Journal of Materials Science and Chemical Engineering, 2024, 12, 30-61
https://www.scirp.org/journal/msce
ISSN Online: 2327-6053
ISSN Print: 2327-6045

Progress in the Study of Microwave Pyrolysis Technology and Its Influencing Factors

Hui Fang[1], Lin Hai[2], Ruisheng Xie[1], Jing Yuan[3,4]*, Qianfeng Zhang[1]*

[1]Institute of Molecular Engineering and Applied Chemistry, Anhui University of Technology, Ma'anshan, China
[2]College of Electronic and Optical Engineering & College of Flexible Electronics (Future Technology), Nanjing University of Posts and Telecommunications, Nanjing, China
[3]Department of Civil Engineering, Tongling University, Tongling, China
[4]Department of Civil Engineering, Manitoba University, Winnipeg, Canada
Email: *154427@tlu.edu.cn, *zhangqf@ahut.edu.cn

How to cite this paper: Fang, H., Hai, L., Xie, R.S., Yuan, J. and Zhang, Q.F. (2024) Progress in the Study of Microwave Pyrolysis Technology and Its Influencing Factors. *Journal of Materials Science and Chemical Engineering*, **12**, 30-61.
https://doi.org/10.4236/msce.2024.1210004

Received: September 23, 2024
Accepted: October 25, 2024
Published: October 28, 2024

Abstract

In recent years, the effective conversion of organic wastes into valuable products has been a focus and difficulty in sustainable energy and environmental management. Organic wastes come from a wide range of sources, and industrial and agricultural sources are the main sources of organic waste in China, which can be controlled by microwave pyrolysis technology. In microwave pyrolysis treatment, catalysts have been the key material, microwave absorber, and catalyst of the research hotspot in recent years. This paper summarises the typical influencing parameters of microwave pyrolysis (including microwave power, pyrolysis temperature and microwave absorber), and also summarises the various catalysts applied in microwave pyrolysis, and looks forward to the potential application prospect of pyrolysis products, and the future development direction.

Keywords

Microwave, Microwave Pyrolysis, Microwave-Catalysed Pyrolysis, Catalyst, Microwave Absorber, Microwave Power, Renewable Energy

1. Introduction

In recent years, with the acceleration of industrialisation, the demand for energy has increased dramatically, especially in developing countries. According to the Statistical Bulletin of the National Economic and Social Development of the People's Republic of China in 2023 published by the National Bureau of Statistics (NBS), China's total energy consumption in 2023 was 5.72 billion tonnes of standard coal, which increased by 5.7% compared with 5.41 billion tonnes of standard coal in 2022. Combined with the total energy consumption of each year published by the National Bureau of Statistics, we can find that China's total energy consumption has shown a year-on-year growth trend since 2016. Therefore, the search for sustainable energy has gradually become a hot issue of common concern. Research shows that in recent years, the proportion of coal consumption in China has been decreasing, from 62.2% in 2016 to 55.3% in 2023. Meanwhile, the proportion of clean energy consumption in China has been increasing, from 19.1% in 2016 to 26.4% in 2023. Therefore, renewable energy and alternative fuels are becoming the forefront of research.

Pyrolysis is a reaction process in which organic waste decomposes and produces new compounds at high temperatures in the absence or presence of a small amount of oxygen [1]. The process breaks chemical bonds through high temperatures to break down organic waste into simpler compounds. It involves reactions such as the breaking of macromolecular bonds, isomerisation and polymerisation of small molecules [2]. The principle of pyrolysis is based on the laws of thermodynamics and the kinetics of chemical reactions. In a high temperature environment, the molecules acquire a large enough energy to break the chemical bonds within the molecule, thus causing a decomposition reaction. Pyrolysis can usually be divided into two stages: primary and secondary pyrolysis [3]. Primary pyrolysis occurs mainly in the breaking of macromolecular chains, generating some small free radicals. Secondary pyrolysis involves further reactions between these free radicals to produce the final product.

The methods of pyrolysis include slow pyrolysis, fast pyrolysis, hydrothermal pyrolysis, catalytic pyrolysis and microwave pyrolysis (MP) [4]. In contrast to conventional pyrolysis methods that utilise heat conduction and heat convection, microwave pyrolysis is a molecular decomposition and transformation technique that utilises microwave radiation energy. The principle is to use the high-frequency oscillations of microwaves to stimulate the intrinsic vibrations and rotations within the molecules, which causes the molecules to undergo chemical bond breaking, thus achieving microwave pyrolysis. The specific differences between microwave heating and conventional heating are shown in **Table 1**. In the last few years, MP has been investigated for the treatment of various organic wastes such as plastics, tyres, microalgae, corn stover, wheat straw and rice straw [5]-[9]. Dipole rotation and ion migration are the two main mechanisms of microwave heating [10]. Microwave heating is based on rapid heating, uniform heating, selective heating, energy efficient, clean and hygienic, non-polluting, and enables a more environmentally sustainable approach [11].

The three valuable products obtained through microwave pyrolysis are mainly solid char, bio-oil and pyrolysis gas [12]. Solid carbon is mainly ash, carbon black and other carbon-containing materials containing pure carbon and polymeric polymers, which can be used as wastewater and exhaust gas treatment, catalyst, soil improvement, filtration and adsorption [13]. Bio-oil mainly consists of organic acids, aromatics, tar, methanol, acetone, and acetic acid, which can be further refined into biofuels [14]. Pyrolysis gas is mainly CH_4, H_2, H_2O, CO, CO_2, NH_3, H_2S, HCN, etc., which can be used as clean gas [15]. The microwave pyrolysis products and their use are shown in **Figure 1**. The yield of the above reaction products depends on the chemical structure, physical form, and pyrolysis temperature of the feedstock. Meanwhile, the main products of pyrolysis depend on the compounds being pyrolysed. For example, microwave pyrolysis of wood produces major products as carbon monoxide, water, hydrocarbon compounds and organic acids [16]. Microwave pyrolysis is an important chemical conversion technology with a wide range of applications, and it can be used in metallurgy for the extraction of metals, in chemistry for the preparation of complex compounds, and in sustainable energy for the production of fuels.

Table 1. Differences between microwave heating and traditional heating.

Traditional heating	Microwave heating
The heating speed is slow	The heating speed is fast
Inuniform heating	Uniform heating
Using heat conduction, heat convection	Using the energy properties of the microwaves
Energy consumption is polluted	Energy conservation and environment protection
External heat	Internal heat

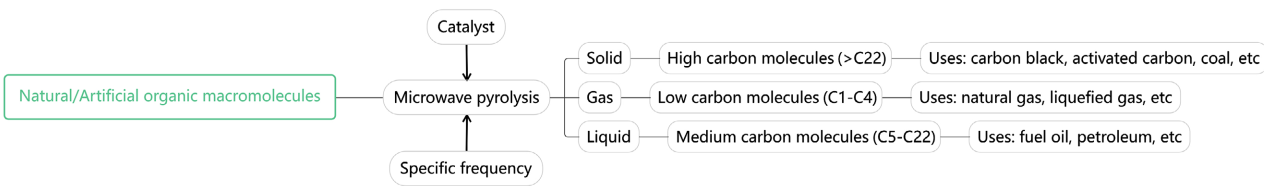

Figure 1. Microwave pyrolysis products and their use.

Microwaves are the higher frequency and shorter wavelength part of the electromagnetic spectrum, usually defined as frequencies between 300 MHz and 300 GHz, corresponding to wavelengths ranging from 1 mm to 1 m [17]. Microwaves are a type of electromagnetic radiation whose energy is between radio waves and infrared rays. Microwaves are able to act directly inside a substance, causing it to increase its temperature dramatically in a short period of time, which greatly reduces the reaction time [18]. Microwaves can also achieve uniform heating of the substance as a whole, avoiding localised and uneven heating that may occur with conventional heating. At the same time, microwaves act directly on the substance with relatively low energy loss, which improves energy utilisation [19]. In MP, the magnetron of the microwave system generates electromagnetic radiation, which causes molecular motion and induces polar molecules to rotate, causing intermolecular friction to generate heat.

The use of catalysts can significantly improve product quality. The most widely studied catalysts in microwave pyrolysis are molecular sieve catalysts and carbonaceous material catalysts. Molecular sieve catalysts are catalysts with a microporous structure, which can promote chemical reactions by controlling the diffusion of reactants and the interaction between reactant molecules. Carbonaceous catalysts can effectively catalyse the microwave pyrolysis process through active sites on their surfaces. These active sites are capable of catalysing a wide range of reactions, including selective oxidation reactions, advanced oxidation reactions, reduction reactions, alkane activation reactions, acid catalysed reactions, electrocatalytic reduction and oxidation reactions. Among them, molecular sieve catalysts have high selectivity for aromatics with uniform microporous structure and acidic sites [20]. And carbonaceous catalysts can increase pyrolysis gas yield [21].

Therefore, the aim of this work is to review the effect of parameters such as microwave power, pyrolysis temperature and microwave absorber on the yield of microwave pyrolysis products. In this regard, microwave absorber was added to maximise the yield of the product and to improve its performance for future applications. The study also describes the application of each different catalyst in microwave pyrolysis. Firstly, it explored the application of molecular sieve catalysts in the conversion of organic waste into high quality biochar. Secondly, it investigates the application of different catalysts made of carbonaceous materials to evaluate their pyrolysis behaviour and the resulting biochar properties. In addition, it investigates the use of metal salt catalysts to enhance the pyrolysis process and improve the biochar quality. Finally, all relevant conclusions are stated.

2. Microwave

Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz. As shown in **Figure 2**, the microwave region of the electromagnetic spectrum, which is located between infrared and radio waves [22]. It, as an electromagnetic wave, also has wave-particle duality, *i.e.*, the volatility and the particle nature.

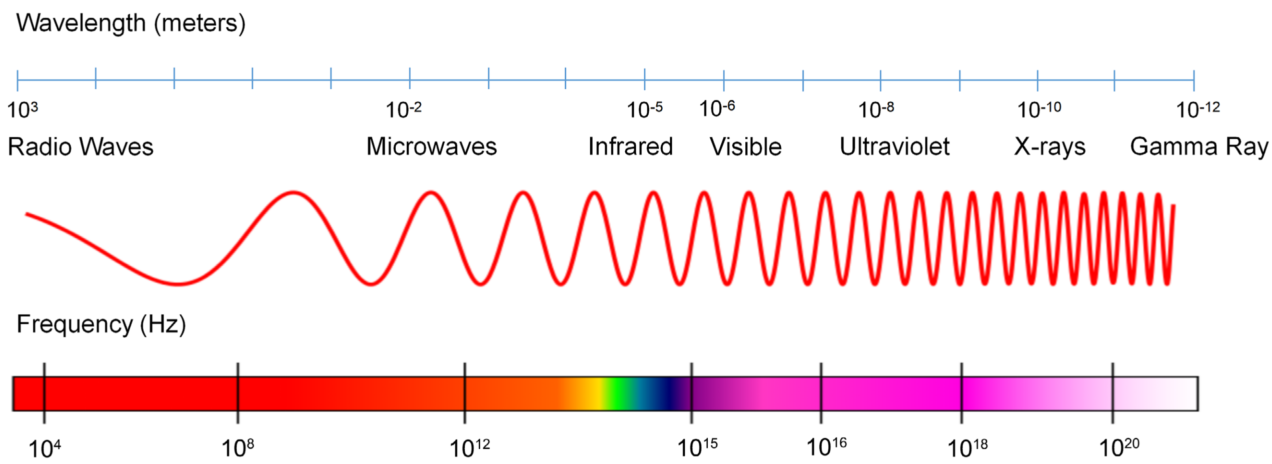

Figure 2. Spectral region map of the microwave.

Microwaves have thermal and non-thermal effects [23]. The thermal effect of microwaves refers to the frictional heat generation of polar molecules under the action of microwave high-frequency electric field and repeated rapid orientation rotation. The non-thermal effect of microwaves refers to other effects besides the thermal effect, such as electrical, magnetic and chemical effects.

As shown in **Figure 3**, the basic properties of microwave are usually presented as three characteristics: transparent, reflector and absorber [24]. For non-metallic materials such as glass, plastics and porcelain, microwaves almost traverse without being absorbed. For polar molecules such as water and food, microwaves are absorbed and heat themselves up. For metallic materials, the microwaves are reflected completely.

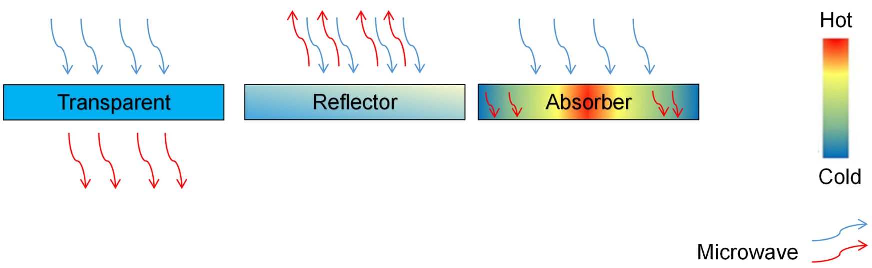

Figure 3. Three characteristics of microwaves.

Microwave heating mechanism is the process of heating an object using the energy properties of microwaves. The dielectric material consists of polar and non-polar molecules. Under the action of microwave electric field, the orientation of polar molecules shifts from the original random distribution state to change in accordance with the electric field [5] [16]. The rapid rotation and vibration of this process causes the molecules to move and rub against each other, thus generating heat. At this time, the field energy of the microwave field is converted into thermal energy within the medium, so that the temperature of the medium increases.

Microwave heating has the characteristics of rapid heating, uniform heating, selective heating, energy saving, high efficiency and environmentally friendly and pollution-free, and is widely used in food, chemical, agriculture and medicine [25]-[27]. The rapidity of microwave heating can make the reaction rate of organic macromolecules be significantly improved, which helps to shorten the reaction time and improve the production efficiency [28]. The uniformity of microwave heating helps to reduce the occurrence of side reactions, thus improving the purity of the product. Microwaves have selective heating properties for polar molecules, so when organic macromolecules contain polar functional groups, these functional groups are preferentially heated in the microwave field, which affects the reactivity of the whole molecule [29]. Due to the changes in reaction rate and reactivity caused by microwave heating, the reaction path of organic macromolecules may be altered, which in turn affects the product species.

During microwave heating, the dielectric properties of a material have a significant impact on the heating effect [11]. Whether a material can be easily heated by microwave is related to its own dielectric constant. The dielectric constant is the main parameter reflecting the dielectric nature or polarisation of piezoelectric material dielectric under the action of electrostatic field, which is usually expressed by ε [30]. The tangent of the dielectric loss angle indicates the microwave attenuation characteristics of the material [31]. The larger the dielectric constant is, the easier a material can be heated. Conversely, materials with smaller dielectric constants are less susceptible to microwaves. This makes microwaves selective heating of materials, *i.e.*, different materials have different heating efficiencies in the microwave field.

Studies have shown that common organic macromolecules have low dielectric constants, which means that they are less able to absorb microwaves [32]. To address this limitation, the introduction of microwave absorbers has become crucial [33]. Microwave absorbers can absorb microwave energy, reduce the reflection and propagation of electromagnetic waves, and reduce the interference of electromagnetic waves. The addition of microwave absorbers in microwave pyrolysis can enhance the heating efficiency, promote the pyrolysis reaction, and influence the pyrolysis products. In recent years, activated carbon, graphite, and silicon carbide have been studied by many scholars as microwave absorbers [34]-[36]. In conclusion, dielectric constant plays an important role in microwave heating and microwave technology, which directly affects the heating efficiency and properties of materials.

3. Parameters Affecting Microwave Pyrolysis

Microwave pyrolysis is to irradiate organic macromolecules with specific frequency electromagnetic waves under the action of catalysts, so that their carbon-carbon bonds are broken and the macromolecules become small molecules, and finally products such as solid-liquid-gas are produced. Compared with the traditional pyrolysis technology, microwave pyrolysis has the following advantages: it occupies less land resources and can be resourced (power, steam and heat); it can inhibit the production of harmful secondary pollutants and reduce the amount of waste; microwaves have obvious catalytic properties for the pyrolysis of organic macromolecules; and it is beneficial to environmental protection because microwaves are clean and hygienic in themselves and do not cause chemical contamination [27]. However, for low dielectric constant and poorly absorbing materials (e.g., plastics, etc.), their absorption of microwave energy is insufficient, which requires the addition of wave-absorbing materials to enhance the conversion rate of microwaves [37]. Microwave pyrolysis is a controllable process, and the yield can be optimised by controlling conditions such as microwave power, pyrolysis temperature and absorber [38] [39]. Among them, catalyst is the key. Therefore, a reasonable optimization of the experimental conditions is required during the experiment, as shown in **Table 2**.

Table 2. Impact factors and optimization methods of microwave pyrolysis techniques.

Influencing factor	Effect on the microwave pyrolysis	Optimization
Microwave power	Higher microwave power usually has a lower biochar yield, while lower microwave power usually increases the biochar yield.	Maintain quality within the appropriate power range (usually 1 KW - 1.2 KW).
Pyrolysis temperature	Suitable pyrolysis temperature can reduce energy consumption, and higher pyrolysis temperature will reduce the biochar yield.	A lower temperature (300˚C - 400˚C) was selected to ensure the maximum production rate.
Microwave absorbers	The addition of microwave absorbent can accelerate the pyrolysis process of organic macromolecules and improve the yield of bio-oil.	Increase the yield by rational selection and combination of different microwave absorbers.
Type	The physicochemical properties of organic macromolecules are a key factor affecting the yield of microwave pyrolysis products.	Biomass types with high lignin content were selected to improve the biochar yield.
Particle size	A larger particle size reduces the pyrolysis rate, but the biochar yield increases.	The particle size is generally controlled at 0.9 mm.
Catalysts	The addition of catalyst can significantly improve the pyrolysis efficiency and product quality during microwave pyrolysis.	Choose the low-cost catalysts.

3.1. Microwave Power

Microwave power is an important factor affecting microwave pyrolysis technology. The size of microwave power directly affects the heating rate and the temperature distribution of the reaction system. Generally speaking, the higher the frequency of microwave, the more heat is generated and the faster the rate of pyrolysis. However, too high a microwave frequency will not always increase the pyrolysis effect, so it is important to choose a suitable microwave frequency.

Earlier studies, mainly focused on increasing the yield of microwave pyrolysis by single adjustment of microwave power. Song *et al.* investigated the effect of three microwave power levels, 270 W, 450 W and 720 W, on the yield of tyre pyrolysis products [40]. With increasing power, the yield of solid products gradually decreased, the yield of liquid products firstly increased and then decreased, and the yield of gas products firstly decreased and then increased [40]. Meanwhile, Li *et al.* reached similar conclusions when pyrolysis of algae was carried out at different microwave powers [41]. This may be due to the fact that when the microwave power is low, the heating rate is slow and the activation energy required for the reaction of organic macromolecules is not reached, making the yield of the very first products low. And with the increase of microwave power, the rate of organic macromolecule reaction is accelerated, and the amount of product generation is also increased, which leads to the increase of product yield. However, when the microwave power exceeded a certain range, although the heating rate was accelerated, the local temperature of the reaction system was too high, which easily triggered side reactions and caused the decomposition of the liquid products into gases, which ultimately lowered the yields of the liquid products and increased the yields of the gaseous products. Huang *et al.* further verified this result by performing microwave pyrolysis of agricultural residues at three different microwave power levels [42]. They found that when the microwave power was at 300 W, the liquid products accounted for about 50 per cent and the gas products only about 20 per cent. However, when the microwave power was increased from 300 W to 500 W, the gas yield increased and the solid and liquid yields decreased.

In recent years, with the continuous development of microwave pyrolysis technology, the reaction performance of microwave power in pyrolysis of a single and its mixed wastes was investigated. Undri *et al.* investigated microwave pyrolysis of high-density polyethylene (HDPE) and polypropylene (PP) in a microwave oven with an operating frequency of 2.45 GHz using tyres or carbon as a wave-absorbent material [43]. When the microwave power was lower than 1.2 - 2.7 kW, HDPE was not completely pyrolysis, while PP was completely pyrolysis into a low-viscosity liquid. Only when the microwave power was increased to 6 kW, HDPE was completely pyrolysis and a liquid product yield of 37% was obtained. Rex *et al.* investigated the effect of different power on the yield of PP and PS microwave pyrolysis products [44]. At low powers of 180 W, 360 W and 540 W, no pyrolysis of waste occurred. However, when the output power of microwave was at 720 W, the waste was pyrolysis and the gas production rate was 51.91%. When the output power of microwave was at 900 W, the gas production rate decreased and the oil production rate was as high as 69.55%. The liquid product finally obtained can be used as fuel to achieve the secondary resource utilisation of the waste.

In general, the increase of microwave power also has a significant effect on the heating rate. When the microwave power is higher, the heating rate is larger and the final temperature is higher [45] [46]. Li *et al.* carried out microwave pyrolysis of algae at different microwave powers and found that larger microwave power could increase the heating rate of algae [41]. Also, microwave power may affect the product selectivity. In some cases, the reaction path can be altered by adjusting the microwave power so that the reaction is more inclined to produce a particular product. This is important for the synthesis of organic macromolecular products with specific structures and functions. Taking the esterification reaction as an example, the traditional esterification reaction usually requires high temperature and long reaction time to achieve high yield. In contrast, when microwave heating is used, rapid esterification can be achieved in a shorter period of time and the product yield can be increased [47].

In conclusion, the effect of microwave power on the products of organic macromolecules is multifaceted. In order to obtain the desired product yield and selectivity, it is necessary to select the appropriate microwave power according to the specific reaction system and target product. In practical applications, it is recommended to determine the best microwave power conditions through experimental optimisation.

3.2. Pyrolysis Temperature

Temperature is a very important influencing factor in the microwave pyrolysis process, which has a great impact on the distribution of pyrolysis products, components, yield and calorific value of pyrolysis gas. As heat can trigger chemical reactions, a higher reaction temperature provides more energy for the raw material to overcome its activation energy barrier, thus promoting waste decomposition.

Elevated temperatures further promote pyrolysis reactions. Elevated temperatures cause secondary reactions to occur in the primary reaction products, such as cyclisation, dehydrogenation and aromatisation. These secondary reactions result in a decrease in the aliphatic fraction and an increase in the aromatic fraction of the pyrolysis oil. Take waste tyre as an example: when the pyrolysis temperature is low, the primary reaction occurs, generating large molecules of aliphatic hydrocarbons (mainly olefins); when the pyrolysis temperature is high or the reaction time is long, the primary reaction product undergoes the secondary reaction. The secondary reaction has two directions, one is the generation of small molecules of gaseous hydrocarbons pyrolysis reaction, and the other is the generation of aromatic hydrocarbons, large molecules of condensed coke-like substances of aromatic cyclisation reaction. Methane and hydrogen are the by-products of the aromatic cyclisation reaction.

A number of scholars have investigated the effect of temperature on the aromatic hydrocarbons of microwave pyrolysis products. Russell *et al.* investigated the microwave pyrolysis of HDPE with activated carbon as a catalyst under different temperature conditions [48]. It was shown that the percentage of alkanes and olefins produced was approximately the same when the temperature was increased from 400˚C to 500˚C. The percentage of olefins produced increased when the temperature was gradually increased from 500˚C. When the temperature was increased to 600˚C, the proportion of aromatics generated was 45.3% of the total compounds. Lei *et al.* investigated the microwave pyrolysis of corn stover at different temperatures, and found that the maximum yield of the product was 76% and the yield of bio-oil was 34% at a temperature of 650˚C, a reaction time of 8 min, and a particle size of 4 mm [49]. Zhang *et al.* demonstrated that the maximum yield of product was 76% and the yield of bio-oil was 34% when the catalytic temperature was increased from 249˚C to 375˚C, the yield of monocyclic aromatic hydrocarbons in bio-oil from microwave-assisted pyrolysis of LDPE increased from 79.3% to 84.34% due to the enhanced hydrogen transfer reaction [50]. However, the continuous increase in temperature prevents the aromatisation reaction of light olefins and reduces the aromatic yield. Therefore, higher pyrolysis temperatures can seriously affect the yield of aromatics.

For microwave pyrolysis of organic macromolecules, when the temperature increases, the biochar yield shows two trends: 1) The char yield decreases; 2) The char yield decreases first and then increases. In the first case, the char yield obtained from microwave pyrolysis of organic macromolecules decreases as the temperature increases. This was reported by Mong *et al.* The char yield from microwave pyrolysis of horse manure decreased from 78.98% to 12% in the temperature range of 350˚C - 550˚C [51]. Also, Antunes *et al.* conducted a related study where the char yield decreased from 91% to 77% when the temperature was increased from 300˚C to 800˚C [52]. This may be due to the further increase in reaction temperature, which promotes secondary decomposition and increases the rate of reaction between carbon, carbon dioxide and water, leading to a decrease in char yield. In the second case, the char yield obtained from microwave pyrolysis of organic macromolecules decreases and then increases as the temperature increases. Dai *et al.* carried out microwave-assisted co-catalytic fast pyrolysis of soap and investigated the effect of catalyst and temperature on the yield of bio-oil and biochar [53].

Temperature had a significant effect on bio-oil yield [54]. Generally, the bio-oil yield increases and then decreases with increasing temperature. This is due to the incomplete cleavage of macromolecular organic matter at low temperatures, and the bio-oil yield is low. And as the temperature increases, the pyrolysis reaction intensifies and the bio-oil yield increases. However, when the temperature is too high, the macromolecular compounds in the bio-oil will be further pyrolysis into gas products, resulting in a decrease in bio-oil yield.

As the temperature increases, the generation of gas products also increases. This is because the small molecule compounds generated from the cleavage of macromolecular organic matter under high temperature conditions are more likely to volatilise into gas products. The gas products mainly include hydrocarbon gases such as H_2, CO, CO_2, and CH_4 [55] [56]. These gas products not only have certain economic value (e.g., H_2 can be used as fuel or chemical raw material), but also can be an important indicator to judge the degree of pyrolysis process.

In summary, the influence of temperature on the products of organic macromolecules is also multifaceted. In practical applications, it is necessary to choose the appropriate pyrolysis temperature according to the specific needs and characteristics of the raw material in order to obtain the ideal product quality.

3.3. Microwave Absorbers

One of the advantages of microwave catalysed reactions is the ease of controlling the direction of radiation, controlling the distribution of the energy field in the pyrolysis furnace, and the ability to achieve large processing capacity, high speed reactions and selective heating. However, low dielectric constant and poorly absorbing materials (e.g., plastics) have insufficient transfer of microwave energy, which requires mixing the materials with microwave absorbers to achieve improved energy absorption and conversion in a short period of time [57] [58].

Activated carbon, silicon carbide and zinc oxide were used as microwave absorbers in related studies [59]-[62]. Salema *et al.* described the microwave pyrolysis product fractions of oil palm empty fruit bunches particles at different proportions of activated carbon absorbers. It was found that the maximum bio-oil yield was 21% when 25% microwave absorber was used [63]. Zhou *et al.* in their study, pyrolysis of straw and soap was carried out by microwave heating, and then, SiC was used as a microwave absorber to increase the temperature rapidly and HZSM-5 was used as a catalyst to improve the quality of bio-oil [64]. Tian *et al.* investigated the use of graphite as a microwave absorber in the production of bio-oil from sewage sludge at different microwave powers [65]. The results showed that when the microwave power was increased from 200 W to 400 W, the bio-oil yield increased from 18.28% to 49.79%. However, when the microwave power was increased from 400 W to 1200 W, the bio-oil yield decreased from 49.79% to 7.16%. It is generally believed that these porous materials help in the adsorption of small molecules of organic matter and more so in their cleavage reaction on the surface of the wave absorbing material.

Microwave absorbers can strongly absorb microwave energy in the microwave field and convert it into thermal energy, thus achieving uniform and rapid heating of organic macromolecules. In the field of organic synthesis, microwave absorbers are often used to accelerate the synthesis reaction of organic macromolecules and improve the yield and purity [66]. For example, when using microwave-assisted synthesis of polymer materials, the addition of appropriate amounts of microwave absorbers can significantly shorten the reaction time and improve the properties of the products. In the field of environmental science, microwave absorbers can be used for the degradation treatment of organic pollutants. Through the absorption of microwave energy and convert it into heat to heat the organic pollutant molecules, prompting its decomposition, oxidation and other reactions, and ultimately converted into harmless substances. After absorbing the electromagnetic wave, the frequency of the incident electromagnetic wave is enhanced due to the nonlinear optical effect. For example, the sum-frequency effect and the frequency doubling effect amplify the frequency of the original electromagnetic wave, which in turn enhances the resonance effect energy effect of microwave on organic matter, making it easier to selectively fracture the carbon-carbon single bond.

Microwave absorbers have both good and bad effects on bio-oil yields. Some microwave absorbers may increase the yield of bio-oil, while others may decrease the yield of bio-oil. Yu *et al.* investigated the pyrolysis of sewage sludge under microwave irradiation using six microwave absorbers [67]. The results showed that NiO, Ni_2O_3, γ-A_2O_3 and TiO_2 increased the bio-oil yield, while CaO and $CaCO_3$ decreased the bio-oil yield. Meanwhile, Liu *et al.* investigated the catalytic pyrolysis of food waste by microwave heating with metal oxides and chloride salts as catalysts [68]. The results showed that MgO, MnO_2 and $CuCl_2$ had a significant catalytic effect on the pyrolysis of food waste, Fe_2O_3 and NaCl had almost no effect, whereas CuO, CaO and $MgCl_2$ had a negative effect and reduced the bio-oil yield.

The porous nature of the absorbent is important in determining the extent of the pyrolysis reaction. Rex *et al.* studied and compared the reaction performance of various absorbents in pyrolysis single waste plastics and their mixed waste plastics [44]. The results of the study showed that the oil yield of both for PP decomposition would be higher than that of rice husk char as absorbent due to the good porous structure of corn husk and coconut husk, the microwave absorption capacity would be stronger, which would help in the pyrolysis of polymers. Therefore, the rational use of agricultural waste as absorbent can increase the yield of pyrolysis oil and further produce low-cost fuel.

In conclusion, the effects of microwave absorbers on organic macromolecular products are multifaceted, including the heating rate, the selectivity of the reaction, and the nature of the product. Different kinds of microwave absorbers have different effects on organic macromolecules, so in practical applications need to choose the appropriate microwave absorber according to the specific situation.

In addition to microwave power, temperature and microwave absorber, the conversion of organic macromolecular products during microwave pyrolysis is also affected by the type of feedstock, particle size and catalyst [69]-[71]. Different kinds of feedstocks have different chemical compositions and structural properties, so their pyrolysis behaviours will be different. The particle size affects the heat uniformity and heat transfer efficiency of the feedstock. Catalysts, on the other hand, can promote or inhibit the generation of specific products by reducing the activation energy of the reaction, changing the reaction path, and so on. In section 4 we will focus on the role of various catalysts in microwave pyrolysis.

4. Catalysts

A catalyst is a substance that can increase the rate of a chemical reaction without altering the chemical equilibrium, and at the same time the quality and chemical properties of the catalyst do not change before or after the reaction. In order to further develop the microwave pyrolysis process, catalysts are introduced to produce higher quality products. The introduction of catalysts not only speeds up the reaction rate, but also helps the waste undergo a pyrolysis reaction on the surface of the wave-absorbing material. With the help of catalytic technology, the radio-energy catalytic pyrolysis products of waste will move towards higher oil yield, higher gas yield and higher carbon content.

Catalyst is the key to microwave pyrolysis. In the actual application process, the use of catalyst directly affects the yield of the product. Therefore, the development and optimisation of catalysts have been the focus of many studies. **Figure 4** briefly summarizes the classification of catalysts used in microwave pyrolysis. In this subsection, the catalysts used in microwave pyrolysis will be highlighted: molecular sieve catalysts, carbonaceous material catalysts, metal oxides/salt catalysts.

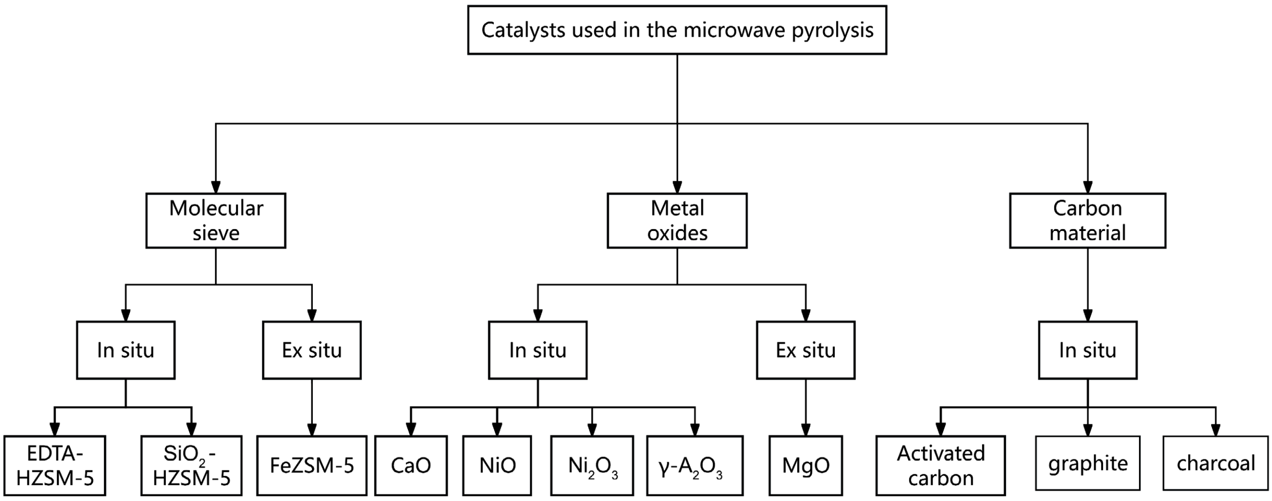

Figure 4. Catalyst classification used in microwave pyrolysis.

4.1. Molecular Sieve Catalyst

Molecular sieve catalysts, also known as zeolite catalysts, are rich in acidic sites and have a unique porous structure, making them the most widely used catalysts. Molecular sieve catalysts have the following characteristics: molecular sieves have a large number of acidic or basic active sites, which can provide high catalytic activity; molecular sieves have a special pore structure and topology, which can selectively adsorb and catalyse molecules, thus realising a high selectivity for the target reaction products; the pore size and pore structure of molecular sieves can be adjusted by synthetic methods, so as to adapt to different types of reactions, and realise the reaction The pore size and pore structure of molecular sieves can be adjusted by synthetic methods to adapt to different types of reactions, so as to achieve the regulation of the reaction rate and product selectivity; molecular sieves have good thermal stability, and can be reacted at high temperatures without deactivation. At present, the main molecular sieve catalysts are HY, HZSM-5, Hβ, ZSM-5, H-Beta, MSU, MCM-41 and so on.

ZSM-5 has excellent catalytic effects including high pyrolysis activity, high selectivity for light olefins and gasoline range aromatics, high resistance to coking and deactivation due to its strong acidity and medium pore size characteristics. Ding *et al.* studied the catalytic microwave pyrolysis of low-density polyethylene (LDPE) with SiC as the microwave absorber and NiO and HY molecular sieves as the catalysts, and the optimum bio-oil yield of 56.53%, of which 93.8% was gasoline [72]. The addition of NiO decreased the bio-oil yield but increased the aromatics yield. This proved that co-catalysis could effectively increase the yield and enhance the performance of pyrolysis oil. Zhang *et al.* converted LDPE to aromatics by microwave-assisted pyrolysis in the presence of ZSM-5 to study the overall reaction mechanism, which further verified the high selectivity of ZSM-5 for aromatics [73]. In conclusion, bio-oils with high quality aromatics were obtained when ZSM-5 molecular sieve catalyst was introduced [74]. This was attributed to the large number of Brönsted acid sites and microporous structure in this catalyst, which facilitated the aromatisation reaction and reduced the occurrence of side reactions. The process readily yields high yields and high quality gasoline with high efficiency and low cost, which is conducive to large-scale industrial production.

Among them, the HZMS-5 catalyst is also favourable for the production of hydrocarbons, especially aromatics. Dai *et al.* performed rapid microwave-assisted catalytic pyrolysis of hydrocarbon-rich bio-oil soap using different catalysts, and found that the addition of the catalysts significantly improved the selectivity of aromatics, and the content of aromatics increased from 5.99% to 29.46% [75]. In addition, the acidity of HZMS-5, which is important for the deoxygenation reaction during pyrolysis (including dehydration, decarboxylation, decarbonylation, etc.). Zhang *et al.* used the HZSM-5 catalyst for microwave-assisted catalytic fast pyrolysis of biomass, in which the increase of SiO_2 significantly decreased the acid sites and pore size of the HZSM-5 catalyst, and the content of oxygenated aromatic compounds ultimately increased and then decreased, while the content of oxygenated aliphatic compounds content first decreased and then increased [76].

To produce fuels in the gasoline range, composite catalysts have been widely used. The composite catalysts showed good arylation and bond breaking ability in catalysis to generate aromatic hydrocarbons. Zou *et al.* carried out microwave-assisted catalytic fast co-pyrolysis of lignin using SiC as microwave absorber and graded ZSM-5/MCM-41 as catalysts, which resulted in a feedstock conversion of 76% and an aromatics selectivity of 50.31% under the optimum reaction conditions [77]. Meanwhile, Zhou *et al.* developed a ZSM-5 structured catalyst coated on a SiC carrier, which showed more than 22% selectivity for gasoline range aromatics [74]. Compared with the conventional ZSM-5 catalyst, the catalytic performance of ZSM-5/SiC was 37 times higher.

Subsequently, related researchers modified the molecular sieve catalysts to change the acidic site distribution and pore structure, which were used to improve the quality of catalytic products. Qu *et al.* showed excellent catalytic performance during microwave pyrolysis of tyres by Ni and Fe modified ZSM-5 molecular sieve catalysts prepared by impregnation method [78]. The modified molecular sieve catalyst significantly improved the selectivity of aromatics in tar. Meanwhile, Liang *et al.* explored the effect of transition metal-modified ZSM-5 on microwave-assisted pyrolysis of rice straw pyrolysis for bio-oil production [79]. Further analysis from the reaction kinetics showed that the addition of transition metal-modified zeolite could increase the reaction rate during the pyrolysis of rice straw.

Molecular sieves are widely used in various catalytic reactions because of their adjustable pore size and stable topology, which can selectively adsorb and catalyse molecules. Molecular sieve catalysts can be widely used in petrochemical, organic synthesis, environmental protection and other fields of reaction, such as catalytic pyrolysis, isomerisation, oxidation, dehydration, dehydrogenation and other reactions.

4.2. Carbonaceous Materials Catalysts

Apart from zeolites, carbonaceous materials are also widely used in microwave catalytic pyrolysis to improve the yield and quality of bio-oil and syngas from various organic wastes. Carbonaceous materials can be used as both catalysts and microwave absorbers due to their outstanding dielectric properties [80]. Carbonaceous materials have the following advantages as catalytic carriers: the well-developed pore structure and large specific surface area of carbonaceous materials enable them to effectively adsorb and purify specific components in liquids or gases; carbonaceous materials have the advantages of being low cost and green as a catalyst or catalyst carrier; the surface chemistry of carbonaceous materials can be adapted to different catalytic reactions by adjusting their surface compounds and ash content; carbonaceous materials The surface chemistry of carbonaceous materials can be adjusted to suit different catalytic reactions by adjusting their surface compounds and ash.

Carbonaceous catalysts have functional groups in the active sites of the surface structure. These active sites enable carbonaceous materials to catalyse a variety of thermocatalytic reactions, including selective oxidation, advanced oxidation, reduction, alkane activation, acid catalysis, and electrocatalytic reduction and oxidation. This paper only describes the role of carbonaceous material catalysts in microwave pyrolysis.

Carbonaceous material catalysts are generally activated carbon, graphite and charcoal. The physical structures of the three are different, making the performance in microwave catalytic pyrolysis process different. Activated carbon is prepared from raw materials containing carbon such as wood, coal and petroleum coke through pyrolysis and activation processing. Graphite is a crystalline form of carbon, consisting of graphene layers, belonging to the hexagonal crystal system, with complete lamellar solvation surfaces. Charcoal is a primitive amorphous porous carbon, generally obtained by pyrolysis of biomass or lignite coke. Therefore, charcoal and graphite can only be used as microwave absorbers to increase the heating rate and thus the yield of the product. Activated carbon, on the other hand, is now widely used in microwave catalytic pyrolysis due to its developed microporous structure, large specific surface area and high adsorption activity.

There are four main types of activated carbon: coal-based activated carbon, wood-based activated carbon, fruit shell activated carbon and coconut shell activated carbon. Coal-based activated carbon is made from high-quality coal as raw material, refined by advanced technology equipment, and refined through a series of processes such as carbonisation, cooling, activation, washing, etc. The shape is divided into granular, columnar, powder, etc. The activated carbon is mainly used in air purification and cleaning, and is widely used in microwave catalytic pyrolysis. Coal activated carbon is mainly used for air purification, waste gas purification, sewage treatment and waste water treatment. Wooden activated carbon is refined from high-quality wood through high-temperature carbonisation, granulation, activation and other processes, and its shape is divided into powder, column, granule and so on. Wooden activated carbon can effectively adsorb a variety of substances and impurities in the liquid, such as colour and other large. Fruit shell activated carbon is mainly made of fruit shells (apricot shells, cherry shells, jujube shells, coconut shells, olive shells, walnut shells, etc.) by carbonisation, activation and refining. Fruit shell activated carbon is widely used in the purification of domestic water, industrial water and wastewater. Coconut shell activated carbon is made from high-quality coconut shell, which is refined after screening, water vapour carbonisation, and then made through a series of processes such as debris removal, activation and sieving. The appearance of black granular, with a developed pore structure, large specific surface area, high adsorption capacity, stable chemical properties and durability and so on. Coconut shell activated carbon is widely used in metallurgy and chemical industry, petroleum and electric power, food and beverage, water purification and metal refining.

The preparation methods of activated carbon mainly include physical method and chemical method. The physical method of preparing activated carbon usually includes carbonisation, activation and treatment. The chemical method of preparing activated carbon mainly adopts the hydrothermal technology, *i.e.*, it is gasified by water vapour at high temperature and then carbonized into carbon under thermal radiation. This process conditions low energy consumption and good product quality.

Activated carbon can be microwave-catalysed pyrolysis of various biomasses, such as microalgae, sewage sludge, lignin and willow jars [81]-[84]. The addition of activated carbon to the microwave pyrolysis process can produce bio-oils of different compositions with relatively high gas yield. Hu *et al.* investigated the microwave-assisted pyrolysis process of Chlorella vulgaris at different microwave power levels, catalysts, activated carbon content and solid residue content [85]. Among them, all four different catalysts promoted the microwave-assisted pyrolysis of Chlorella well, but the activated carbon was the most effective, with a bio-oil gas yield of 87.47% [85]. Chen *et al.* analysed the microwave-assisted co-pyrolysis reaction of Chlorella and high-density polyethylene (HDPE) using activated carbon as a microwave absorber [86]. The results showed that Chlorella/HDPE = 1:1 was the optimal mixing ratio, while 40% activated carbon was the optimal addition amount, which greatly improved the co-pyrolysis characteristics [86].

Activated carbon resulted in a significant increase in the hydrocarbon and phenolic content of the bio-oil. Mamaeva *et al.* compared the microwave-catalysed pyrolysis of lignocellulosic biomass with activated carbon and lignite coal, respectively, and found that activated carbon in the presence of an alternating current (AC) significantly increased the selectivity of phenolics in the bio-oil, with a phenolics content of 61.19% at 300˚C [87]. Further, Bu *et al.* investigated the microwave-catalysed pyrolysis of biomass using activated carbon as a catalyst and found that the phenolics content of bio-oil was 66.89% at a temperature of 589 K, a catalyst to biomass ratio of 3:1 and a reaction time of 8 min [88]. Overall, activated carbon improved the selectivity of phenolic compounds in bio-oil.

Charcoal and graphite were also studied as microwave absorbers in microwave-assisted catalytic pyrolysis. Domínguez *et al.* pyrolysed sewage sludge at microwave energy using graphite and charcoal as absorbers and concluded that microwave pyrolysis produces higher yields of H_2 and CO than conventional pyrolysis [89]. Wang *et al.* investigated microwave-assisted catalytic pyrolysis of sewage sludge with graphite, and found that, at a microwave power of 400 W, the bio oil yield was 49.79% [90].

In summary, carbonaceous material catalysts can play a key role in the microwave pyrolysis process through their specific surface structure and active sites. By modifying and optimising the carbonaceous material catalysts, their catalytic efficiency and selectivity can be further improved, allowing them to show progress in applications such as tar reforming and improving the properties of biomass pyrolysis products.

4.3. Metal Oxides/Salt

Metal oxides (e.g., CaO, NiO, CuO, MgO, etc.) have received attention in microwave-catalysed pyrolysis processes for reducing coke formation and lowering the acidity of bio-oils [91]-[94]. Metal oxides, due to their high dielectric constants, can be used as absorbers to enhance the absorption of microwave energy and ultimately affect the composition of pyrolysis products.

Metal oxides can be used as microwave absorbers to improve bio-oil yields and reduce the calorific value of solid residues. CaO, NiO, CuO, MgO and Fe_2O_3 are common catalysts used in microwave-catalysed pyrolysis. Generally, the presence of CaO and MgO contributes to the formation of gaseous components, while NiO, CuO and Fe_2O_3 contribute to the formation of liquid components [95] [96]. Huang *et al.* selected four metal oxides, NiO, CuO, CaO and MgO, as catalysts for microwave pyrolysis of corn stover, and showed that the metal oxides increased the maximum temperature and produced more gaseous or liquid hydrocarbons, but reduced the calorific value of the solid residue [97]. Selvam *et al.* used a non-homogeneous catalyst, ZnO, for microwave-assisted depolymerisation of PET and compared its performance with that of conventional glycolysis [98]. The results showed that microwave heating could rapidly depolymerise PET into monomers with a selectivity of up to 95% in a short period of time. Ma *et al.* showed that CaO promoted the formation of aromatic compounds, whereas Fe_2O_3 inhibited the formation of aromatic compounds [96]. CaO has a better catalytic effect in microwave pyrolysis, which is mainly attributed to the fact that positive ions on the surface of CaO interact with the negative ions of the organic molecules interactions, allowing the activation energy of pyrolysis to be lowered and the C-C bonds to be broken more easily. In addition to increasing the bio-oil yield, metal oxides can also increase the reaction rate.

In addition to metal oxides, metal salts and alkaline microwave pyrolysis catalysts have been explored in recent years. The mixture of different catalysts is also important for heating rate and product quality. Mohamed *et al.* found that K_3PO_4, zeolite and bentonite all showed good catalytic activity in microwave-assisted pyrolysis, and that a mixture of 10% K_3PO_4 with 10% zeolite significantly reduced the water content of bio-oil compared to bio-oils with only 10% zeolite and only 10% K_3PO_4, with a significant reduction in water content of bio-oil of 39.5% and 25.7%, demonstrating the potential synergistic effect of the catalyst mixture [99]. Fodah *et al.* concluded that $NaCO_3$ could be used as a catalyst for microwave pyrolysis of corn stover, and that the addition of the catalyst increased the rate of heat-up, maximum temperature, and the calorific value of the biochar, and led to an increase in the bio-oil yield as compared to the non-catalytic conditions [100]. Chen *et al.* and Zhao *et al.* also investigated the use of Na_2CO_3 as a catalyst and reported that Na_2CO_3 did not undergo chemical changes before and after microwave radiation [101] [102]. Therefore, the selection of a suitable catalyst can improve the efficiency of microwave heating and thus promote exothermic reactions.

Metals are sometimes used as catalysts for microwave pyrolysis of organic wastes. Dong *et al.* reported that rice husk charcoal-based iron catalysts (RHC/Fe) with strong microwave absorption properties under heated conditions have been used to catalyse the cleavage of two types of biomass materials, sargassum and pine shavings [103]. Among them, RHC/Fe produced higher gases than RHC for the pyrolysis of Sargassum and pine shavings, which could be attributed to the incorporation of Fe to promote the formation of microporous structure in RHC, as well as the high catalytic performance and significant selectivity for the pyrolysis of biomass. In conclusion, the biochar-based catalysts showed high catalytic activity in terms of catalytic performance.

In general, molecular sieve catalysts, carbonaceous material catalysts, and metal oxide/salt catalysts have different advantages and disadvantages due to their different characteristics and different catalytic characteristics. In **Table 3**, the section is detailed.

Table 3. Advantages and disadvantages of molecular sieve catalysts, carbon material catalysts, and metal oxide/salt catalysts.

Catalyst type	Features	Catalytic action	Advantage	Shortcoming
Molecular sieve catalysts	Crystalline microporous aluminosilicate material with a high surface acidity.	Microwave absorbent; dehydration, removal, decarboxylation and aromatization may occur.	High selectivity of the aromatic hydrocarbons.	Microwave absorbance difference; low microwave pyrolysis liquid product.
Carbon material catalysts	Solid products produced by biomass pyrolysis have rich functional groups.	Microwave absorbent; dehydration and decarboxylation reactions; high phenolic content in microwave pyrolysis products.	High heating efficiency; abundant functional groups.	Separation separation; easy to deactivation.
Metal oxide/salt catalysts	A great variety.	Microwave absorbent; high content of solid carbon and ketones in microwave pyrolysis products.	High content of microwave pyrolysis gas products (especially H_2); low price.	Easy to stop.

Although the introduction of the catalysts led to a significant increase in the selectivity of the products, there were still problems such as the complexity of the catalytic system and the low conversion rate. In addition, this paper has not mentioned many problems in terms of feedstock impurities, catalyst coking and deactivation, and process design. These problems can not be solved without the development of catalytic system, and catalytic technology will play an important role in the chemical recycling process of waste. In the future, the focus of research in this field will remain on the development of efficient catalysts and catalytic systems.

5. Potential Application Prospect

The products of microwave pyrolysis have great potential application prospects. The products mainly include solid, liquid and gas forms, which have different properties and potential application values.

The solid products of microwave pyrolysis can be used to produce activated carbon. Lam converted orange peels into 70% activated carbon by microwave pyrolysis [104]. Activated carbon under microwave pyrolysis is chemically stable, thermally stable, high adsorption capacity, high specific surface area and microporous structure. Therefore, activated carbon has a variety of potential applications. Firstly, activated carbon is widely used in water treatment and air purification due to its excellent adsorption properties, which can remove harmful substances and odours. Secondly, in chemical production, due to its microporous structure, activated carbon can be used as a catalyst to improve the activity and stability of the catalyst. Finally, the porous structure of activated carbon can also provide reaction sites for metals and be used as a metal catalyst carrier. Shen *et al.* used rice husk char-loaded nickel-iron catalyst for biomass pyrolysis, and the conversion efficiency of tar reached 92.3% under optimised conditions [105]. The results of the study showed that the activated carbon produced by microwave pyrolysis has extraordinary promise.

Biochar is one of the solid products of microwave pyrolysis. Biochar produced by microwave pyrolysis has higher properties compared to conventional pyrolysis. It is characterised by high carbon, rich plant nutrients, rich pore structure, large specific surface area and more oxygen-containing active groups. These properties make biochar versatile and a focus of research in several disciplines. In the field of agriculture, biochar is rich in carbon, which can increase the carbon content of soil and improve soil fertility. Most of the biochar is alkaline, and adding biochar to acidic soil can balance the pH of the soil and ultimately increase crop yield. This is an application of biochar as a soil amendment [106]. In the environmental field, biochar can adsorb metal ion pollution due to its large specific surface area and rich pore structure [107]. Meanwhile, biochar can effectively remove organic pollutants from the environment. Biochar is a renewable energy source with good adsorption properties, which can be used as an adsorbent to reduce the emission of greenhouse gases such as CO_2, N_2O, and CH_4. In the energy field, biochar can be used as capacitor electrodes and anode materials for lithium-ion batteries. In the chemical field, biochar can also be used as a catalyst that may enhance catalytic activity. In the construction field, components such as calcium silicate are separated from biochar, which can be used as raw materials for building materials and have good market prospects.

The liquid products of microwave pyrolysis can be separated into fuel oils with different boiling points after being treated with processes such as oil-water separation and distillation. These fuel oils have a wide range of applications. In the field of transport, fuel oils can be used as fuel for vehicles and aviation, replacing traditional gasoline or diesel, and reducing environmental pollution. In the industrial field, fuel oil can be used as fuel for industrial equipment to provide heat energy. In the chemical field, fuel oil, after further processing, can be used as a raw material for chemical production and for the synthesis of various chemicals. In addition, the water separated from the liquid product can be used for agricultural irrigation and urban greening after waste water treatment to meet the purification standard, so as to achieve the recycling of water resources.

The gas product of microwave pyrolysis can be directly used for gas after treatment. This gas is usually rich in combustible components, such as CH_4 and H_2, and is suitable for use as clean energy. This not only reduces dependence on fossil fuels, but also lowers carbon emissions, which is in line with the current requirements of sustainable development.

Microwave pyrolysis technology not only converts waste into valuable products, but also achieves the goal of harmless and reduced treatment. The potential applications of microwave pyrolysis products are extensive, covering a wide range of fields such as agriculture, construction, environment, energy and chemicals. By optimising the microwave pyrolysis process, the quality of the products can be further improved and the areas of application can be expanded. In the future, microwave pyrolysis technology will play a more important role in waste treatment and resource recovery.

6. Future Prospect

Microwave pyrolysis offers significant environmental and sustainability advantages, but there are also potential emissions issues. The following is a comprehensive assessment of microwave pyrolysis technology.

Microwave pyrolysis technology efficiently converts waste into useful energy sources such as solid, liquid and gaseous products through microwave heating. This technology is more energy efficient than the conventional pyrolysis process because microwave heating has the characteristics of selective heating, rapid heating and uniform heating, which can improve energy utilisation. At the same time, the process only requires electrical energy, does not produce secondary pollution, reduces greenhouse gas emissions, and is very safe and environmentally friendly for treating waste. Compared with traditional pyrolysis technology, microwave pyrolysis is a more environmentally friendly waste treatment method, that can efficiently treat waste, reduce the consumption of traditional fossil fuels, alleviate environmental pollution, and achieve green and sustainable development.

Despite the environmental advantages of microwave pyrolysis technology, the initial investment cost is high, which limits its industrial application. On the one hand, microwave pyrolysis has a relatively small processing capacity due to equipment and technology limitations, which may affect its application in large-scale waste treatment. On the other hand, the process of microwave pyrolysis is complex and the mechanism of pyrolysis has not been fully determined, which may affect the stability and efficiency of the process.

Microwave pyrolysis does not completely eliminate the pollution problem, but only converts solid pollution into gas pollution. Therefore, in practical application, the waste gas generated needs to be strictly controlled and treated to ensure environmental safety and compliance with national emission standards. For example, it needs to meet the emission requirements of GB 16297 and be treated in accordance with GB 37822 "Volatile organic compounds without organized emission control standards".

The microwave pyrolysis process has a closed nature that prevents the emission of waste gases into the environment. The microwave pyrolysis equipment should be equipped with exhaust gas purification system and tail gas online monitoring function to ensure that the tail gas emission meets the standard. At the same time, it is equipped with a microwave shielding device and a monitoring device with automatic alarm function to prevent microwave leakage from harming researchers.

During the microwave pyrolysis process, the pyrolysis efficiency and product quality can be improved by optimising the process parameters such as pyrolysis temperature, microwave power, catalyst and microwave absorber. Studies have shown that the use of catalysts can improve the quality and yield of pyrolysis products. However, the use of catalysts may also bring new environmental issues such as catalyst recovery and disposal.

Microwave pyrolysis requires lower pyrolysis temperatures and shorter pyrolysis times, resulting in significantly lower energy consumption than conventional pyrolysis. In addition, microwave pyrolysis equipment operates stably without the need for an external heat source, further reducing energy consumption. Microwave pyrolysis technology is capable of converting waste into valuable energy sources such as bio-oil, renewable gas and solid charcoal. These products can be used for energy production and industrial applications, thus realising the resourceful use of waste. Microwave pyrolysis technology not only improves the recycling rate of renewable resources, but also realises the unity of economic and environmental benefits.

Microwave pyrolysis, as an emerging energy-efficient technology, has demonstrated its potential in a number of areas, including the treatment of plastics, rubber, fibres and biomass. The development of this technology is helping to drive the research and development of sustainable materials and processes for green and sustainable development.

The microwave pyrolysis process offers significant environmental and sustainability advantages in terms of reduced energy consumption, reduced environmental pollution, resource utilisation and improved efficiency. However, potential exhaust emissions and catalyst usage issues require further attention. Overall, despite some challenges, microwave pyrolysis technology has a promising application in achieving green and sustainable development.

Looking into the future, microwave pyrolysis technology has a wide range of application fields, with great development potential and application value. Future research should focus on the functional modification and application expansion of biochar, and at the same time strengthen the integrated application of microwave pyrolysis and other green energy technologies to promote the sustainable development of biomass energy and environmental protection. With the continuous development of microwave technology, the performance of microwave pyrolysis equipment will continue to improve, such as higher heating efficiency, lower energy consumption, better treatment effects, etc., which will further promote the market application of microwave pyrolysis technology. In order to promote the development of environmental protection industry, the government can also introduce some policy measures, such as financial subsidies, tax incentives, etc., to provide strong support for the development of microwave pyrolysis technology market. In short, with the continuous progress of society, the market prospect of microwave pyrolysis technology will be more and more broad.

7. Conclusion

This paper summarises the influencing factors of microwave pyrolysis, including microwave power, pyrolysis temperature and microwave absorber, etc., and the product quality can be further improved by optimising these parameters. In addition, this paper focuses on reviewing the development status of catalysts (molecular sieve catalyst, carbonaceous material catalyst, metal oxide/salt catalyst) in microwave pyrolysis technology, describing the influence of catalysts on the yield and quality of pyrolysis products, as well as the prospects for the application of pyrolysis products in various fields.

The main findings are as follows:

1) There are many obvious advantages of using microwave heating compared with conventional pyrolysis. These advantages include rapid heating, selective heating, uniform heating, environmental protection and energy efficiency. These unique advantages play an important role in the development of microwave pyrolysis.

2) Compared with traditional pyrolysis, microwave pyrolysis technology can reduce pyrolysis temperature and activation energy, reduce the formation of coke on the catalyst, enhance the pore structure and adsorption capacity, and increase the yield and improve the quality of biochar.

3) The quality of the product can be effectively improved through in-depth study of the microwave mechanism, optimisation of pyrolysis conditions and

exploration of efficient catalysts. The products obtained by microwave pyrolysis are different from those obtained by conventional pyrolysis. The bio-oil obtained by microwave pyrolysis has a higher calorific value, fewer impurities and a higher yield of gas products. Biochar under microwave radiation has a greater specific surface area, more micropores and higher yield.

4) The amount of microwave power can directly affect the heating rate and the temperature distribution of the reaction system. When the microwave power is low, the heating rate is slower and the rate of product generation and yield are lower. On the contrary, when the microwave power is too high, although the heating rate is accelerated, but it is easy to trigger side reactions or lead to product decomposition, also unfavourable to the generation of products. Therefore, in the moderate microwave power range, the yield can be maximised and the quality can be maintained.

5) Pyrolysis temperature has a significant effect on the yield of the product. Generally speaking, at lower pyrolysis temperatures, the yield of bio-oil gradually increased with the increase of microwave pyrolysis temperature, and finally reached the maximum value. Subsequently, when the microwave pyrolysis temperature was further increased, the yield of bio-oil slightly decreased, but the yield of pyrolysis gas significantly increased. Among them, the H_2 and CO yields in pyrolysis gas accounted for more than half. This is because, as the temperature increases, the chemical bonds of the macromolecular compounds in the bio-oil are more easily broken, resulting in reactions such as decarboxylation, decarbonylation, and carbon-carbon bond breaking, which generate gas products and small-molecule liquid products.

6) Microwave absorber plays a vital role in microwave pyrolysis. a) Microwave absorbers can efficiently absorb microwave energy and rapidly warm up, making this warming process more rapid and uniform than the traditional heating method. b) The addition of microwave absorbers can reduce the power and temperature conditions required for pyrolysis, making the pyrolysis reaction take place under milder conditions. This helps to reduce energy consumption and improve the efficiency of the pyrolysis process. c) Some microwave absorbers also have a certain catalytic effect in the pyrolysis process, which can accelerate the pyrolysis reaction and improve the distribution of pyrolysis products. d) The optimisation of the distribution of pyrolysis products can be achieved by selecting suitable microwave absorbers and adjusting their addition ratio. Different microwave absorbers have different effects on the pyrolysis products.

7) The application of a catalyst can significantly improve product quality. The researchers used different catalysts mixed into the microwave pyrolysis experiments of organic macromolecules, and different catalysts played different effects. For example: alkali metal carbonates can improve the yield of gas and solid carbon, reduce the yield of bio-oil, and can promote the release of hydrogen in the raw material, so that the H_2/CO in the air product increases; K^+ can promote the generation of CO, CO_2, but hardly affects the generation of H_2O; NaCl can promote

the cellulose reaction in the generation of H_2O, CO and CO_2; some catalysts can promote the absorption of microwave, showing a good catalytic effect. The development of low-cost and high-performance catalysts is still the main direction for the future development of microwave pyrolysis technology.

8) With the continuous and in-depth research on the microwave pyrolysis of waste to produce combustible pyrolysis gas and light pyrolysis oil, it can effectively reduce the environmental pollution and ease the pressure on the environment, and achieve the harmless and resourceful use of waste, so the use of microwave pyrolysis method to treat waste has a very good application prospect.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Bridgwater, A. (2000) Fast Pyrolysis Processes for Biomass. *Renewable and Sustainable Energy Reviews*, **4**, 1-73. https://doi.org/10.1016/s1364-0321(99)00007-6

[2] Collard, F. and Blin, J. (2014) A Review on Pyrolysis of Biomass Constituents: Mechanisms and Composition of the Products Obtained from the Conversion of Cellulose, Hemicelluloses and Lignin. *Renewable and Sustainable Energy Reviews*, **38**, 594-608. https://doi.org/10.1016/j.rser.2014.06.013

[3] Kan, T., Strezov, V. and Evans, T.J. (2016) Lignocellulosic Biomass Pyrolysis: A Review of Product Properties and Effects of Pyrolysis Parameters. *Renewable and Sustainable Energy Reviews*, **57**, 1126-1140. https://doi.org/10.1016/j.rser.2015.12.185

[4] Azizi, K., Keshavarz Moraveji, M. and Abedini Najafabadi, H. (2018) A Review on Bio-Fuel Production from Microalgal Biomass by Using Pyrolysis Method. *Renewable and Sustainable Energy Reviews*, **82**, 3046-3059. https://doi.org/10.1016/j.rser.2017.10.033

[5] Nazari, M., Aguilar, M.M., Ghislain, T. and Lavoie, J.M. (2024) Microwave-Assisted Pyrolysis of Biomass Waste for Production of High-Quality Biochar: Corn Stover and Hemp Stem Case Studies. *Biomass and Bioenergy*, **187**, Article 107302. https://doi.org/10.1016/j.biombioe.2024.107302

[6] Hamzah, H.T., Sridevi, V., Surya, D.V., Ramesh, P., Rao, C.S., Palla, S., *et al.* (2024) Synergistic Effects and Product Yields in Microwave-Assisted-in-Situ Co-Pyrolysis of Rice Straw and Paraffin Wax. *Process Safety and Environmental Protection*, **182**, 45-55. https://doi.org/10.1016/j.psep.2023.11.048

[7] Suresh, A., Alagusundaram, A., Kumar, P.S., Vo, D.N., Christopher, F.C., Balaji, B., *et al.* (2021) Microwave Pyrolysis of Coal, Biomass and Plastic Waste: A Review. *Environmental Chemistry Letters*, **19**, 3609-3629. https://doi.org/10.1007/s10311-021-01245-4

[8] Bing, W., Hongbin, Z., Zeng, D., Yuefeng, F., Yu, Q. and Rui, X. (2021) Microwave Fast Pyrolysis of Waste Tires: Effect of Microwave Power on Product Composition and Quality. *Journal of Analytical and Applied Pyrolysis*, **155**, Article 104979. https://doi.org/10.1016/j.jaap.2020.104979

[9] Chen, C., Qi, Q., Huang, D., Zeng, T., Bu, X., Huang, Y., *et al.* (2021) Effect of Additive Mixture on Microwave-Assisted Catalysis Pyrolysis of Microalgae. *Energy*, **229**, Article 120752. https://doi.org/10.1016/j.energy.2021.120752

[10] Zhang, X., Rajagopalan, K., Lei, H., Ruan, R. and Sharma, B.K. (2017) An Overview of a Novel Concept in Biomass Pyrolysis: Microwave Irradiation. *Sustainable Energy & Fuels*, **1**, 1664-1699. https://doi.org/10.1039/c7se00254h

[11] Aguilar-Reynosa, A., Romaní, A., Ma. Rodríguez-Jasso, R., Aguilar, C.N., Garrote, G. and Ruiz, H.A. (2017) Microwave Heating Processing as Alternative of Pretreatment in Second-Generation Biorefinery: An Overview. *Energy Conversion and Management*, **136**, 50-65. https://doi.org/10.1016/j.enconman.2017.01.004

[12] Monzavi, M., Chen, Z., Solouki, A. and Chaouki, J. (2022) Microwave-Assisted Catalytic Pyrolysis of Paraffin Wax. *Fuel*, **320**, Article 123886. https://doi.org/10.1016/j.fuel.2022.123886

[13] Duran-Jimenez, G., Monti, T., Titman, J.J., Hernandez-Montoya, V., Kingman, S.W. and Binner, E.R. (2017) New Insights into Microwave Pyrolysis of Biomass: Preparation of Carbon-Based Products from Pecan Nutshells and Their Application in Wastewater Treatment. *Journal of Analytical and Applied Pyrolysis*, **124**, 113-121. https://doi.org/10.1016/j.jaap.2017.02.013

[14] Wang, Y., Zeng, Z., Tian, X., Dai, L., Jiang, L., Zhang, S., *et al.* (2018) Production of Bio-Oil from Agricultural Waste by Using a Continuous Fast Microwave Pyrolysis System. *Bioresource Technology*, **269**, 162-168. https://doi.org/10.1016/j.biortech.2018.08.067

[15] Zhou, N., Zhou, J., Dai, L., Guo, F., Wang, Y., Li, H., *et al.* (2020) Syngas Production from Biomass Pyrolysis in a Continuous Microwave Assisted Pyrolysis System. *Bioresource Technology*, **314**, Article 123756. https://doi.org/10.1016/j.biortech.2020.123756

[16] Miura, M., Kaga, H., Sakurai, A., Kakuchi, T. and Takahashi, K. (2004) Rapid Pyrolysis of Wood Block by Microwave Heating. *Journal of Analytical and Applied Pyrolysis*, **71**, 187-199. https://doi.org/10.1016/s0165-2370(03)00087-1

[17] Refaat, A.A., El Sheltawy, S.T. and Sadek, K.U. (2008) Optimum Reaction Time, Performance and Exhaust Emissions of Biodiesel Produced by Microwave Irradiation. *International Journal of Environmental Science & Technology*, **5**, 315-322. https://doi.org/10.1007/bf03326026

[18] Li, H., Li, J., Fan, X., Li, X. and Gao, X. (2019) Insights into the Synergetic Effect for Co-Pyrolysis of Oil Sands and Biomass Using Microwave Irradiation. *Fuel*, **239**, 219-229. https://doi.org/10.1016/j.fuel.2018.10.139

[19] Wu, C., Budarin, V.L., Gronnow, M.J., De Bruyn, M., Onwudili, J.A., Clark, J.H., *et al.* (2014) Conventional and Microwave-Assisted Pyrolysis of Biomass under Different Heating Rates. *Journal of Analytical and Applied Pyrolysis*, **107**, 276-283. https://doi.org/10.1016/j.jaap.2014.03.012

[20] Li, Z., Zhong, Z., Zhang, B., Wang, W., Seufitelli, G.V.S. and Resende, F.L.P. (2020) Effect of Alkali-Treated HZSM-5 Zeolite on the Production of Aromatic Hydrocarbons from Microwave Assisted Catalytic Fast Pyrolysis (MACFP) of Rice Husk. *Science of The Total Environment*, **703**, Article 134605. https://doi.org/10.1016/j.scitotenv.2019.134605

[21] Dong, Q., Niu, M., Bi, D., Liu, W., Gu, X. and Lu, C. (2018) Microwave-Assisted Catalytic Pyrolysis of Moso Bamboo for High Syngas Production. *Bioresource Technology*, **256**, 145-151. https://doi.org/10.1016/j.biortech.2018.02.018

[22] Sajjadi, B., Abdul Aziz, A.R. and Ibrahim, S. (2014) Investigation, Modelling and Reviewing the Effective Parameters in Microwave-Assisted Transesterification. *Renewable and Sustainable Energy Reviews*, **37**, 762-777. https://doi.org/10.1016/j.rser.2014.05.021

[23] Motasemi, F. and Afzal, M.T. (2013) A Review on the Microwave-Assisted Pyrolysis Technique. *Renewable and Sustainable Energy Reviews*, **28**, 317-330. https://doi.org/10.1016/j.rser.2013.08.008

[24] Zhang, S., Qiu, Q., Zeng, C., Paik, K., He, P. and Zhang, S. (2024) A Review on Heating Mechanism, Materials and Heating Parameters of Microwave Hybrid Heated Joining Technique. *Journal of Manufacturing Processes*, **116**, 176-191. https://doi.org/10.1016/j.jmapro.2024.02.055

[25] Raček, J., Chorazy, T., Komendová, R., Kučerík, J. and Hlavínek, P. (2022) Characteristics of a Solid Carbonaceous Product of Microwave Pyrolysis/Torrefaction of Sewage Sludge for the Use in Agriculture and Blue-Green Infrastructure. *Desalination and Water Treatment*, **258**, 223-240. https://doi.org/10.5004/dwt.2022.28423

[26] Fodah, A.E.M., Ghosal, M.K. and Behera, D. (2021) Microwave-Assisted Pyrolysis of Agricultural Residues: Current Scenario, Challenges, and Future Direction. *International Journal of Environmental Science and Technology*, **19**, 2195-2220. https://doi.org/10.1007/s13762-020-03099-9

[27] Li, H., Xu, J., Mbugua Nyambura, S., Wang, J., Li, C., Zhu, X., *et al.* (2022) Food Waste Pyrolysis by Traditional Heating and Microwave Heating: A Review. *Fuel*, **324**, Article 124574. https://doi.org/10.1016/j.fuel.2022.124574

[28] Jones, D.A., Lelyveld, T.P., Mavrofidis, S.D., Kingman, S.W. and Miles, N.J. (2002) Microwave Heating Applications in Environmental Engineering—A Review. *Resources, Conservation and Recycling*, **34**, 75-90. https://doi.org/10.1016/s0921-3449(01)00088-x

[29] Ren, L., Zhang, K., Zhang, Y., Wang, F., Yang, F. and Cheng, F. (2023) Mechanism of Gas Production under Microwave/Conventional Pyrolysis of Sewage Sludge: Mechanism of Microwave Energy Action on Oxygen-Containing Functional Groups. *Chemical Engineering Journal*, **464**, Article 142511. https://doi.org/10.1016/j.cej.2023.142511

[30] Mohamed, B.A., Bi, X., Li, L.Y., Leng, L., Salama, E. and Zhou, H. (2021) Bauxite Residue as a Catalyst for Microwave-Assisted Pyrolysis of Switchgrass to High Quality Bio-Oil and Biochar. *Chemical Engineering Journal*, **426**, Article 131294. https://doi.org/10.1016/j.cej.2021.131294

[31] Li, Q., Yin, X., Duan, W., Kong, L., Hao, B. and Ye, F. (2013) Electrical, Dielectric and Microwave-Absorption Properties of Polymer Derived Sic Ceramics in X Band. *Journal of Alloys and Compounds*, **565**, 66-72. https://doi.org/10.1016/j.jallcom.2013.02.176

[32] He, M., Zhao, J., Wang, D., Liang, Q., Wang, T., Zhao, S., *et al.* (2024) Microwave-assisted Catalytic Pyrolysis of Biomass with Biochar Materials Derived from Spent Lithium-Ion Batteries: Microwave Absorption and Pyrolysis Characteristics. *Journal of Environmental Chemical Engineering*, **12**, Article 112099. https://doi.org/10.1016/j.jece.2024.112099

[33] Pang, H., Duan, Y., Huang, L., Song, L., Liu, J., Zhang, T., *et al.* (2021) Research Advances in Composition, Structure and Mechanisms of Microwave Absorbing Materials. *Composites Part B: Engineering*, **224**, Article 109173. https://doi.org/10.1016/j.compositesb.2021.109173

[34] Suriapparao, D.V. and Vinu, R. (2015) Resource Recovery from Synthetic Polymers via Microwave Pyrolysis Using Different Susceptors. *Journal of Analytical and Applied Pyrolysis*, **113**, 701-712. https://doi.org/10.1016/j.jaap.2015.04.021

[35] Negi, P., Chhantyal, A.K., Dixit, A.K., Kumar, S. and Kumar, A. (2021) Activated Carbon Derived from Mango Leaves as an Enhanced Microwave Absorbing Material.

Sustainable Materials and Technologies, **27**, e00244. https://doi.org/10.1016/j.susmat.2020.e00244

[36] Liu, X., Zhang, Z. and Wu, Y. (2011) Absorption Properties of Carbon Black/Silicon Carbide Microwave Absorbers. *Composites Part B*: *Engineering*, **42**, 326-329. https://doi.org/10.1016/j.compositesb.2010.11.009

[37] Fan, S., Zhang, Y., Cui, L., Xiong, Q. and Maqsood, T. (2023) Conversion of Polystyrene Plastic into Aviation Fuel through Microwave-Assisted Pyrolysis as Affected by Iron-Based Microwave Absorbents. *ACS Sustainable Chemistry & Engineering*, **11**, 1054-1066. https://doi.org/10.1021/acssuschemeng.2c05880

[38] Hossain, M.A., Jewaratnam, J., Ganesan, P., Sahu, J.N., Ramesh, S. and Poh, S.C. (2016) Microwave Pyrolysis of Oil Palm Fiber (OPF) for Hydrogen Production: Parametric Investigation. *Energy Conversion and Management*, **115**, 232-243. https://doi.org/10.1016/j.enconman.2016.02.058

[39] Palla, S., Surya, D.V., Pritam, K., Puppala, H., Basak, T. and Palla, V.C.S. (2024) A Critical Review on the Influence of Operating Parameters and Feedstock Characteristics on Microwave Pyrolysis of Biomass. *Environmental Science and Pollution Research*, **31**, 57570-57593. https://doi.org/10.1007/s11356-024-33607-0

[40] Song, Z., Yang, Y., Sun, J., Zhao, X., Wang, W., Mao, Y., *et al.* (2017) Effect of Power Level on the Microwave Pyrolysis of Tire Powder. *Energy*, **127**, 571-580. https://doi.org/10.1016/j.energy.2017.03.150

[41] Li, L., Ma, X., Xu, Q. and Hu, Z. (2013) Influence of Microwave Power, Metal Oxides and Metal Salts on the Pyrolysis of Algae. *Bioresource Technology*, **142**, 469-474. https://doi.org/10.1016/j.biortech.2013.05.080

[42] Huang, Y., Chiueh, P., Kuan, W. and Lo, S. (2015) Effects of Lignocellulosic Composition and Microwave Power Level on the Gaseous Product of Microwave Pyrolysis. *Energy*, **89**, 974-981. https://doi.org/10.1016/j.energy.2015.06.035

[43] Undri, A., Rosi, L., Frediani, M. and Frediani, P. (2014) Efficient Disposal of Waste Polyolefins through Microwave Assisted Pyrolysis. *Fuel*, **116**, 662-671. https://doi.org/10.1016/j.fuel.2013.08.037

[44] Rex, P., Masilamani, I.P. and Miranda, L.R. (2020) Microwave Pyrolysis of Polystyrene and Polypropylene Mixtures Using Different Activated Carbon from Biomass. *Journal of the Energy Institute*, **93**, 1819-1832. https://doi.org/10.1016/j.joei.2020.03.013

[45] Suriapparao, D.V., Nagababu, G., Yerrayya, A. and Sridevi, V. (2021) Optimization of Microwave Power and Graphite Susceptor Quantity for Waste Polypropylene Microwave Pyrolysis. *Process Safety and Environmental Protection*, **149**, 234-243. https://doi.org/10.1016/j.psep.2020.10.055

[46] Shvets, A., Vershinina, K., Vinogrodskiy, K. and Kuznetsov, G. (2023) Microwave Pyrolysis of Woody Biomass: Influence of Radiation Power on the Composition of Conversion Products. *Applied Sciences*, **13**, Article 7926. https://doi.org/10.3390/app13137926

[47] Kabza, K.G., Chapados, B.R., Gestwicki, J.E. and McGrath, J.L. (2000) Microwave-induced Esterification Using Heterogeneous Acid Catalyst in a Low Dielectric Constant Medium. *The Journal of Organic Chemistry*, **65**, 1210-1214. https://doi.org/10.1021/jo990515c

[48] Russell, A.D., Antreou, E.I., Lam, S.S., Ludlow-Palafox, C. and Chase, H.A. (2012) Microwave-Assisted Pyrolysis of HDPE Using an Activated Carbon Bed. *RSC Advances*, **2**, Article 6756. https://doi.org/10.1039/c2ra20859h

[49] Lei, H., Ren, S. and Julson, J. (2009) The Effects of Reaction Temperature and Time

and Particle Size of Corn Stover on Microwave Pyrolysis. *Energy & Fuels*, **23**, 3254-3261. https://doi.org/10.1021/ef9000264

[50] Zhang, X., Lei, H., Zhu, L., Qian, M., Zhu, X., Wu, J., *et al.* (2016) Enhancement of Jet Fuel Range Alkanes from Co-Feeding of Lignocellulosic Biomass with Plastics via Tandem Catalytic Conversions. *Applied Energy*, **173**, 418-430. https://doi.org/10.1016/j.apenergy.2016.04.071

[51] Mong, G.R., Chong, C.T., Ng, J., Chong, W.W.F., Lam, S.S., Ong, H.C., *et al.* (2020) Microwave Pyrolysis for Valorization of Horse Manure Biowaste. *Energy Conversion and Management*, **220**, Article 113074. https://doi.org/10.1016/j.enconman.2020.113074

[52] Antunes, E., Schumann, J., Brodie, G., Jacob, M.V. and Schneider, P.A. (2017) Biochar Produced from Biosolids Using a Single-Mode Microwave: Characterisation and Its Potential for Phosphorus Removal. *Journal of Environmental Management*, **196**, 119-126. https://doi.org/10.1016/j.jenvman.2017.02.080

[53] Dai, L., Fan, L., Liu, Y., Ruan, R., Wang, Y., Zhou, Y., *et al.* (2017) Production of Bio-Oil and Biochar from Soapstock via Microwave-Assisted Co-Catalytic Fast Pyrolysis. *Bioresource Technology*, **225**, 1-8. https://doi.org/10.1016/j.biortech.2016.11.017

[54] Lin, J., Sun, S., Ma, R., Fang, L., Zhang, P., Qu, J., *et al.* (2018) Characteristics and Reaction Mechanisms of Sludge-Derived Bio-Oil Produced through Microwave Pyrolysis at Different Temperatures. *Energy Conversion and Management*, **160**, 403-410. https://doi.org/10.1016/j.enconman.2018.01.060

[55] Beneroso, D., Bermúdez, J.M., Arenillas, A. and Menéndez, J.A. (2013) Microwave Pyrolysis of Microalgae for High Syngas Production. *Bioresource Technology*, **144**, 240-246. https://doi.org/10.1016/j.biortech.2013.06.102

[56] Zhang, S., Dong, Q., Zhang, L. and Xiong, Y. (2015) High Quality Syngas Production from Microwave Pyrolysis of Rice Husk with Char-Supported Metallic Catalysts. *Bioresource Technology*, **191**, 17-23. https://doi.org/10.1016/j.biortech.2015.04.114

[57] Zhang, Y., Cui, Y., Liu, S., Fan, L., Zhou, N., Peng, P., *et al.* (2020) Fast Microwave-Assisted Pyrolysis of Wastes for Biofuels Production—A Review. *Bioresource Technology*, **297**, Article 122480. https://doi.org/10.1016/j.biortech.2019.122480

[58] Suriapparao, D.V., Vinu, R., Shukla, A. and Haldar, S. (2020) Effective Deoxygenation for the Production of Liquid Biofuels via Microwave Assisted Co-Pyrolysis of Agro Residues and Waste Plastics Combined with Catalytic Upgradation. *Bioresource Technology*, **302**, Article 122775. https://doi.org/10.1016/j.biortech.2020.122775

[59] Chuayjumnong, S., Karrila, S., Jumrat, S. and Pianroj, Y. (2020) Activated Carbon and Palm Oil Fuel Ash as Microwave Absorbers for Microwave-Assisted Pyrolysis of Oil Palm Shell Waste. *RSC Advances*, **10**, 32058-32068. https://doi.org/10.1039/d0ra04966b

[60] Singh, S., Bhaskar, R., Narayanan, K.B., Kumar, A. and Debnath, K. (2024) Development of Silicon Carbide (SiC)-Based Composites as Microwave-Absorbing Materials (MAMs): A Review. *Journal of the European Ceramic Society*, **44**, 7411-7431. https://doi.org/10.1016/j.jeurceramsoc.2024.05.032

[61] Yang, H., Yuan, J., Li, Y., Hou, Z., Jin, H., Fang, X., *et al.* (2013) Silicon Carbide Powders: Temperature-Dependent Dielectric Properties and Enhanced Microwave Absorption at Gigahertz Range. *Solid State Communications*, **163**, 1-6. https://doi.org/10.1016/j.ssc.2013.03.004

[62] Ma, Z., Zhang, Y., Cao, C., Yuan, J., Liu, Q. and Wang, J. (2011) Attractive Microwave Absorption and the Impedance Match Effect in Zinc Oxide and Carbonyl Iron

Composite. *Physica B: Condensed Matter*, **406**, 4620-4624. https://doi.org/10.1016/j.physb.2011.09.039

[63] Salema, A.A. and Ani, F.N. (2012) Pyrolysis of Oil Palm Empty Fruit Bunch Biomass Pellets Using Multimode Microwave Irradiation. *Bioresource Technology*, **125**, 102-107. https://doi.org/10.1016/j.biortech.2012.08.002

[64] Zhou, Y., Wang, Y., Fan, L., Dai, L., Duan, D., Liu, Y., *et al.* (2017) Fast Microwave-Assisted Catalytic Co-Pyrolysis of Straw Stalk and Soapstock for Bio-Oil Production. *Journal of Analytical and Applied Pyrolysis*, **124**, 35-41. https://doi.org/10.1016/j.jaap.2017.02.026

[65] Tian, Y., Zuo, W., Ren, Z. and Chen, D. (2011) Estimation of a Novel Method to Produce Bio-Oil from Sewage Sludge by Microwave Pyrolysis with the Consideration of Efficiency and Safety. *Bioresource Technology*, **102**, 2053-2061. https://doi.org/10.1016/j.biortech.2010.09.082

[66] Abramovitch, R.A. (1991) Applications of Microwave Energy in Organic Chemistry. A Review. *Organic Preparations and Procedures International*, **23**, 683-711. https://doi.org/10.1080/00304949109458244

[67] Yu, Y., Yu, J., Sun, B. and Yan, Z. (2014) Influence of Catalyst Types on the Microwave-Induced Pyrolysis of Sewage Sludge. *Journal of Analytical and Applied Pyrolysis*, **106**, 86-91. https://doi.org/10.1016/j.jaap.2014.01.003

[68] Liu, H., Ma, X., Li, L., Hu, Z., Guo, P. and Jiang, Y. (2014) The Catalytic Pyrolysis of Food Waste by Microwave Heating. *Bioresource Technology*, **166**, 45-50. https://doi.org/10.1016/j.biortech.2014.05.020

[69] Fricler, V.Y., Nyashina, G.S., Vershinina, K.Y., Vinogrodskiy, K.V., Shvets, A.S. and Strizhak, P.A. (2023) Microwave Pyrolysis of Agricultural Waste: Influence of Catalysts, Absorbers, Particle Size and Blending Components. *Journal of Analytical and Applied Pyrolysis*, **171**, Article 105962. https://doi.org/10.1016/j.jaap.2023.105962

[70] Huang, Y., Kuan, W. and Chang, C. (2018) Effects of Particle Size, Pretreatment, and Catalysis on Microwave Pyrolysis of Corn Stover. *Energy*, **143**, 696-703. https://doi.org/10.1016/j.energy.2017.11.022

[71] Jing, X., Dong, J., Huang, H., Deng, Y., Wen, H., Xu, Z., *et al.* (2021) Interaction between Feedstocks, Absorbers and Catalysts in the Microwave Pyrolysis Process of Waste Plastics. *Journal of Cleaner Production*, **291**, Article 125857. https://doi.org/10.1016/j.jclepro.2021.125857

[72] Ding, K., Liu, S., Huang, Y., Liu, S., Zhou, N., Peng, P., *et al.* (2019) Catalytic Microwave-Assisted Pyrolysis of Plastic Waste over Nio and HY for Gasoline-Range Hydrocarbons Production. *Energy Conversion and Management*, **196**, 1316-1325. https://doi.org/10.1016/j.enconman.2019.07.001

[73] Zhang, X., Lei, H., Yadavalli, G., Zhu, L., Wei, Y. and Liu, Y. (2015) Gasoline-Range Hydrocarbons Produced from Microwave-Induced Pyrolysis of Low-Density Polyethylene over ZSM-5. *Fuel*, **144**, 33-42. https://doi.org/10.1016/j.fuel.2014.12.013

[74] Zhou, N., Dai, L., Lyu, Y., Wang, Y., Li, H., Cobb, K., *et al.* (2022) A Structured Catalyst of ZSM-5/SiC Foam for Chemical Recycling of Waste Plastics via Catalytic Pyrolysis. *Chemical Engineering Journal*, **440**, Article 135836. https://doi.org/10.1016/j.cej.2022.135836

[75] Dai, L., Fan, L., Duan, D., Ruan, R., Wang, Y., Liu, Y., *et al.* (2017) Production of Hydrocarbon-Rich Bio-Oil from Soapstock via Fast Microwave-Assisted Catalytic Pyrolysis. *Journal of Analytical and Applied Pyrolysis*, **125**, 356-362. https://doi.org/10.1016/j.jaap.2017.03.003

[76] Zhang, B., Zhong, Z., Chen, P. and Ruan, R. (2015) Microwave-Assisted Catalytic

Fast Pyrolysis of Biomass for Bio-Oil Production Using Chemical Vapor Deposition Modified HZSM-5 Catalyst. *Bioresource Technology*, **197**, 79-84. https://doi.org/10.1016/j.biortech.2015.08.063

[77] Zou, R., Wang, Y., Jiang, L., Yu, Z., Zhao, Y., Wu, Q., *et al.* (2019) Microwave-Assisted Co-Pyrolysis of Lignin and Waste Oil Catalyzed by Hierarchical ZSM-5/MCM-41 Catalyst to Produce Aromatic Hydrocarbons. *Bioresource Technology*, **289**, Article 121609. https://doi.org/10.1016/j.biortech.2019.121609

[78] Qu, B., Zhang, Y.S., Wang, T., Choi, H.S., Zhang, Y., Fu, Z., *et al.* (2024) Pyrolysis-catalysis of Waste Tire to Enhance the Aromatics Selectivity via Metal-Modified ZSM-5 Catalysts. *Process Safety and Environmental Protection*, **190**, 138-148. https://doi.org/10.1016/j.psep.2024.07.041

[79] Liang, J., Morgan, H.M., Liu, Y., Shi, A., Lei, H., Mao, H., *et al.* (2017) Enhancement of Bio-Oil Yield and Selectivity and Kinetic Study of Catalytic Pyrolysis of Rice Straw over Transition Metal Modified ZSM-5 Catalyst. *Journal of Analytical and Applied Pyrolysis*, **128**, 324-334. https://doi.org/10.1016/j.jaap.2017.09.018

[80] Menéndez, J.A., Arenillas, A., Fidalgo, B., Fernández, Y., Zubizarreta, L., Calvo, E.G., *et al.* (2010) Microwave Heating Processes Involving Carbon Materials. *Fuel Processing Technology*, **91**, 1-8. https://doi.org/10.1016/j.fuproc.2009.08.021

[81] Chen, C., Ling, H., Wei, D., Wei, Y., Fan, D. and Zhao, J. (2023) Microwave Catalytic Co-Pyrolysis of Chlorella Vulgaris and Oily Sludge by Nickel-X (X=Cu, Fe) Supported on Activated Carbon: Characteristic and Bio-Oil Analysis. *Journal of the Energy Institute*, **111**, Article 101401. https://doi.org/10.1016/j.joei.2023.101401

[82] Bu, Q., Lei, H., Wang, L., Wei, Y., Zhu, L., Zhang, X., *et al.* (2014) Bio-Based Phenols and Fuel Production from Catalytic Microwave Pyrolysis of Lignin by Activated Carbons. *Bioresource Technology*, **162**, 142-147. https://doi.org/10.1016/j.biortech.2014.03.103

[83] Chen, C., Wei, Y., Wei, G., Qiu, S., Yang, G. and Bi, Y. (2023) Microwave Co-Pyrolysis of Mulberry Branches and Chlorella Vulgaris under Carbon Material Additives. *Energy*, **284**, Article 128757. https://doi.org/10.1016/j.energy.2023.128757

[84] Chen, Y. (2016) Microwave Pyrolysis of Oily Sludge with Activated Carbon. *Environmental Technology*, **37**, 3139-3145. https://doi.org/10.1080/09593330.2016.1178333

[85] Hu, Z., Ma, X. and Chen, C. (2012) A Study on Experimental Characteristic of Microwave-Assisted Pyrolysis of Microalgae. *Bioresource Technology*, **107**, 487-493. https://doi.org/10.1016/j.biortech.2011.12.095

[86] Chen, C., Fan, D., Zhao, J., Qi, Q., Huang, X., Zeng, T., *et al.* (2022) Study on Microwave-Assisted Co-Pyrolysis and Bio-Oil of Chlorella Vulgaris with High-Density Polyethylene under Activated Carbon. *Energy*, **247**, Article 123508. https://doi.org/10.1016/j.energy.2022.123508

[87] Mamaeva, A., Tahmasebi, A., Tian, L. and Yu, J. (2016) Microwave-Assisted Catalytic Pyrolysis of Lignocellulosic Biomass for Production of Phenolic-Rich Bio-Oil. *Bioresource Technology*, **211**, 382-389. https://doi.org/10.1016/j.biortech.2016.03.120

[88] Bu, Q., Lei, H., Ren, S., Wang, L., Zhang, Q., Tang, J., *et al.* (2012) Production of Phenols and Biofuels by Catalytic Microwave Pyrolysis of Lignocellulosic Biomass. *Bioresource Technology*, **108**, 274-279. https://doi.org/10.1016/j.biortech.2011.12.125

[89] Domínguez, A., Menéndez, J.A., Inguanzo, M. and Pís, J.J. (2006) Production of Bio-Fuels by High Temperature Pyrolysis of Sewage Sludge Using Conventional and Microwave Heating. *Bioresource Technology*, **97**, 1185-1193. https://doi.org/10.1016/j.biortech.2005.05.011

[90] Wang, W., Wang, B., Sun, J., Mao, Y., Zhao, X. and Song, Z. (2016) Numerical Simulation of Hot-Spot Effects in Microwave Heating Due to the Existence of Strong Microwave-Absorbing Media. *RSC Advances*, **6**, 52974-52981. https://doi.org/10.1039/c6ra05191j

[91] Li, C., Liu, C., Xia, H., Zhang, L., Liu, D. and Shu, B. (2023) Microwave Catalytic Co-Pyrolysis of Waste Printed Circuit Boards and Alkaline Metal Compounds for Br Conversion and Material Recovery. *The Journal of the Minerals*, *Metals & Materials Society*, **75**, 3555-3567. https://doi.org/10.1007/s11837-023-06000-4

[92] Chen, C., Qiu, S., Ling, H., Zhao, J., Fan, D. and Zhu, J. (2023) Effect of Transition Metal Oxide on Microwave Co-Pyrolysis of Sugarcane Bagasse and Chlorella Vulgaris for Producing Bio-Oil. *Industrial Crops and Products*, **199**, Article 116756. https://doi.org/10.1016/j.indcrop.2023.116756

[93] State, R.N., Volceanov, A., Muley, P. and Boldor, D. (2019) A Review of Catalysts Used in Microwave Assisted Pyrolysis and Gasification. *Bioresource Technology*, **277**, 179-194. https://doi.org/10.1016/j.biortech.2019.01.036

[94] Wu, Q., Wang, Y., Peng, Y., Ke, L., Yang, Q., Jiang, L., *et al.* (2020) Microwave-Assisted Pyrolysis of Waste Cooking Oil for Hydrocarbon Bio-Oil over Metal Oxides and HZSM-5 Catalysts. *Energy Conversion and Management*, **220**, Article 113124. https://doi.org/10.1016/j.enconman.2020.113124

[95] Kuan, W., Huang, Y., Chang, C. and Lo, S. (2013) Catalytic Pyrolysis of Sugarcane Bagasse by Using Microwave Heating. *Bioresource Technology*, **146**, 324-329. https://doi.org/10.1016/j.biortech.2013.07.079

[96] Ma, R., Huang, X., Zhou, Y., Fang, L., Sun, S., Zhang, P., *et al.* (2017) The Effects of Catalysts on the Conversion of Organic Matter and Bio-Fuel Production in the Microwave Pyrolysis of Sludge at Different Temperatures. *Bioresource Technology*, **238**, 616-623. https://doi.org/10.1016/j.biortech.2017.04.103

[97] Huang, Y., Kuan, W., Chang, C. and Tzou, Y. (2013) Catalytic and Atmospheric Effects on Microwave Pyrolysis of Corn Stover. *Bioresource Technology*, **131**, 274-280. https://doi.org/10.1016/j.biortech.2012.12.177

[98] Selvam, E., Luo, Y., Ierapetritou, M., Lobo, R.F. and Vlachos, D.G. (2023) Microwave-assisted Depolymerization of PET over Heterogeneous Catalysts. *Catalysis Today*, **418**, Article 114124. https://doi.org/10.1016/j.cattod.2023.114124

[99] Mohamed, B.A., Kim, C.S., Ellis, N. and Bi, X. (2016) Microwave-Assisted Catalytic Pyrolysis of Switchgrass for Improving Bio-Oil and Biochar Properties. *Bioresource Technology*, **201**, 121-132. https://doi.org/10.1016/j.biortech.2015.10.096

[100] Mahmoud Fodah, A.E., Ghosal, M.K. and Behera, D. (2021) Bio-Oil and Biochar from Microwave-Assisted Catalytic Pyrolysis of Corn Stover Using Sodium Carbonate Catalyst. *Journal of the Energy Institute*, **94**, 242-251. https://doi.org/10.1016/j.joei.2020.09.008

[101] Chen, M., Wang, J., Zhang, M., Chen, M., Zhu, X., Min, F., *et al.* (2008) Catalytic Effects of Eight Inorganic Additives on Pyrolysis of Pine Wood Sawdust by Microwave Heating. *Journal of Analytical and Applied Pyrolysis*, **82**, 145-150. https://doi.org/10.1016/j.jaap.2008.03.001

[102] Zhao, X., Wang, W., Liu, H., Ma, C. and Song, Z. (2014) Microwave Pyrolysis of Wheat Straw: Product Distribution and Generation Mechanism. *Bioresource Technology*, **158**, 278-285. https://doi.org/10.1016/j.biortech.2014.01.094

[103] Dong, Y., Tian, B., Guo, F., Du, S., Zhan, Y., Zhou, H., *et al.* (2021) Application of Low-Cost Fe-Based Catalysts in the Microwave-Assisted Pyrolysis of Macroalgae and Lignocellulosic Biomass for the Upgradation of Bio-Oil. *Fuel*, **300**, Article 120944.

https://doi.org/10.1016/j.fuel.2021.120944

[104] Lam, S.S., Liew, R.K., Wong, Y.M., Azwar, E., Jusoh, A. and Wahi, R. (2016) Activated Carbon for Catalyst Support from Microwave Pyrolysis of Orange Peel. *Waste and Biomass Valorization*, **8**, 2109-2119. https://doi.org/10.1007/s12649-016-9804-x

[105] Shen, Y., Zhao, P., Shao, Q., Ma, D., Takahashi, F. and Yoshikawa, K. (2014) *In-Situ* Catalytic Conversion of Tar Using Rice Husk Char-Supported Nickel-Iron Catalysts for Biomass Pyrolysis/Gasification. *Applied Catalysis B: Environmental*, **152**, 140-151. https://doi.org/10.1016/j.apcatb.2014.01.032

[106] Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H.P., *et al*. (2012) Biochar: A Synthesis of Its Agronomic Impact Beyond Carbon Sequestration. *Journal of Environmental Quality*, **41**, 973-989. https://doi.org/10.2134/jeq2011.0069

[107] Qi, G., Pan, Z., Zhang, X., Chang, S., Wang, H., Wang, M., *et al*. (2023) Microwave Biochar Produced with Activated Carbon Catalyst: Characterization and Adsorption of Heavy Metals. *Environmental Research*, **216**, Article 114732. https://doi.org/10.1016/j.envres.2022.114732