numerous chemical processes, reducing reliance on fossil fuels. Innovative ways are being used to address issues such as feedstock variability and process economics. Advanced feedstock pretreatment, reactor design, and process optimization are expected to increase PP pyrolysis's viability on a larger scale. With a focus on the circular economy and resource efficiency, PP pyrolysis could greatly contribute to reducing plastic waste and improving resource usage.

Polystyrene (PS) is well-known for its insulating characteristics and adaptability, and it is used in an array of applications including packaging, electronics, and insulation. The development of ways to extract useful styrene monomers from the pyrolysis process is crucial for the future of PS pyrolysis. Styrene is an important precursor for many chemicals and plastics, and it is possible to design a closed-loop system in which waste PS becomes a profitable feedstock. Microwave and plasma-assisted pyrolysis approaches are being investigated to improve the process's efficiency and selectivity while avoiding the limitations associated with classic thermal pyrolysis. Styrene recovery and process efficiency are likely to improve as innovation advances, making PS pyrolysis more appealing both ecologically and economically. This technique might turn PS waste into a resource for sustainable chemical and material production by leveraging the value of pyrolysis products.

The pyrolysis of polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS) has a bright future, with continuing research and development targeted at producing more efficient and sustainable pyrolysis processes. Product yields, selectivity, and overall process efficiency are projected to improve as technology advances in catalyst research, reactor design, and process optimization. The use of pyrolysis products as feedstock for the manufacture of valuable chemicals and materials could help to move the economy toward a more circular and sustainable model.

However, issues like as energy consumption, scalability, and economic feasibility persist. To solve these issues and realize the full potential of plastic pyrolysis as a solution to plastic waste management and resource conservation, researchers, industry stakeholders, and policymakers must continue to collaborate. As technology advances and the global emphasis on sustainability rises, pyrolysis has the potential to play a critical role in determining the future of plastic waste management.

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