



Research Progress on Gas Generation from Waste Plastics Through Pyrolysis

Ji Guangxiong^{1,2,3} · Liu Bingguo^{1,2,3} · Luo Guolin⁴ · Yuwen Chao^{1,2,3} · Peng Fang⁴ · Gong Siyu^{1,2,3} · Guo Shenghui^{1,2,3} · Chen Wang^{1,2,3} · Hou Keren^{1,2,3}

Received: 22 January 2024 / Revised: 6 June 2024 / Accepted: 2 July 2024 / Published online: 5 July 2024
© The Author(s), under exclusive licence to Korean Institute of Chemical Engineers, Seoul, Korea 2024

Abstract

Plastic pyrolysis technology, as an efficient and stable path for chemical recycling of waste plastics, alleviates current energy pressures and solves the problem of continuous accumulation of waste plastics in the environment. At present, the vast majority of research on plastic pyrolysis is focused on how to improve the yield and quality of liquid fuels, while there is generally little research on the gases generated by plastic pyrolysis. However, gases such as H₂, CH₄, and light hydrocarbons generated during pyrolysis also have high utilization value, and have very considerable application prospects in chemical, aerospace, and metallurgical fields. In addition, compared with the separation difficulties of liquid products, the treatment of gas products is easier and more conducive to subsequent utilization. This article discusses and analyzes the yield and composition of gases generated by plastic in three different pyrolysis methods: direct pyrolysis, catalytic pyrolysis, and microwave pyrolysis. Compared to traditional direct pyrolysis, catalytic pyrolysis and microwave pyrolysis can treat plastic waste more efficiently and energy-efficient, and have higher gas yields. This article also discusses various factors such as temperature that influence the formation of gas products and their importance. Finally, the challenges faced are proposed, aiming to provide reference and direction for future research on improving the yield of gas generated by plastic pyrolysis.

Keywords Pyrolysis technology · Waste plastics · Gas · Influence factors · Challenges

Introduction

Plastics have become a fundamental product to ensure a modern level of quality of life. Due to its low manufacturing cost, light weight, and good durability, plastics have become increasingly widely used, leading to the gradual replacement of traditional materials, such as wood, metal, and ceramics [1]. Since production began in 1950, global plastic production has grown by an average of 9% annually. The production level in 2018 reached 359 million tons [2]. Most of these plastic products produced annually are used for disposable items, such as shopping bags, cups, and straws [3]. These plastic products have a relatively short lifespan and are usually discarded after less than a month of use [4], and they are difficult to degrade in nature, causing significant environmental pollution. Since the invention of plastic, the environmental problems caused by its accumulation have been troubling people, and people have been searching for ways to actively address this problem. In the past few years, governments around the world have also implemented some public policies to improve the management of waste plastics,

✉ Liu Bingguo
bingoliu@126.com

✉ Yuwen Chao
ywchao0000@126.com

¹ Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, Yunnan, China

² Key Laboratory of Unconventional Metallurgy, Kunming University of Science and Technology, Kunming 650093, Yunnan, China

³ National Local Joint Laboratory of Engineering Application of Microwave Energy and Equipment Technology, Kunming University of Science and Technology, Kunming 650093, Yunnan, China

⁴ Qujing Zhongyi Fine Chemical Co., Ltd., Qujing 655003, Yunnan, China

and under the promotion of these policies, the management of waste plastics has also achieved results. Compared to the beginning of the twenty-first century, the proportion of recycled waste plastics and waste plastics used for energy utilization in various countries around the world has increased, and the amount of waste plastics sent to landfills and directly burned is also gradually decreasing. Although the global management plan for waste plastics is slowly improving, the current situation is far from satisfactory, and the environmental problems and resource waste caused by waste plastics are still severe.

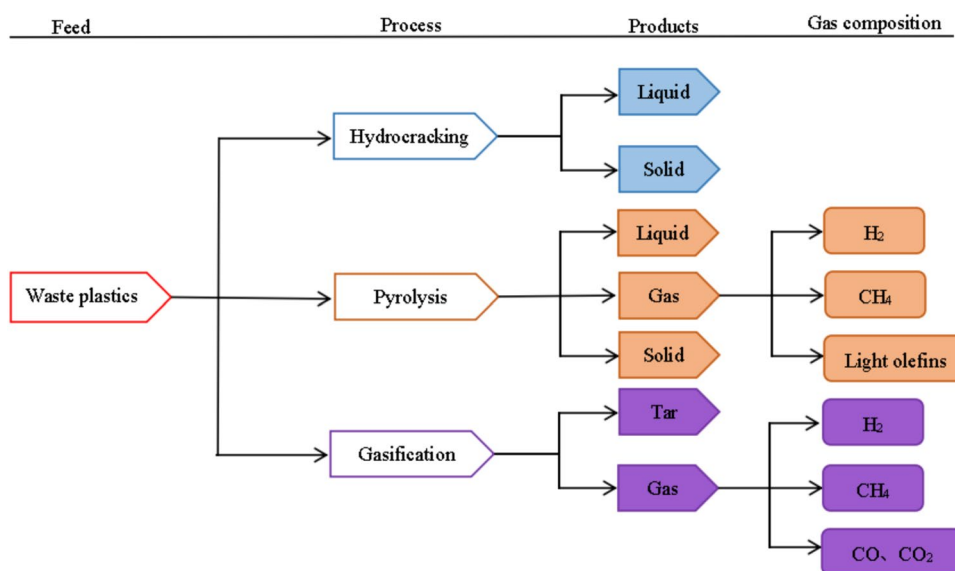
At present, the treatment methods for waste plastics are mainly divided into three categories, namely landfill, incineration, and recycling. However, due to the fact that plastic waste after consumption is usually composed of mixed plastics with unknown components and often contains various pollutants, including organic (such as food residues) and inorganic (such as inks) pollutants, less than 20% of plastic is recycled and reused, while the vast majority is directly buried in soil or discarded in oceans and rivers, and a portion is burned [5]. But the harm that incineration and landfill bring to the environment and people's lives is enormous. During the incineration process, a series of harmful by-products [6] such as carbon dioxide, toxic pollutants (such as dioxins) [7], heavy metals, and particulate matter are generated, which are highly dangerous and can cause global warming and some health problems, including respiratory symptoms, decreased lung function, and high cancer risk [8, 9]. The effect of landfill method in treating waste plastics is also not ideal. As most plastics are non-biodegradable, the degradation of buried plastics is slow and often takes hundreds of years to complete. Moreover, with the continuous increase of plastic landfill volume, more and more land is occupied, wasting a large amount of land resources. At

the same time, plastic is prone to chemical reactions with groundwater and toxic substances containing water in the landfill site after being buried, resulting in toxic leachate, which affects the quality of surrounding soil and leads to land degradation [10]. Irresponsibly handling plastic waste not only has adverse impacts on ecosystems and biodiversity [11], but also poses immeasurable harm to human health. Both from an ecological and energy perspective, landfill and incineration methods for treating waste plastics are not very advantageous. The use of chemical recycling to treat waste plastics can not only alleviate the pressure of environmental pollution, but also reuse these waste resources to generate a series of valuable products, such as oil, gas, and carbon.

Chemical recovery is a stable and efficient treatment approach, which has good treatment effects even on plastics with impurities or contamination [12–14]. The main chemical recycling route for waste plastics is shown in Fig. 1. Among the numerous chemical recovery paths, pyrolysis is the most efficient, stable, and primary method for treating waste plastics [1, 2, 15–17]. At present, most research on plastic pyrolysis is focused on the liquid generated during the pyrolysis process, and improving the yield and quality of oil has always been the main research direction of plastic pyrolysis. However, there is little research on the gas generated during plastic pyrolysis. However, the gases generated during pyrolysis also have great utilization value, such as H_2 and CH_4 , which can be used as reducing agents in industries, such as metallurgy, as well as fuels in industries, such as petrochemical and aerospace. Especially, H_2 , as a clean energy source, has very good application prospects. In addition, the generated light hydrocarbons can also become high-value chemicals after treatment.

This article aims to study and analyze the effects of different pyrolysis pathways and influencing factors on gas

Fig. 1 Main route plan for chemical recycling of waste plastics



products during plastic pyrolysis, as well as the reaction mechanism of gas generation, to obtain the best solution to improve the target gas yield during plastic pyrolysis. It also points out the current challenges faced by plastic pyrolysis technology and the future research needs to be carried out.

Plastic Composition

The most common plastics in daily life include polystyrene (PS), polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), etc. They have been widely used due to their excellent performance. More than 60% of the produced urban plastic waste is composed of polyolefins, mainly high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) [18]. According to a report on plastic production in Europe, the demand distribution of different plastics produced in 2016 is shown in Fig. 2a [19]. From Fig. 2a, it can be observed that polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) account for almost half of the total plastic production and dominate the market demand. Polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET), and polystyrene (PS) are also several plastics in high demand, accounting for 10%, 7.5%, 7.4%, and 6.7% of the market demand, respectively. Correspondingly, the plastic waste generated mainly comes from the aforementioned plastic products. Figure 2b shows the detailed distribution of plastic demand by different industries in Europe in 2016. It can be seen from the figure that the packaging industry accounted for the largest proportion of plastic consumption, reaching 39.9%. The applications of plastics in the packaging industry include plastic bags, beverage bottles, and sealing materials, which are mainly made of polypropylene (PP) and polyethylene (PE). At the same time, a large portion of these plastic products belong to disposable items and are the main contributors to urban waste. The second largest consumer of plastic is the construction industry, which accounts for 19.7% of plastic consumption. Plastic can be

seen in floors, drainage pipes, insulation walls, and doors and windows [20]. Among them, polyvinyl chloride (PVC) is the most commonly used plastic in construction. In addition, the proportion of plastic consumption in the automotive industry, power industry, household plastics, agriculture, and other industries is 10%, 6.2%, 4.2%, 3.3%, and 16.7%, respectively.

Currently, countries around the world are seeking to develop a clean and circular economy. In such a major trend, the management of waste plastics becomes particularly important. A key factor leading to plastic pollution is the poor sustainability of plastic usage, with significant differences in the lifespan of plastics across different industries [1]. Geyer et al. plotted the life distribution of plastic products in different industries as a lognormal probability distribution function, as shown in Fig. 3 [21]. From the figure, it can be seen that plastic products in the packaging industry have the shortest service life, with the vast majority being discarded after less than a year of use. Next are plastic products in the consumer goods and industrial product industries. The plastic products used in the construction industry have the longest service life, with an average service life of several decades. Combining Figs. 2b and 3, we can find that the packaging industry has the largest proportion of plastic consumption, but the plastic service life in this industry is extremely short. From a long-term perspective, if reasonable plastic waste management methods and efficient disposal of waste plastics are not adopted, the short service life of plastics will pose significant environmental risks [22–24].

The complex composition of solid waste plastics is a major challenge in the chemical recovery process. When dealing with waste plastics, the treatment object is often a mixed type of plastic mixed with other types of plastics and components, which brings great difficulties to the regulation of reaction conditions. Therefore, accurate characterization of the composition of raw materials is beneficial for precise regulation of reaction conditions, thereby reducing side reactions during pyrolysis and increasing the yield of valuable products [25]. At the same time, it is also crucial

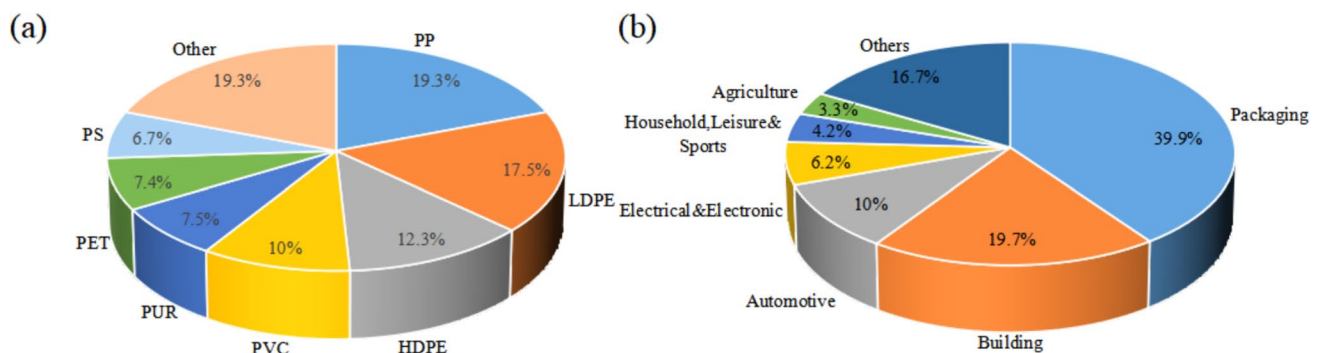


Fig. 2 Distribution of demand for different plastics produced in Europe (a) and demand for plastics by different industries (b) [19]

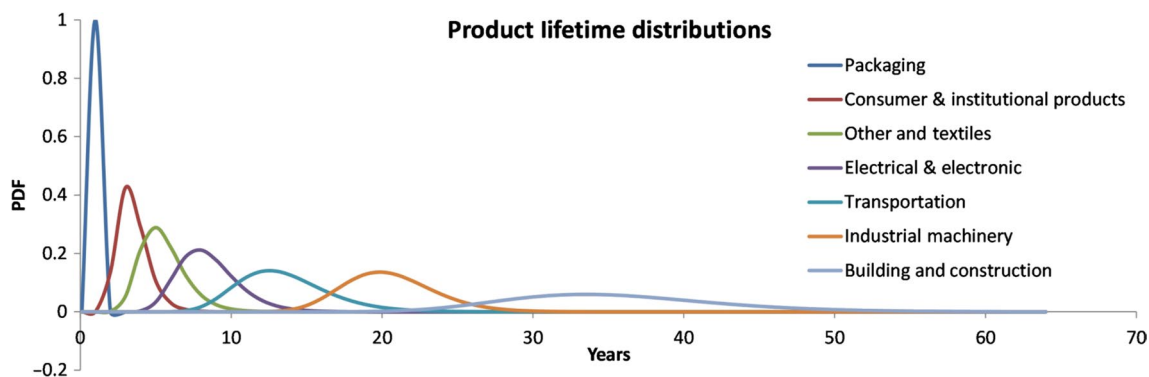


Fig. 3 Life distribution of plastic products in different industries [21]

to understand the reaction mechanisms of different types of plastics during the cracking process. Table 1 shows the elemental composition analysis of different waste materials [26].

From the table, it can be observed that, except for PVC, the main components of other plastic waste are C, H, and O, and the molar ratio of C/H has a significant impact on the yield of the product obtained from plastic pyrolysis [27]. For example, a higher C/H molar ratio can lead to higher biochar production and lower tar production. Balancing the elemental content of plastic waste through pre adsorption or adding biomass may be a solution to this problem [26]. In addition, as polymers, the structure of plastics also affects the distribution of pyrolysis products to a certain extent. Different structures exhibit different thermochemical properties during the pyrolysis process, and even similar polymer structures may have completely different thermochemical properties. Therefore, in addition to the elemental composition and reaction mechanism, the chemical structure of plastic polymers is also a research focus in the chemical recovery process. A deeper understanding of the relationship

between plastic chemical structure and cracking is crucial for developing a reasonable plastic pyrolysis plan.

Pyrolysis Method

Pyrolysis, also known as thermal decomposition, refers to the process of decomposing a compound by heating it up. For plastics, during pyrolysis, the long-chain macromolecular structure will decompose into smaller fragments, forming low molecular gas, fuel oil and coke. Compared to landfilling and incineration, using pyrolysis technology to treat waste plastics is a very green and environmentally friendly method that produces almost no pollution to the environment. In addition, pyrolysis also has the advantage of not requiring a strict classification step before the mixed plastic waste is used as a raw material. During the pyrolysis process, the operating conditions determine the yield and composition of the product. According to different operating conditions, pyrolysis can be divided into three categories: slow pyrolysis, conventional pyrolysis, and rapid pyrolysis.

Table 1 Analysis of element composition of different wastes [26]

Waste type	C (%)	H (%)	O (%)	N (%)	Other (%)
PE	86.0	11.2	2.4	0.2	S:0.2
PS	86.1	6.3	1.7	0.3	S:0.2
PVC	38.3	4.5	–	0.2	S:0.6, Cl:56.4
PET	62.9	4.3	32.6	0.04	S:0.1
Waste electrical and electronic equipment (mainly ABS and HIPS)	85.3	7.8	0.98	3.4	Cl:0.02, Br:0.13
Plastics (PS, PE, PVC, PP or PET)	38.3–86.1	4.3–12.7	1.9–57.0	0.04–5.7	S:0–0.1
Municipal plastic waste	79.8	15.5	2.0	2.8	–
Municipal solid waste	29.9–45.3	4.6–6.1	22.0–39.5	1.3–2.3	S:0.2–1.5
Fiber waste from paper recycling mill (containing plastic)	47.5–67.0	6.7–11.2	21.6–45.6	–	–
HDPE	85.4	14.2	0.15	0.08	–
Combustible solid waste (containing PVC)	45.3	6.1	39.5	1.28	S:0.23
PP	86.9	12.5	0.32	0.28	S:0.03

Table 2 summarizes the processes of these three pyrolysis methods and the classification of the products [2]. Due to the long time consumption, high energy consumption, low efficiency, and poor selectivity of slow pyrolysis, it is generally not the preferred method for plastic pyrolysis. Researchers prefer conventional pyrolysis with low time and energy consumption, as well as good selectivity and efficiency. Conventional pyrolysis can be divided into direct pyrolysis and catalytic pyrolysis. Compared to the previous two pyrolysis methods, rapid pyrolysis occurs relatively late and there is relatively little research on it. Microwave pyrolysis is a representative rapid pyrolysis method, which has attracted much attention in recent years due to its extremely low time and energy consumption, as well as excellent selectivity. However, microwave pyrolysis relies heavily on the dielectric properties of the material. Plastic, due to its low dielectric constant, hardly absorbs microwave radiation and converts it into heat. Therefore, when conducting microwave pyrolysis of plastics, it is often necessary to add microwave absorbers such as carbon or metal catalysts to assist in pyrolysis. However, sometimes due to material properties, the heat generated by microwaves may not be effectively transferred, leading to the formation of hotspots at certain locations [28].

Conventional Pyrolysis

Direct Pyrolysis

Direct pyrolysis refers to the process of directly heating plastics to undergo cracking at high temperatures and produce liquid oil and gases. During the pyrolysis process, there are a series of steps, mainly including initiation, formation of unstable secondary compounds, and termination through hydrocarbon chain breakage or free radical recombination [4, 29]. In this process, the C–C bond and C–H bond in the polymer chain break due to the structural defect or distortion of the electron cloud. Pyrolysis can be divided into depolymerization reaction type, random cracking type, and intermediate type according to the different positions of bond breaks within macromolecules. When the depolymerization reaction type plastic is thermally cracked, the polymer will dissociate, mainly cutting off the chemical bond between the single molecules to generate monomer. This type of plastic

mainly includes PS, PMMA, etc., and their pyrolysis has a high monomer recovery rate [30–32]. The fracture of chemical bond in the molecule of randomly cracked plastics during pyrolysis is random, and a certain number of molecular compounds combined by carbon atoms and hydrogen atoms will be produced, which results in a wide distribution of products, including gas, liquid hydrocarbon, wax and solid residues [4, 33–35]. This type of plastic mainly includes PP, PE, etc. However, the pyrolysis of most plastics belongs to the intermediate type, and under appropriate pyrolysis conditions, products with certain economic value can be obtained. Table 3 shows the product distribution of some plastics during direct pyrolysis.

In the direct pyrolysis process, temperature is clearly the most important factor in controlling the pyrolysis rate and ultimately affecting product quality. When the pyrolysis temperature is below 400 °C, it is easy to form liquid and has a high tendency to coke [44]. When the temperature is between 400 and 600 °C, the main cracking products are mixed light hydrocarbons, naphtha, heavy oil, kerosene, and waxy solids. When the temperature exceeds 600 °C, gas gradually becomes the main product of pyrolysis, such as CH₄. Due to the higher temperature, the bonds between polymer chains are more likely to break, so the gas yield during the reaction process increases with the increase of pyrolysis temperature. According to reports, when the temperature increases from 400 to 800 °C, the gas production of HDPE significantly increases, and the main part of the gas is composed of 1-olefins [44, 45]. Elordi et al. [46] continuously pyrolysis HDPE in spouted bed and found that as the pyrolysis temperature increased from 500 to 700 °C, the gas yield also increased from 1.5% to 39.4%. Hernandez [37] also found the same phenomenon when batch processing HDPE using a fluidized bed reactor. When the pyrolysis temperature is 500 °C, the gas yield is 15.2%, and as the temperature increases to 800 °C, the gas yield also increases to 66.3%. In addition, it has been confirmed that the pyrolysis gas yields of PP, PE, and LDPE increase with the increase of pyrolysis temperature [38, 39]. The researchers also studied the gas yield of plastic mixtures during pyrolysis. Cho et al. [40] investigated the gas yield of mixed plastics composed of PP, PE, PS, and other secondary plastics, such as PMMA and PET at 677–773 °C. The experiment found that as the temperature increased from 677 to 773 °C, the gas yield

Table 2 Process and main pyrolysis products of pyrolysis methods [2]

Pyrolysis methods	Residence time (min)	Heating rate (°C/sec)	Pyrolysis temperature (°C)	Main pyrolysis products
Slow pyrolysis	Hours to days	0.1–1	400	Char
Conventional pyrolysis	5–60	1–1000	400–600	Char, liquid and gas
Rapid pyrolysis	Less than 0.1	Greater than 1000	400	Liquid and gas

Table 3 Product distribution of some plastics during direct pyrolysis process

Waste plastics	Temperature (°C)	Product distribution in weight (wt%)				References
		Gas	Oil	Wax	Residue	
LDPE	430	12.8	79.3	–	7.9	[36]
HDPE	500–800	15.2–66.3	40.9–13.6	7.4–5.8	36.5–14.3	[37]
PP	668–746	54.4–65.9	43.1–29.6	0.5–0.5	2–4	[38]
PE	660–728	36.6–59.3	61–38.2	1.7–0.5	0.7–2	
LDPE	500–700	10.8–71.4	43.9–24.6	45.3–4	–	[39]
PP–PE–PS–Other plastics mixture	677–773	57.8–64.4	35.3–25.9	1.9–2.5	5–7.2	[40]
PP–HDPE–LDPE mixture	450–525	47.87–69.98	26.68–28.8	–	25.46–1.23	[41]
PE	800	46.3	42.6	–	0	[42]
PS	800	5.7	84.3	–	2.3	
PVC	800	44.4	31.3	–	15.6	
PET	800	47.2	38.2	–	4.5	
PS	450	–	80	–	19.6	[25]
PP–PE–PS–PET mixture	600–700	18–51	45–37	36–9.8	1.8–2.3	[43]

increased from 57.8% to 64.4%, while the oil yield decreased from 35.3% to 25.9%. Similarly, Papuga et al. [41] reported the pyrolysis of PP–HDPE–LDPE mixture at 450–525 °C. At the lowest temperature studied, the yields of gas, oil, and residue were 47.87%, 26.68%, and 25.46%, respectively. When the temperature rises to 525 °C, the yields of gas, oil, and residue are 69.98%, 28.8%, and 1.23%, respectively. However, excessively high temperatures are more likely to lead to the cyclization reaction producing more aromatic hydrocarbons, which are formed in the reaction environment of Diels–Alder condensation and dehydrogenation of olefins [47]. Therefore, good temperature control is the key to increasing gas yield and reducing side reaction products.

In addition to pyrolysis temperature, residence time also affects gas yield. Increasing residence time appropriately is beneficial for wax cracking and improving gas yield. Berruoco et al. [48] studied the effect of different residence times on gas yield at 650 °C. When the residence time was increased from 0.8 to 1.5 s, the gas yield increased from 20.3% to 31.5%, and the wax yield decreased from 51.9% to 34.1%. However, for olefinic plastics, prolonged residence time can enhance the cyclization reaction during pyrolysis, leading to an increase in aromatics. Mastral et al. [49] reported the yield of aromatics at 800 °C in a free fall reactor. When the residence time is 1 s, the yield of aromatics is 1.7%. When the residence time increases to 6 s, the yield of aromatics sharply increases to 49% (mainly polycyclic aromatic hydrocarbons). Elordi et al. [46] obtained a BTX yield of less than 3% for continuous pyrolysis of HDPE in a conical spouted bed reactor at 700 °C, due to the short residence time, which limits the formation of aromatic compounds. Therefore, selecting an appropriate residence time is beneficial for improving gas yield while also inhibiting the formation of harmful products, such as aromatic hydrocarbons.

For different types of plastics, due to their different C/H molar ratios and structures, there is also a certain gap in their pyrolysis gas yield. Zhou et al. [42] conducted pyrolysis experiments on PE, PS, PVC, and PET in a fixed bed reactor under conditions of pyrolysis temperature of 800 °C, heating rate of 350 °C/min, and no catalyst. The experiments found that the gas yields of PE, PVC, and PET were 46.3%, 44.4%, and 47.2%, respectively. The gas yield of PS is only 5.7%, while the bio oil yield is as high as 84.3%. The reason is that PS belongs to the depolymerization reaction type plastic, which is easier to generate monomers during the pyrolysis process. Therefore, the pyrolysis of PS has a higher oil yield and a lower gas yield. When studying the pyrolysis of PP and PE, Jung et al. found that at similar pyrolysis temperatures, the gas yield generated by the pyrolysis of PP was higher than that of PE, and with the decrease of pyrolysis temperature, the gap between the pyrolysis gas yield of PP and PE was increasing [38]. This is because the C–H bond of PP is more likely to break than PE, which makes it easier to produce gas. In addition, parameters such as heating rate and reactor type can also have a certain impact on pyrolysis performance, thereby affecting gas yield.

Catalytic Pyrolysis

The pyrolysis reaction is mainly characterized by the breaking of C–C bond, accompanied by the breaking of C–H bond. The thermal effect is an endothermic process. Therefore, in order for the reaction to proceed smoothly, the external environment must provide energy greater than the C–C bond energy. Due to the immaturity of early technology, plastic pyrolysis methods were all simple direct pyrolysis methods. Although this method can provide the energy required to break the C–C bond, it has drawbacks, such as

high energy consumption, low efficiency, and weak selectivity. Therefore, to treat waste plastics with lower energy consumption and higher efficiency, catalytic pyrolysis method has been developed, which involves adding catalysts during the pyrolysis stage. Catalysts play a very important role in the catalytic pyrolysis process, improving product quality and reducing reaction temperature and residence time. In addition, the acidic sites on the catalyst surface will accelerate the reaction rate, affect the reaction mechanism, improve selectivity, and thereby reduce the yield of liquid products and increase the yield of gaseous products [50]. Table 4 shows the distribution of pyrolysis products of various plastics in the presence of different catalysts.

In the presence of catalysts, the decomposition of waste plastics can be completed in two stages. The first stage is related to the disintegration of short chain branches, while the second stage is related to the degradation of the molecular main chain of the main chain. Catalytic cracking is carried out by forming positively charged carbon cations, which are formed by adding protons or removing hydrogen and two electrons from paraffin molecules. In general, carbon cations are unstable, so the properties of the alkyl group connected to it determine the stability of the carbocation. Alkyl σ bond electrons have a “superconjugation” effect on the empty p-orbitals of cations, which can be achieved using their own σ electrons to stabilize electron deficient C atoms. This effect has a stabilizing effect on the electron deficient carbon, which can make the planar carbon cation structure

obtain additional stability. The grade of carbon cations can be determined based on the number of alkyl groups they are connected to. Because alkyl has the inductive effect of electron donor, the more alkyl on the positively charged carbon, the greater the inductive effect of electron donor, which makes the positive charge more dispersed, thus leading to the more stable carbon cations. Among them, the inductive effect of third-grade carbon cations is the largest, so the stability is the best. In the catalytic pyrolysis process of plastics, carbon cations mainly undergo three processes: C–C bond breakage, isomerization, and hydrogen transfer. The C–C bond will break to produce olefins and new carbocations, while the newly formed carbon cations will continue to generate shorter carbon chain olefins through a series of similar reactions. Subsequently, isomerization causes the rearrangement of carbon cations to form third-grade ions, which then undergo cleavage to produce branched molecules. Hydrogen transfer reaction involves the reaction between olefins adsorbed on adjacent active site. At the active site, an olefin molecule will be converted into cycloalkenes and rearranged to form aromatics.

Comparing Tables 3 and 4, it can be found that the use of catalysts promotes the pyrolysis of plastics and significantly reduces the pyrolysis reaction temperature. Senthil Kumar et al. [53] used activated carbon and charcoal as catalysts to pyrolysis PP–PE–PS mixture at 240 °C, respectively, and obtained high oil yields of 82.43% and 95.54%, respectively. This is because the addition of activated carbon and

Table 4 Distribution of pyrolysis products of various plastics in the presence of different catalysts

Waste plastics	Catalysts	Temperature (°C)	residence time (min)	Product distribution in weight (wt%)				Reference
				Gas	Oil	Wax	Residue	
PP	HUSY	360	15	36.73	51.83	–	6.76	[51]
PP	HZSM-5	360	15	67.41	25.54	–	3.92	
PP	HMOR	360	15	59.86	27.95	–	7.17	
PP	SAHA	360	15	22.54	63.65	–	9.83	
PP	MCM-41	360	15	25.47	60.56	–	8.74	
LDPE	ZSM-5	375	–	72.73	24.94	–	2.33	[52]
PP–PE–PS mixture	Activated carbon	240	45	2.35	82.43	–	15.22	[53]
PP–PE–PS mixture	Charcoal	240	35	2.13	95.54	–	2.33	
LDPE	HZSM-5	Above 300	–	70.7	18.3	–	0.5	[54]
HDPE	HZSM-5	Above 300	–	72.6	17.3	–	0.7	
PE	Y-Zeolite (HY8)	440	20	7.61	60.35	32.05	<0.5	[55]
PE	Y-Zeolite (HY26)	440	20	21.11	70.39	8.51	<0.5	
PE	HZSM-5 (SM55)	440	20	25.74	67.28	6.98	<0.5	
PE	HZSM-5 (SM27)	440	20	32.03	62.16	5.81	<0.5	
LDPE	n-HZSM-5	425–475	120	44.9–74.3	6.8–21.9	0.8–0.8	–	[56]
LDPE	Al-MCM-41	425–475	120	10.1–54.3	39.8–42.4	1.3–1.5	–	
LDPE–HDPE–PP mixture	Z–N catalyst	650	3.23 s	54.3	–	–	–	[57]
PP	Al-HMS (Si/Al=99)	380	–	65.5	31.2	–	3.1	[58]

charcoal greatly reduces the melting point of the plastic, so that PP–PE–PS mixture can also obtain a high oil production rate at a low temperature of 240 °C. There are many kinds of catalysts. According to the number of phases involved, catalysts can be divided into homogeneous catalysts and heterogeneous catalysts. Commonly used homogeneous catalysts include iron chloride, aluminum chloride, and titanium chloride [59]. However, for the catalytic pyrolysis of plastics, heterogeneous catalysts are the first choice because they are easy to be separated from the reaction system after the reaction, which not only improves the product quality, but also facilitates the reuse of catalysts and reduces the use cost [60]. HZSM-5, HY, H β and HUSY have been widely used as heterogeneous catalysts, which have promoted the carbon cation cracking of pyrolysis volatiles, followed by isomerization, oligomerization cracking and hydrogen transfer reactions [61]. There are numerous reports on adding catalysts to improve gas yield. Muhammad et al. [62] compared the gas production under noncatalytic and catalytic conditions using HIPS and ABS as pyrolysis raw materials. The catalytic reaction in this study was carried out in a two-stage pyrolysis catalytic reactor system, as shown in Fig. 4. The experimental result indicated that the addition of catalysts increases the gas production. Similarly, Donaj et al. reached the same conclusion when studying the pyrolysis of polyolefins in the presence of catalysts. Donaj found that under the same pyrolysis conditions, when there is no catalyst during the pyrolysis process, the yield of gaseous products is 36.9%, and when there is a catalyst, the yield increases to 54.3% [57]. Hernandez et al. [37, 63] studied the batch catalytic pyrolysis of HDPE on HZSM-5 zeolite in the range of 500–800 °C. At a pyrolysis temperature of 500 °C, they achieved gas yields of up to 88.3%, with propylene and butene yields of 19.5% and 25.7%, respectively. At the same time, they also achieved a high gas yield of 83.4% using HUSY zeolite as a catalyst, but compared to the HZSM-5 catalyst, the content of light olefins was significantly reduced. From the report by Hernandez et al., it can be seen that the total gas yield and gas component yield vary with the use of different catalysts. The reason is that the pore size distribution, acidity, and specific surface area of different catalysts are different.

The pore size distribution of catalysts affects the distribution of pyrolysis products. Salmasi et al. [64] found that smaller pore sizes are beneficial for the formation of small molecule gases, while larger pore sizes increase the yield of oil and coke. Elordi et al. [65] showed through research that there is a significant correlation between the yield of low-carbon olefins and the pore size of the catalyst. HZSM-5 has the highest yield of low-carbon olefins due to its smallest pore size, while HY and H β produce more C5–C11 components due to their larger pore size. Manos et al. [66] also reached a similar conclusion when studying the effect of

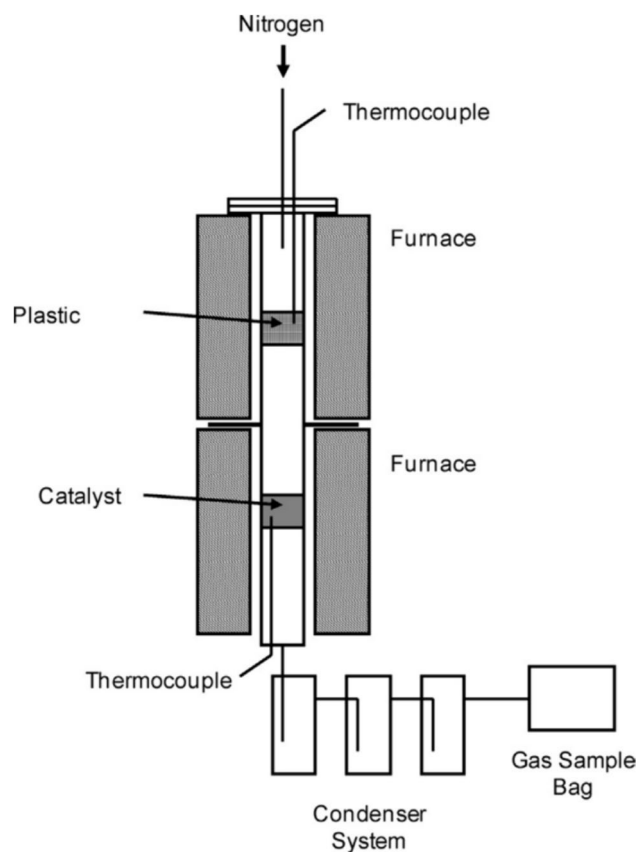


Fig. 4 Schematic diagram of two-stage pyrolysis catalytic reactor system [62]

the porous structure of catalysts on product distribution: the larger the pore size of the catalyst, the greater the molecular weight of the cracking product, that is, the larger the pore size of the catalyst, the higher the molecular weight of hydrocarbons produced. In addition, the porous structure and uniform pore shape play a crucial role in the process of macromolecules formed during plastic degradation reaching the acid sites of the catalyst [67]. The acidity of the catalyst also has a significant impact on the distribution of products, especially gas products. Many studies have shown that using catalysts with higher acidity results in higher yields of gaseous products. Syamsiro et al. [68] compared the processes of direct pyrolysis and catalytic pyrolysis and found that the higher acidity of natural zeolite increased the surface area of the catalyst, thereby increasing the yield of gas products. Zeaiter used H-Beta high acid content catalyst for catalytic pyrolysis of waste HDPE, achieving a high gas yield of 95.7% [35]. Due to the presence of long chains in polyethylene, cracking occurs randomly, making it easier for this type of plastic to generate gas during catalytic pyrolysis [69]. However, too high acidity will promote the formation of polycyclic aromatic hydrocarbons and carbon deposits. Elordi et al. [70] investigated the effect of acidity of the

HZSM-5 catalyst on the pyrolysis of HDPE. The results showed that the generation of light hydrocarbons was mainly caused by acid sites. When the acidity of the catalyst was low, the pyrolysis products were mainly low-carbon olefins. As the acidity increased, more aromatic hydrocarbons were formed, leading to a decrease in the selectivity of low-carbon olefins. Carbon deposition can lead to catalyst deactivation and reduce the service life of the catalyst, which is a common problem during the use of the catalyst. Vasile et al. [71] significantly reduced the carbon deposition on the catalyst by modifying it to reduce the acidity of the catalyst. In addition, studies have found that the carbon deposition rate of large pore catalysts is higher than that of small pore catalysts [72]. Therefore, strong acidity and large pore size can lead to rapid deactivation of the catalyst. It is recommended to use a catalyst with moderate acidity and small pore size for plastic cracking reaction. This not only helps to improve the service life of the catalyst, but also helps to increase the yield of gaseous products. However, some scholars have proposed different views, with Sun et al. [73] suggesting that a larger catalyst pore size is beneficial for inhibiting the formation of carbon deposition. Sun et al. [74] also reached a similar conclusion, stating that catalysts with smaller pore sizes are more prone to carbon deposition issues.

The gas yield during the pyrolysis process is also closely related to the contact mode between the catalyst and the polymer. The contact methods between catalysts and polymers include liquid phase contact and gas phase contact, also known as in situ catalysis and non in situ catalysis, and their working principles are shown in Fig. 5a, b. In gas phase contact (non in situ catalysis) thermal degradation, plastics are first thermally degraded into hydrocarbon vapors, and then react in contact with catalysts fixed on a fixed bed. In the thermal degradation of liquid phase contact (in situ catalysis), the catalyst and

plastic are contained in the same reactor system and heated to the specified operating temperature [75]. In gas phase contact, due to the further reaction of thermally degraded hydrocarbons with the catalyst to generate gas, the gas yield generated by catalytic pyrolysis in gas phase contact is higher than that of direct pyrolysis, while the liquid yield is lower than that of direct pyrolysis. For catalytic pyrolysis in liquid phase contact, the liquid yield is generally higher than that of direct pyrolysis, but at the cost of residue yield, while the gas yield is not significantly different from that of direct pyrolysis. Sakata et al. [76] used a silica alumina catalyst to catalyze the pyrolysis of PP at a pyrolysis temperature of 380 °C. The experiment found that compared to liquid phase contact, the gas yield in gas phase contact was higher, while liquid phase contact produced a higher proportion of liquid products. Due to different contact methods leading to different distribution of catalytic pyrolysis products, it is of great significance to strengthen the research on the contact methods between catalysts and polymers to improve the gas yield of plastic catalytic pyrolysis. In addition, other factors, including the catalyst/plastic ratio, can also have a certain impact on the distribution of gas–solid liquid products during catalytic pyrolysis.

At present, many scientific researchers have done a lot of work on the catalytic pyrolysis process of waste plastics and the development of catalysts, and have achieved some results. However, although the addition of catalysts improves the pyrolysis method of plastics, the use of catalysts increases costs, and the catalysts are prone to coke deposition and deactivation, and the catalysts themselves are not easily recyclable. Therefore, it is necessary to further improve the catalytic pyrolysis process, reduce the cost of catalyst use, and improve the recovery rate of catalyst use.

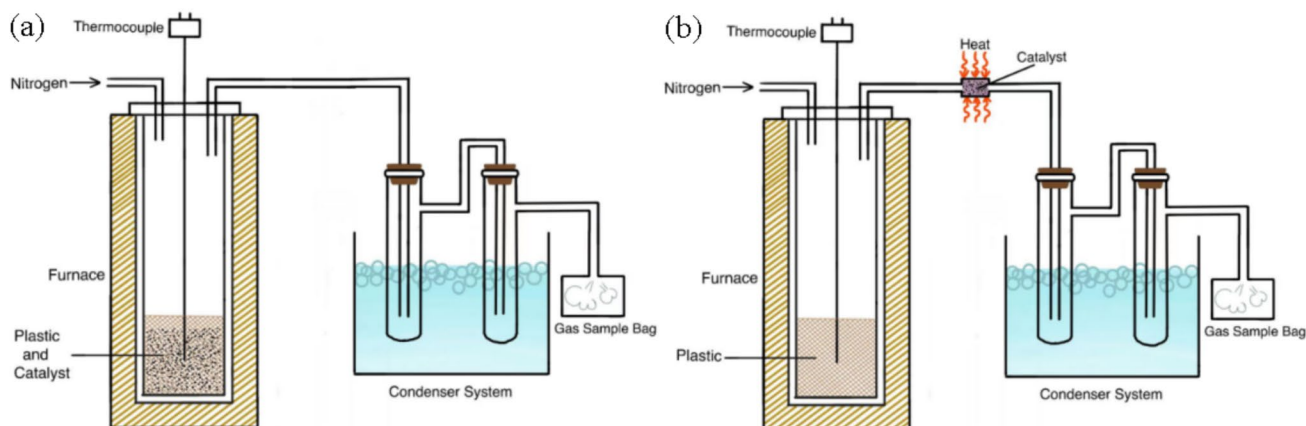


Fig. 5 Different contact modes between catalyst and polymer: **a** liquid phase contact (in situ catalysis); **b** gas phase contact (non in situ catalysis)

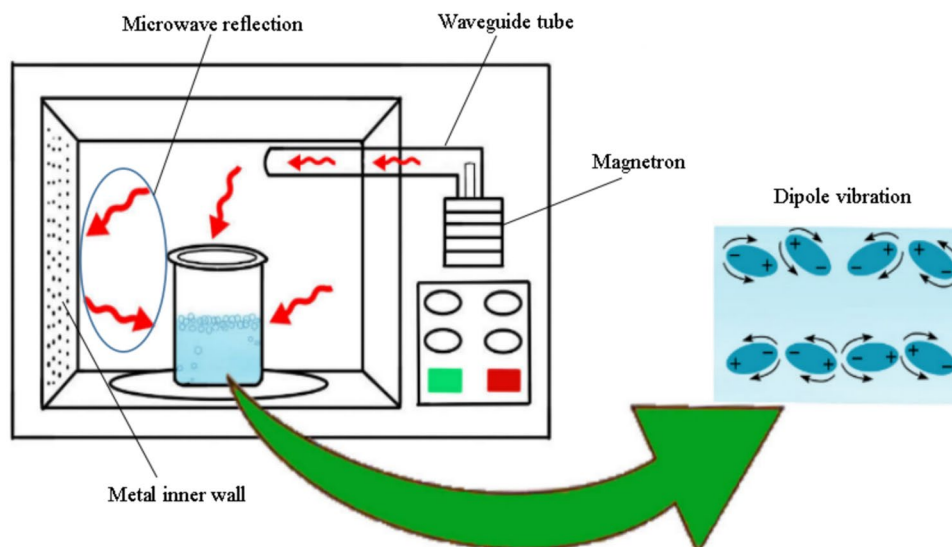
Microwave Pyrolysis

Introduction to Microwave and Heating Mechanism

Microwave is part of the electromagnetic spectrum, its frequency is between 300 MHz and 300 GHz, and the corresponding wavelength is between 1 and 1 mm. It has the characteristics of easy clustering, high directionality, and linear propagation, and can be used to transmit high-frequency signals in unobstructed free space of the line of sight. During World War II, microwave technology was first applied in practical applications during the development of high-definition radar. Afterwards, with the invention of cavity magnetrons with inexpensive, efficient, and high-power microwave sources, the use of microwave technology became more widespread [77]. Among them, using microwave heating is the most common use. Microwave heating is a heating method that relies on objects absorbing microwave energy to convert it into heat energy, causing the overall temperature of the body to rise simultaneously. Figure 6 shows a schematic diagram of the microwave heating mechanism. Unlike traditional heating methods, it generates “internal frictional heat” by high-frequency reciprocating motion of the dipole inside the heated object, which increases the temperature of the heated object. During this period, there is no need for any heat transfer process, and the internal and external parts of the object can be heated simultaneously, with a fast and uniform heating speed. In addition, compared to traditional heating, microwave heating has lower energy consumption, usually only a fraction of the energy consumption of traditional heating. Previously, microwave heating was mainly used for food processing, but with

the continuous development and research of microwave technology, the application of microwave heating in fields such as metal melting, chemical synthesis, and pyrolysis has gradually increased. The effect of microwave heating varies for different materials, and the fundamental reason is that different materials have different abilities to absorb microwave energy and convert it into heat energy. The ability of a material to convert incident microwave energy into thermal energy depends on the loss tangent parameter, which is the ratio of the material's dielectric factor to dielectric constant. The dielectric factor gives the characteristic of a material converting stored microwave energy into heat, while the dielectric constant describes the storage space of microwave energy. According to the loss tangent value, materials can be divided into high (>0.5), medium ($0.1\text{--}0.5$), and low (<0.1) microwave absorbers. According to the interaction between materials and the electric field components of microwave fields, materials can be divided into insulators, reflectors, and absorbers. Common microwave absorbers include water, ceramics, carbon materials, and metal powders, which have significant loss tangent values. When microwaves pass through these materials, the vast majority of microwave energy is absorbed and converted into thermal energy. Materials such as plastic and glass that have very small tangent loss values are called insulators, meaning that there is almost no loss when microwaves pass through them. For microwave reflectors, microwaves are generally unable to penetrate them and will be reflected back. Metal blocks are the most common microwave reflectors, and when heating metal blocks with microwaves, they may even generate arcs or sparks [78]. The reason is that when microwaves heat metal, they provide energy for the outer orbital electrons of the metal, causing free electrons on the metal

Fig. 6 Schematic diagram of microwave heating mechanism



surface to start moving rapidly, while preventing electromagnetic waves from entering the metal, so that electromagnetic waves can only be reflected. If a metal object with obvious edges, such as a metal fork is heated, it will cause the concentration of electric fields in certain areas to form a large potential difference, leading to dielectric breakdown of the air. The resulting charge becomes strong enough to ionize the surrounding air and ultimately generate sparks.

Application of Microwave in Plastic Pyrolysis

Microwave-assisted pyrolysis is a new plastic pyrolysis technology that reduces the processing time of raw materials, improves heating rate, and reduces energy consumption compared to traditional pyrolysis. Due to the fact that plastic itself is an insulator, it does not absorb microwaves. Therefore, when using microwave pyrolysis of plastics, it is necessary to mix some microwave absorbers, such as silicon carbide, metal powder, etc. During the pyrolysis process, microwave electromagnetic energy is preferentially absorbed by microwave absorbers, and then heat is rapidly generated on the microwave absorbers, which are then transferred to the plastic to achieve the purpose of heating the plastic. Many of these absorbers have catalytic effects on plastic pyrolysis, such as metal catalysts, activated carbon, etc. Here, we collectively refer to them as absorbing catalysts. The addition of such catalysts not only has the effect of absorbing microwaves to generate heat, but also has a very good catalytic effect under the combined action of microwave. Because in the process of microwave-assisted catalytic pyrolysis, microwave can improve the selectivity and activity of the catalyst in the reaction, prolong the catalyst's service life, greatly reduce the side reactions of traditional plastic catalytic pyrolysis, and reduce the distribution of chemical products. There are many factors that can affect the results of plastic microwave pyrolysis, including microwave power,

microwave temperature, type of plastic, type of absorbent, and type of catalyst, all of which can affect the distribution of pyrolysis products. Therefore, exploring the mechanism of these factors in plastic microwave pyrolysis can help to minimize the cost of plastic microwave pyrolysis and improve the yield of valuable products. Table 5 shows the distribution of pyrolysis products of some plastics in microwave field.

The Influence of Microwave Temperature and Power

Similar to direct pyrolysis, the microwave temperature also greatly affects the gas yield of plastic pyrolysis. Fan et al. [79] studied the microwave-assisted pyrolysis of low-density polyethylene using magnesium oxide. In this study, silicon carbide (SiC) was used as a microwave absorber, while magnesium oxide was loaded as a catalyst in a separate catalyst bed, through which volatile compounds produced by plastic pyrolysis would pass and undergo further cracking. Fan found that the gas yield always increases with the increase of pyrolysis temperature, with the liquid yield increasing from 24.2 wt% at 350 °C to 30.1 wt% at 500 °C. However, as the temperature further increases, the liquid yield decreases. This is because the increase in temperature intensifies the decomposition reaction of the liquid, converting more liquid products into gas compounds. In addition, these researchers also studied the effect of catalytic reaction temperature on the yield of pyrolysis products. They found that as the catalytic reaction temperature increased, the gas yield significantly increased, while the liquid yield showed the opposite trend. This is because an increase in temperature will enhance the catalytic activity of magnesium oxide, thereby promoting the degradation of long-chain hydrocarbon macromolecules. Zhou et al. [80] studied the effect of microwave temperature on gas yield without the addition of a catalyst. Research has found that when the temperature increases from 500 to 740 °C, the yield of non-condensable

Table 5 Distribution of some plastic pyrolysis products in microwave field

Waste plastics	Catalysts	Microwave absorbers	Pyrolysis temperature (°C)	catalytic reaction temperature (°C)	Product distribution in weight (wt%)				References
					Gas	Oil	Wax	Residue	
LDPE	MgO	SiC	350	450	26.3	24.2	–	49.5	[79]
LDPE	MgO	SiC	500	450	66.7	30.1	–	3.2	
LDPE	MgO	SiC	500	350	56.6	38.5	–	4.9	
LDPE	MgO	SiC	500	550	72.8	24.4	–	2.8	
LDPE	No	SiC	500	–	52.8	46.3	–	0.9	
HDPE	No	SiC	500	–	17.6	33.2	40.5	8.7	[80]
HDPE	No	SiC	620	–	37.6	40.2	15.7	6.5	
HDPE	No	SiC	740	–	74.7	18.3	1.3	5.7	
Pure PP	No	SiC	620	–	48.6	44.8	5.2	1.4	
LDPE	ZSM-5	—	480	375	75.59	22.16	–	2.26	[52]

gas increases from 17.6 to 74.7 wt%, while the yield of wax decreases from 40.5 to 1.3 wt%. In addition, the yield of liquid products increases first and then decreases with the increase of temperature. The level of microwave power directly affects the heating rate of microwave pyrolysis. Dai et al. [81] found in their experiment that when the microwave power was increased from 800 to 1000 W, the heating rate increased from 257 to 402 °C/min. Liu [82] found that the heating rate at 1400W microwave power was almost four times that of 400W when using microwave to heat mixed waste. Undri et al. [83] believed that lower microwave power would prolong the pyrolysis residence time, thereby promoting the gasification and condensation reactions of pyrolysis steam and increasing liquid yield. At the same time, lower microwave power also reduces the reaction that may form carbon or gas products.

The Impact of Different Types of Plastics

The type of plastic has always been a very important factor in any pyrolysis methods. As mentioned in direct pyrolysis, the C/H molar ratio and structure of different plastics are different, so their pyrolysis product distribution is also different. Zhou et al. [80] conducted pyrolysis experiments on HDPE, pure PP, and PP with fillers at a microwave temperature of 620 °C. Zhou observed that the gas yield of pure PP pyrolysis (48.6%) was higher than that of HDPE (37.6%), indicating that PP is more prone to thermal degradation than HDPE. C₃H₆, CH₄, C₂H₄, C₃H₈, and C₄H₈ account for the majority of the volume of pure PP pyrolysis gas, while the pyrolysis gas of HDPE is mainly composed of H₂, CH₄, C₂H₄, and C₃H₆, which account for over 80% of the total volume. Undri [84] discovered a similar situation during the experimental process, where he found that under the same experimental conditions, PP was completely pyrolyzed, while HDPE was only partially pyrolyzed. This is consistent with many research results based on thermogravimetric analysis, which indicate that the activation energy of HDPE thermal degradation is higher than that of PP [85]. Fan [79] achieved 46.3% liquid yield and 52.8% gas yield by pyrolysis of LDPE using a microwave reactor without catalyst. At the same time, Fan also found that aromatic hydrocarbons and fatty hydrocarbons are the main components in petroleum products. Zhang et al. [52] also studied the microwave pyrolysis of LDPE and used ZSM-5 catalyst during the pyrolysis process. The highest gas yield obtained by Zhang through experiments is 75.59%, and the highest oil yield is 32.58%. Here, they found a large amount of monocyclic aromatic hydrocarbons present in the pyrolysis oil. This is due to the structure of LDPE, which has a high degree of branching short chain, which is conducive to the cracking, condensation and aromatization of small olefins to form branched aromatics.

The Influence of Absorbers and Catalysts

Silicon carbide, activated carbon, and metal powder are widely used as absorbers in microwave pyrolysis. Rex et al. [86] used rice husk charcoal (RHC), corn husk charcoal (CHC), and coconut sheath charcoal (CSC) as absorbers for microwave pyrolysis of polystyrene waste and polypropylene waste, respectively. The experiment found that when corn husk charcoal was used as the absorbent, the gas yield of polystyrene waste microwave pyrolysis was the highest (15.80%), while the gas yield using coconut sheath charcoal as the absorbent was the lowest (10.50%). In addition, under the condition of rice husk charcoal as the absorbent, there was the lowest oil yield and the highest residue yield. Meanwhile, Rex found that the gas yield generated by microwave pyrolysis of polypropylene waste using the above three types of carbon as absorbents was much higher than that of polystyrene waste, with 80.70% (RHC), 58.77% (CHC), and 41.70% (CSC), respectively. This is because compared with polystyrene, polypropylene is easier to break its internal chemical bond during pyrolysis, and its randomness is stronger, so it is easier to generate gas products. Khaghanikavkani et al. [87] used carbon blocks and silicon carbide powder as absorbers for microwave pyrolysis of HDPE. Khaghanikavkani found through research that the gas yield using silicon carbide as an absorber is higher than that of carbon blocks, because silicon carbide has a higher loss coefficient and thermal conductivity, which lead to the plastic reaching the pyrolysis temperature in a short period of time. Therefore, compared to experiments using carbon blocks as absorbers, the pyrolysis products are exposed to high temperatures for a longer time, which leads to more severe decomposition of the polymer chain and the generation of more gas products.

Adding catalysts to the microwave pyrolysis process is currently a relatively effective method for plastic pyrolysis. Under the combined action of microwave and catalyst, not only does it shorten the time of plastic pyrolysis, reduce energy consumption, but also improve the selectivity of chemical reactions. Like plastic catalytic pyrolysis without microwave, microwave-assisted catalytic pyrolysis is also divided into in-situ catalysis and non in-situ catalysis based on the contact mode between the catalyst and the polymer. During the experimental process, the catalytic method will be determined based on the type, function, and possible reactions of the catalyst. Ding et al. [88] used silicon carbide as an absorber and HY zeolite as a non in-situ catalyst to catalyze microwave pyrolysis of LDPE. The reaction device is shown in Fig. 7. They found that as the ratio of HY to LDPE increased from 0 to 1:5, the gas yield first decreased and then increased. In addition, they also found that HY zeolite reduced the content of most C₁–C₃ hydrocarbons and increased the content of C₄₊ gas. These phenomena indicate

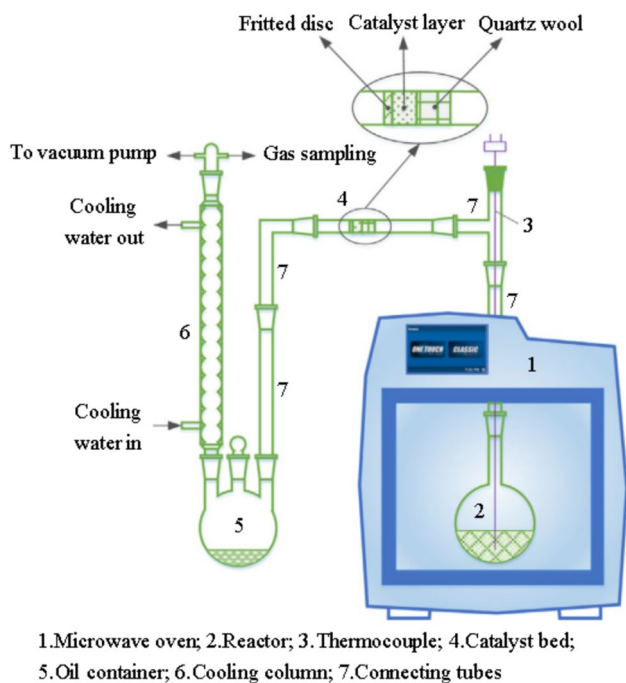


Fig. 7 Device diagram of microwave catalytic reaction system [88]

that HY zeolite promotes the conversion of light gases into compounds with relatively larger molecules. These researchers also studied the co catalysis of NiO and HY in the same reaction device. They added NiO as an in situ catalyst to the raw material to improve the quality of oil products while minimizing adverse decreases in oil production. In the experimental design, the mass ratio of NiO to HY increased from 1:15 to 1:3. The other conditions are: pyrolysis temperature is 500 °C, catalytic temperature is 450 °C, and the ratio of HY to LDPE is 1:10. Compared with using HY catalyst alone, the addition of NiO slightly increased the yield of natural gas from 41.80 to 47.77–50.46 wt%, while the yield of oil decreased slightly from 56.54 to 48.08–51.23 wt%. The reason why NiO has a relatively small impact on product yield here may be due to the low ratio of NiO to LDPE (ranging from 1:150 to 1:30). Ding also found that NiO reduced the normal aliphatic structure, promoted the formation of aromatic compounds, and thus increased the octane number of the oil. Fan et al. [89] found in the microwave pyrolysis of LDPE using silicon carbide as an absorber and HZSM-5 as a non in-situ catalyst that as the catalyst loading increased from 5% to 20%, the gas yield increased from 56.0 to 70.3 wt%, while the condensate yield decreased from 41.5 to 25.4 wt%. This is because the HZSM-5 catalyst used in this experiment has a strong catalytic effect on C–C cracking, enhancing the decomposition of long-chain aliphatics. Researchers [90] used activated carbon and molecular sieve catalysts (MS4A and MS13X) to pyrolysis HDPE in a microwave reactor. This study shows that when molecular sieve

catalysts are introduced, they promote the end chain fracture reaction, resulting in the generation of more gases, and MS13X has a better catalytic effect on promoting end chain fracture than MS4A in the pyrolysis system. In this study, activated carbon not only serves as a microwave absorber, but also has a catalytic effect on the production of liquid products. Jie et al. [91] studied the process of microwave-assisted plastic pyrolysis into hydrogen and high-value carbon in the presence of FeAlO_x catalyst. Here, FeAlO_x is both a catalyst and an absorber. Jie found that unlike traditional plastic catalytic pyrolysis processes where both the plastic and the catalyst must be heated, this process selectively generates heat on the catalyst and then transfers it to the plastic. This is an important difference, because the heat flow is from the surface of the catalyst and mass transfer will obviously occur in the same direction, which will help neutral hydrogen molecules or atoms to be desorbed from the active site on the catalyst surface. Traditional catalytic pyrolysis mainly heats up through thermal convection and conduction, which is usually affected by heat and mass transfer limitations. Jie et al. believe that microwave catalyzed pyrolysis is beneficial for avoiding many side reactions generated by the self-decomposition of plastic polymers, thereby reducing the distribution of pyrolysis products and selectively increasing the yield of valuable products.

Conclusion and Challenge

With the increasingly serious pollution caused by plastic waste to the environment, the chemical recycling and reuse of waste plastics has received unprecedented attention. Among the numerous chemical recycling pathways, pyrolysis is currently a relatively green and environmentally friendly, efficient and stable plastic waste treatment technology. But the vast majority of research on plastic pyrolysis focuses on how to produce high-value and high-yield liquid products, such as petroleum. Although there is much less research on pyrolysis gases of waste plastics than liquids, pyrolysis gases also have high utilization value, such as H_2 and CH_4 , which have very good application prospects in many industries. This article provides a detailed explanation of the pyrolysis mechanism, gas yield and composition of plastics in different pyrolysis pathways, and discusses and analyzes the effects of factors, such as pyrolysis temperature, plastic type, catalyst type, and absorber type on pyrolysis gas products.

Although the pyrolysis technology has gradually matured in the recycling of waste plastic recycling, and a synergistic regulation mechanism targeting multiple products can be formed based on the generation mechanism of different pyrolysis products, so as to avoid the production of harmful by-products while generating a large number of valuable

gases. However, due to various uncontrollable factors, there are still many key issues in the precise regulation of many target products. From a long-term perspective, pyrolysis will be the main path for the chemical recovery of waste plastics for a considerable period of time. Therefore, strengthening research on plastic pyrolysis and solving the problems existing in the pyrolysis process are of great significance for improving the environment and reusing resources. The conclusions and challenges that can be drawn from the direct pyrolysis, catalytic pyrolysis, and microwave pyrolysis of waste plastics are as follows.

1. During the pyrolysis process, the pyrolysis temperature and residence time have a significant impact on the distribution of plastic pyrolysis products. At higher temperatures, gas products are more likely to be generated, but excessive temperatures can promote the cyclization reaction to produce more aromatic hydrocarbons. Similarly, extending the residence time is beneficial for wax cracking and improving gas yield, but excessive residence time can enhance the cyclization reaction during pyrolysis, leading to an increase in aromatics. Therefore, appropriate pyrolysis temperature and residence time are necessary factors for improving gas yield and reducing the generation of harmful by-products.
2. Due to differences in C/H molar ratio and structure, different types of plastics have significant differences in their pyrolysis conditions and product distribution. However, the relationship between the structure and C/H molar ratio of different plastics and pyrolysis conditions is not yet clear. Further research is needed to investigate the cracking mechanism of different types of plastics under different pyrolysis conditions, to obtain the optimal pyrolysis conditions for producing target gases for different types of plastics and provide scientific guidance for subsequent development.
3. Adding catalysts during the pyrolysis process not only improves the selectivity and quality of the product, reduces the pyrolysis temperature and residence time, but also largely avoids the generation of non-target products. Although the addition of catalysts has greatly improved the process of plastic pyrolysis, there are still many problems to be solved. The main challenges faced by plastic catalytic pyrolysis are the easy deactivation and low recovery rate of catalysts. The factors of catalysts themselves and the effects of plastic pyrolysis products are the key to studying how to improve catalyst activity and recovery rate. Therefore, strengthening the research on the mechanism of catalyst action and the impact of plastic pyrolysis products on the catalyst is of great significance for improving the plastic catalytic pyrolysis process and reducing pyrolysis costs. In addition, the contact mode between the polymer and the

catalyst also affects the distribution of pyrolysis products. Under gas phase contact (non in situ catalysis) conditions, there is more abundant gas production, while liquid phase contact (in situ catalysis) generates more liquid products.

4. Compared with traditional plastic pyrolysis, microwave pyrolysis has higher efficiency and lower energy consumption. However, this technology emerged relatively late and has been studied relatively little, resulting in many challenges. One of the challenges of microwave pyrolysis is the formation of hot spots, which can lead to uneven heating and easily lead to the solidification of pyrolysis oil generated during plastic pyrolysis on the reactor wall. Microwave temperature and power are key factors in the formation of hot spots. Therefore, good temperature and power control are necessary conditions for improving pyrolysis performance. Another challenge of microwave pyrolysis is the lack of research on the application of metal catalysts in microwave. At present, most microwave catalytic pyrolysis requires the addition of both absorbing agents and catalysts, while metal catalysts have a dual effect of absorbing and catalyzing in the process of plastic microwave pyrolysis, which reduces costs while also reducing other side reactions. However, due to the belief that metals can generate arcs and sparks, which can cause damage to microwave equipment, the presence of metal catalysts is generally avoided during microwave catalytic pyrolysis. Therefore, it is necessary to strengthen the research on the interaction mechanism between microwaves and metals, and establish the correlation mechanism between the two, laying the foundation for the more reasonable and efficient application of metal catalysts in plastic microwave catalytic pyrolysis. In addition, accurate measurement of temperature is also a difficulty in microwave pyrolysis. Currently, most of the temperature measurement tools used in microwave are easily limited by time and space, which leads to low accuracy in temperature measurement and often cannot represent the accurate temperature of reactants. Therefore, it is necessary to improve and improve the microwave temperature measurement system to accurately monitor the temperature of reactants and provide a basis for the production of target products during plastic pyrolysis.

Acknowledgements The National Natural Science Foundation of China (Grant No.51961020) supported this work. The authors would like to thank Yunnan Province "Xingdian Talent Support Plan" industrial innovative talents (XDYC-CYCX-2022-0044).

Data availability Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- G. Lopez, M. Artetxe, M. Amutio, J. Bilbao, M. Olazar, Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. *Renew. Sustain. Energy Rev.* **73**, 346–368 (2017)
- S. Kartik, H.K. Balsora, M. Sharma, A. Saptoru, R.K. Jain, J.B. Joshi et al., Valorization of plastic wastes for production of fuels and value-added chemicals through pyrolysis—a review. *Thermal Sci. Eng. Progress* **32**, 101316 (2022)
- M.M. Ismail, I. Dincer, A new renewable energy based integrated gasification system for hydrogen production from plastic wastes. *Energy* **270**, 126869 (2023)
- D.S. Achilias, C. Roupakias, P. Megalokonomos, A.A. Lappas, E.V. Antonakou, Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). *J. Hazard. Mater.* **149**, 536–542 (2007)
- G. Celik, R.M. Kennedy, R.A. Hackler, M. Ferrandon, A. Tennakoon, S. Patnaik et al., Upcycling single-use polyethylene into high-quality liquid products. *ACS Cent. Sci.* **5**, 1795–1803 (2019)
- D.C. Ashworth, P. Elliott, M.B. Toledano, Waste incineration and adverse birth and neonatal outcomes: a systematic review. *Environ. Int.* **69**, 120–132 (2014)
- D.-D. Yao, C.-H. Wang, Pyrolysis and in-line catalytic decomposition of polypropylene to carbon nanomaterials and hydrogen over Fe- and Ni-based catalysts. *Appl. Energy* **265**, 114819 (2020)
- M. Franchini, M. Rial, E. Buiatti, F. Bianchi, Health effects of exposure to waste incinerator emissions: a review of epidemiological studies. *Annali dell'Istituto Superiore di Sanita* **40**, 101–115 (2005)
- N. Yang, H. Zhang, M. Chen, L.-M. Shao, P.-J. He, Greenhouse gas emissions from MSW incineration in China: impacts of waste characteristics and energy recovery. *Waste Manage.* **32**, 2552–2560 (2012)
- E.L. Teuten, J.M. Saquing, D.R.U. Knappe, M.A. Barlaz, S. Jonsson, A. Bjorn et al., Transport and release of chemicals from plastics to the environment and to wildlife. *Philos. Trans. R. Soc. B: Biol. Sci.* **364**, 2027–2045 (2009)
- J.-P. Lange, Managing plastic waste—sorting, recycling, disposal, and product redesign. *ACS Sustain. Chem. Eng.* **9**, 15722–15738 (2021)
- K. Ragaert, L. Delva, K. Van Geem, Mechanical and chemical recycling of solid plastic waste. *Waste Manage.* **69**, 24–58 (2017)
- R.K. Singh, B. Ruj, A.K. Sadhukhan, P. Gupta, Conventional pyrolysis of plastic waste for product recovery and utilization of pyrolytic gases for carbon nanotubes production. *Environ. Sci. Pollut. Res.* **29**, 20007–20016 (2022)
- K.K. Jha, T.T.M. Kannan, Alternate fuel preparation in low cost from waste plastic: a review. *Mater. Today: Proc.* **37**, 3656–3657 (2021)
- S.D. Anuar Sharuddin, F. Abnisa, W.M.A. Wan Daud, M.K. Aroua, A review on pyrolysis of plastic wastes. *Energy Convers. Manage.* **115**, 308–326 (2016)
- B. Kunwar, H.N. Cheng, S.R. Chandrashekar, B.K. Sharma, Plastics to fuel: a review. *Renew. Sustain. Energy Rev.* **54**, 421–428 (2016)
- S.L. Wong, N. Ngadi, T.A.T. Abdullah, Current state and future prospects of plastic waste as source of fuel: a review. *Renew. Sustain. Energy Rev.* **50**, 1167–1180 (2015)
- X.Q. Jia, C. Qin, T. Friedberger, Z.B. Guan, Z. Huang, Efficient and selective degradation of polyethylenes into liquid fuels and waxes under mild conditions. *Sci. Adv.* **2**, e1501591 (2016)
- TPE magazine international Group, *Plastics - the Facts 2017*. An analysis of European plastics production, demand and waste data. *TPE Mag. Int.* **9**, 93 (2018)
- AIE. The future of petrochemicals: Towards more sustainable plastics and fertilisers. International Energy Agency 2018.
- R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made. *Sci. Adv.* **3**, e1700782 (2017)
- F.M. Tsai, T.D. Bui, M.L. Tseng, M.K. Lim, J.Y. Hu, Municipal solid waste management in a circular economy: a data-driven bibliometric analysis. *J. Clean. Prod.* **275**, 124132 (2020)
- M.A. Charitopoulou, K.G. Kalogiannis, A.A. Lappas, D.S. Achilias, Novel trends in the thermo-chemical recycling of plastics from WEEE containing brominated flame retardants. *Environ. Sci. Pollut. Res. Int.* **28**, 59190–59213 (2021)
- A. Ramos, A. Rouboa, Renewable energy from solid waste: life cycle analysis and social welfare. *Environ. Impact Assess. Rev.* **85**, 106469 (2020)
- J.A. Onwudili, N. Insura, P.T. Williams, Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time. *J. Anal. Appl. Pyrol.* **86**, 293–303 (2009)
- X.H. Zhao, M. Korey, K. Li, K. Copenhagen, H. Tekinalp, S. Celik et al., Plastic waste upcycling toward a circular economy. *Chem. Eng. J.* **428**, 131928 (2022)
- X. Hu, H.Y. Guo, M. Gholizadeh, B. Sattari, Q. Liu, Pyrolysis of different wood species: Impacts of C/H ratio in feedstock on distribution of pyrolysis products. *Biomass Bioenerg.* **120**, 28–39 (2019)
- P.H.M. Putra, S. Rozali, M.F.A. Patah, A. Idris, A review of microwave pyrolysis as a sustainable plastic waste management technique. *J. Environ. Manage.* **303**, 114240 (2022)
- A. Marcilla, M.I. Beltran, R. Navarro, Thermal and catalytic pyrolysis of polyethylene over HZSM5 and HUSY zeolites in a batch reactor under dynamic conditions. *Appl. Catal. B* **86**, 78–86 (2009)
- M. Artetxe, G. Lopez, M. Amutio, I. Barbarias, A. Arregi, R. Aguado et al., Styrene recovery from polystyrene by flash pyrolysis in a conical spouted bed reactor. *Waste Manage.* **45**, 126–133 (2015)
- B.S. Kang, S.G. Kim, J.S. Kim, Thermal degradation of poly(methyl methacrylate) polymers: kinetics and recovery of monomers using a fluidized bed reactor. *J. Anal. Appl. Pyrol.* **81**, 7–13 (2008)
- Y. Mo, L. Zhao, Z.H. Wang, C.L. Chen, G.Y.A. Tan, J.Y. Wang, Enhanced styrene recovery from waste polystyrene pyrolysis using response surface methodology coupled with Box-Behnken design. *Waste Manage.* **34**, 763–769 (2014)
- F. Obeid, J. Zeaiter, A.H. Al-Muhtaseb, K. Bouhadir, Thermocatalytic pyrolysis of waste polyethylene bottles in a packed bed reactor with different bed materials and catalysts. *Energy Convers. Manage.* **85**, 1–6 (2014)
- W.C. Huang, M.S. Huang, C.F. Huang, C.C. Chen, K.L. Ou, Thermochemical conversion of polymer wastes into hydrocarbon fuels over various fluidizing cracking catalysts. *Fuel* **89**, 2305–2316 (2010)
- J. Zeaiter, A process study on the pyrolysis of waste polyethylene. *Fuel* **133**, 276–282 (2014)
- Q. Zhou, L. Zheng, Y.Z. Wang, G.M. Zhao, B. Wang, Catalytic degradation of low-density polyethylene and polypropylene

- using modified ZSM-5 zeolites. *Polym. Degrad. Stab.* **84**, 493–497 (2004)
37. M.R. Hernandez, A.N. Garcia, A. Marcilla, Catalytic flash pyrolysis of HDPE in a fluidized bed reactor for recovery of fuel-like hydrocarbons. *J. Anal. Appl. Pyrol.* **78**, 272–281 (2007)
 38. S.H. Jung, M.H. Cho, B.S. Kang, J.S. Kim, Pyrolysis of a fraction of waste polypropylene and polyethylene for the recovery of BTX aromatics using a fluidized bed reactor. *Fuel Process. Technol.* **91**, 277–284 (2010)
 39. P.T. Williams, E.A. Williams, Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. *J. Anal. Appl. Pyrol.* **51**, 107–126 (1999)
 40. M.H. Cho, S.H. Jung, J.S. Kim, Pyrolysis of mixed plastic wastes for the recovery of benzene, toluene, and xylene (BTX) aromatics in a fluidized bed and chlorine removal by applying various additives. *Energy Fuels* **24**, 1389–1395 (2010)
 41. S.V. Papuga, P.M. Gvero, L.M. Vukic, Temperature and time influence on the waste plastics pyrolysis in the fixed bed reactor. *Therm. Sci.* **20**, 731–741 (2016)
 42. H. Zhou, C.F. Wu, J.A. Onwudili, A.H. Meng, Y.G. Zhang, P.T. Williams, Polycyclic aromatic hydrocarbons (PAH) formation from the pyrolysis of different municipal solid waste fractions. *Waste Manage.* **36**, 136–146 (2015)
 43. G. Grause, S. Matsumoto, T. Kameda, T. Yoshioka, Pyrolysis of mixed plastics in a fluidized bed of hard burnt lime. *Ind. Eng. Chem. Res.* **50**, 5459–5466 (2011)
 44. Ghosh P, Sengupta S, Singh L, Sahay A. Life cycle assessment of waste-to-bioenergy processes: a review. *Bioreactors* 2020; 105–122.
 45. D. Almeida, M.D. Marques, Thermal and catalytic pyrolysis of plastic waste. *Polimeros-Ciencia e Tecnologia* **26**, 44–51 (2015)
 46. G. Elordi, M. Olazar, G. Lopez, M. Artetxe, J. Bilbao, Product yields and compositions in the continuous pyrolysis of high-density polyethylene in a conical spouted bed reactor. *Ind. Eng. Chem. Res.* **50**, 6650–6659 (2011)
 47. C.M. Simon, W. Kaminsky, Chemical recycling of polytetrafluoroethylene by pyrolysis. *Polym. Degrad. Stab.* **62**, 1–7 (1998)
 48. C. Berruero, F.J. Mastral, E. Esperanza, J. Ceamanos, Production of waxes and tars from the continuous pyrolysis of high density polyethylene. Influence of operation variables. *Energy Fuels* **16**, 1148–1153 (2002)
 49. J.F. Mastral, C. Berruero, J. Ceamanos, Pyrolysis of high-density polyethylene in free-fall reactors in series. *Energy Fuels* **20**, 1365–1371 (2007)
 50. M. Rehan, A.S. Nizami, O. Taylan, B.O. Al-Sasi, A. Demirbas, Determination of wax content in crude oil. *Pet. Sci. Technol.* **34**, 799–804 (2016)
 51. Y.H. Lin, H.Y. Yen, Fluidised bed pyrolysis of polypropylene over cracking catalysts for producing hydrocarbons. *Polym. Degrad. Stab.* **89**, 101–108 (2005)
 52. X.S. Zhang, H.W. Lei, G. Yadavalli, L. Zhu, Y. Wei, Y.P. Liu, Gasoline-range hydrocarbons produced from microwave-induced pyrolysis of low-density polyethylene over ZSM-5. *Fuel* **144**, 33–42 (2015)
 53. P. Senthil Kumar, M. Bharathikumar, C. Prabhakaran, S. Vijayan, K. Ramakrishnan, Conversion of waste plastics into low-emissive hydrocarbon fuels through catalytic depolymerization in a new laboratory scale batch reactor. *Int. J. Energy Environ. Eng.* **8**, 167–173 (2017)
 54. S. Devasahayam, Review: opportunities for simultaneous energy/materials conversion of carbon dioxide and plastics in metallurgical processes. *Sustain. Mater. Technol.* **22**, e00119 (2019)
 55. J. Schirmer, J.S. Kim, E. Klemm, Catalytic degradation of polyethylene using thermal gravimetric analysis and a cycled-spheres-reactor. *J. Anal. Appl. Pyrol.* **60**, 205–217 (2001)
 56. J. Aguado, D.P. Serrano, M.G. San, Feedstock recycling of polyethylene in a two-step thermo-catalytic reaction system. *J. Anal. Appl. Pyrol.* **79**, 415–423 (2008)
 57. P.J. Donaj, W. Kaminsky, F. Buzeto, W. Yang, Pyrolysis of polyolefins for increasing the yield of monomers' recovery. *Waste Manage.* **32**, 840–846 (2012)
 58. S. Chaianansutcharit, R. Katsutath, A. Chaisuwan, T. Bhaskar, A. Nigo, A. Muto et al., Catalytic degradation of polyolefins over hexagonal mesoporous silica: effect of aluminum addition. *J. Anal. Appl. Pyrol.* **80**, 360–368 (2007)
 59. K. Moorthy Rajendran, V. Chintala, A. Sharma, S. Pal, J.K. Pandey, P. Ghodke, Review of catalyst materials in achieving the liquid hydrocarbon fuels from municipal mixed plastic waste (MMPW). *Mater. Today Commun.* **24**, 100982 (2020)
 60. S.M. Al-Salem, A. Antelava, A. Constantinou, G. Manos, A. Dutta, A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *J. Environ. Manage.* **197**, 177–198 (2017)
 61. M. Boronat, A. Corma, Are carbenium and carbonium ions reaction intermediates in zeolite-catalyzed reactions? *Appl. Catal. A* **336**, 2–10 (2008)
 62. C. Muhammad, J.A. Onwudili, P.T. Williams, Catalytic pyrolysis of waste plastic from electrical and electronic equipment. *J. Anal. Appl. Pyrol.* **113**, 332–339 (2015)
 63. M.R. Hernandez, A. Gomez, A.N. Garcia, J. Agullo, A. Marcilla, Effect of the temperature in the nature and extension of the primary and secondary reactions in the thermal and HZSM-5 catalytic pyrolysis of HDPE. *Appl. Catal. A General* **317**, 183–194 (2007)
 64. S.S.Z. Salmasi, M.S. Abbas-Abadi, M.N. Haghghi, H. Abedini, The effect of different zeolite based catalysts on the pyrolysis of poly butadiene rubber. *Fuel* **160**, 544–548 (2015)
 65. G. Elordi, M. Olazar, G. Lopez, Catalytic pyrolysis of HDPE in continuous mode over zeolite catalysts in a conical spouted bed reactor. *J. Anal. Appl. Pyrol.* **85**, 345–351 (2009)
 66. G. Manos, A. Garforth, J. Dwyer, Catalytic degradation of high-density polyethylene over different zeolitic structures. *Ind. Eng. Chem. Res.* **39**, 1198–1202 (2000)
 67. J.W. Park, J.H. Kim, G. Seo, The effect of pore shape on the catalytic performance of zeolites in the liquid-phase degradation of HDPE. *Polym. Degrad. Stab.* **76**, 495–501 (2002)
 68. M. Syamsiro, H. Saptoadi, T. Norsujianto, P. Noviasri, S. Cheng, Z. Alimuddin et al., Fuel oil production from municipal plastic wastes in sequential pyrolysis and catalytic reforming reactors. *Energy Procedia* **47**, 180–188 (2014)
 69. K.H. Lee, Effects of the types of zeolites on catalytic upgrading of pyrolysis wax oil. *J. Anal. Appl. Pyrol.* **94**, 209–214 (2012)
 70. G. Elordi, M. Olazar, M. Artetxe, P. Castano, J. Bilbao, Effect of the acidity of the HZSM-5 zeolite catalyst on the cracking of high density polyethylene in a conical spouted bed reactor. *Appl. Catal. A* **415–416**, 89–95 (2012)
 71. C. Vasile, H. Pakdel, B. Mihai, Thermal and catalytic decomposition of mixed plastics. *J. Anal. Appl. Pyrol.* **57**, 287–303 (2001)
 72. J. Jae, G.A. Tompsett, A.J. Foster, Investigation into the shape selectivity of zeolite catalysts for biomass conversion. *J. Catal.* **279**, 257–268 (2011)
 73. K. Sun, Q.X. Huang, Y. Chi, J.H. Yan, Effect of ZnCl₂-activated biochar on catalytic pyrolysis of mixed waste plastics for producing aromatic-enriched oil. *Waste Manage.* **81**, 128–137 (2018)
 74. Y.L. Sun, Y. Ma, S.Y. Li, C.T. Yue, Research progress in pyrolysis and catalytic pyrolysis of polyolefin plastics. *Chem. Ind. Eng. Progress* **40**, 2784–2801 (2021)
 75. Y. Sakata, M. Azhar Uddin, A. Muto, Y. Kanada, K. Koizumi, K. Murata, Catalytic degradation of polyethylene into fuel oil over mesoporous silica (KFS-16) catalyst. *J. Anal. Appl. Pyrol.* **43**, 15–25 (1997)

76. Y. Sakata, M. Azhar Uddin, A. Muto, Degradation of polyethylene and polypropylene into fuel oil by using solid acid and non-acid catalysts. *J. Anal. Appl. Pyrol.* **51**, 135–155 (1999)
77. K.N. Aishwarya, S. Nangarthody, Microwave assisted pyrolysis of plastic waste. *Procedia Technol.* **25**, 990–997 (2016)
78. J. Sun, W.L. Wang, Q.Y. Yue, Review on microwave-matter interaction fundamentals and efficient microwave-associated heating strategies. *Materials* **9**, 231 (2016)
79. L.L. Fan, Y.N. Zhang, S.Y. Liu, N. Zhou, P. Chen, Y.H. Liu et al., Ex-situ catalytic upgrading of vapors from microwave-assisted pyrolysis of low-density polyethylene with MgO. *Energy Convers. Manage.* **149**, 432–441 (2017)
80. N. Zhou, L.L. Dai, Y.C. Lv, H. Li, W.Y. Deng, F.Q. Guo et al., Catalytic pyrolysis of plastic wastes in a continuous microwave assisted pyrolysis system for fuel production. *Chem. Eng. J.* **418**, 129412 (2021)
81. M.Q. Dai, H. Xu, Z.S. Yu, S.W. Fang, L. Chen, W.L. Gu et al., Microwave-assisted fast co-pyrolysis behaviors and products between microalgae and polyvinyl chloride. *Appl. Therm. Eng.* **136**, 9–15 (2018)
82. Z. Liu, H.Q. Wang, X.D. Zhang, J.W. Liu, Y.Y. Zhou, Dechlorination of organochloride waste mixture by microwave irradiation before forming solid recovered fuel. *Waste Manage.* **62**, 118–124 (2017)
83. A. Undri, M. Frediani, L. Rosi, P. Frediani, Reverse polymerization of waste polystyrene through microwave assisted pyrolysis. *J. Anal. Appl. Pyrol.* **105**, 35–42 (2014)
84. A. Undri, L. Rosi, M. Frediani, P. Frediani, Efficient disposal of waste polyolefins through microwave assisted pyrolysis. *Fuel* **116**, 662–671 (2014)
85. A. Aboulkas, K. El Harfi, A. El Bouadili, Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms. *Energy Convers. Manage.* **51**, 1363–1369 (2010)
86. P. Rex, I.P. Masilamani, L.R. Miranda, Microwave pyrolysis of polystyrene and polypropylene mixtures using different activated carbon from biomass. *J. Energy Inst.* **93**, 1819–1832 (2020)
87. E. Khaghanikavkani, M.M. Farid, J. Holdem, A. Williamson, Microwave pyrolysis of plastic. *J. Chem. Eng. Process Technol.* (2013). <https://doi.org/10.4172/2157-7048.1000150>
88. K. Ding, S.S. Liu, Y. Huang, S.Y. Liu, N. Zhou, P. Peng et al., Catalytic microwave-assisted pyrolysis of plastic waste over NiO and HY for gasoline-range hydrocarbons production. *Energy Convers. Manage.* **196**, 1316–1325 (2019)
89. L.L. Fan, Z.Y. Su, J.B. Wu, Z.G. Xiao, P. Huang, L. Liu et al., Integrating continuous-stirred microwave pyrolysis with ex-situ catalytic upgrading for linear low-density polyethylene conversion: effects of parameter conditions. *J. Anal. Appl. Pyrol.* **157**, 105213 (2021)
90. X.D. Jing, J.Q. Dong, H.L. Huang, Y.X. Deng, H. Wen, Z.H. Xu et al., Interaction between feedstocks, absorbers and catalysts in the microwave pyrolysis process of waste plastics. *J. Clean. Prod.* **291**, 125857 (2021)
91. X.Y. Jie, W.S. Li, D. Slocombe, Y.G. Gao, I. Banerjee, S. Gonzalez-Cortes et al., Microwave-initiated catalytic deconstruction of plastic waste into hydrogen and high-value carbons. *Nat. Catal.* **3**, 902–912 (2020)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.