

Microwave-driven conversion of waste plastics to high-value chemicals: Progress, challenges, prospects

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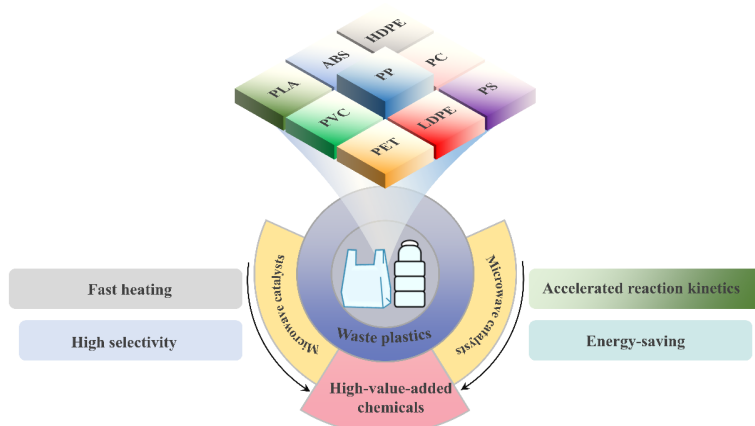


Cite This: *Carbon Future* 2026, 3, 9200082



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ABSTRACT: Microwave catalytic technology provides a new method for chemical recycling of waste plastics. This review summarizes the research progress in microwave catalytic conversion of waste plastics. It introduces the synergistic effect of microwave dielectric heating and catalytic reactions. The depolymerization pathways of typical waste plastics are reviewed. The design and structure-activity relationships of microwave-absorbing catalysts are discussed. The effects of reaction parameters on product distribution are also analyzed. Then the challenges facing this field are discussed, including unclear reaction mechanisms, rapid catalyst deactivation, and difficulties in scaling up the process. Finally, future research directions are proposed, which involve clarifying multi-scale reaction mechanisms, developing high-stability catalysts, and designing continuous reaction devices.



KEYWORDS: waste plastics, chemical recycling, microwave catalysis.

1 Introduction

Plastics, high-molecular-weight polymers derived from petroleum and natural gas, are manufactured via cracking and polymerization, featuring low density, high strength and good chemical stability¹. These properties make them widely used in packaging, construction, electronics, and medical devices². Common plastics include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and poly(ethylene terephthalate) (PET)³. However, the massive use of plastics has led to waste accumulation⁴. Since most waste plastic is not effectively recycled, this results in a huge loss of hydrocarbon resources and creates environmental pollution. Moreover, microplastics (< 5 mm) formed from plastic debris are now found in water, soil, and organisms, posing risks to ecosystems and human health^{5–7}.

Traditional disposal methods include mechanical recycling, landfilling, and incineration⁸. Mechanical recycling generally fails to maintain the original performance of plastics, since each cycle of

reprocessing inevitably triggers polymer chain degradation⁹. As for landfill treatment, it squanders scarce land resources and allows certain hazardous additives contained in plastics to gradually leach out, bringing potential environmental hazards. Meanwhile, incineration offers a rapid solution for plastic waste disposal, yet it releases toxic by-products including dioxins¹⁰. Therefore, above methods have low efficiency and high pollution risks. Chemical recycling is a promising alternative, which can convert waste plastics into monomers, chemicals, or fuels¹¹. Conventional pyrolysis requires high temperatures (> 400 °C) and long reaction times and it also gives poor product selectivity¹². Besides traditional pyrolysis methods, several other chemical recycling methods have also attracted widespread attention. For example, solvent decomposition methods (such as hydrolysis, glycolysis, and methanol decomposition) can effectively depolymerize polyester plastics (PET, polylactic acid (PLA), etc.)¹³. However, this method requires a large amount of solvent, usually generates secondary waste, and is not suitable for treating polyolefins. Meanwhile, noble metal-catalyzed hydrogenolysis and hydrocracking (e.g., using Pt, Pd, and Ru) can convert plastic waste into small molecule chemicals under mild conditions¹⁴. However, this method relies on high-purity hydrogen and expensive catalysts, which greatly increases the cost of the reaction. In addition, catalytic pyrolysis using solid acids or zeolites can improve the selectivity of the target product, but still

Received: May 22, 2026; Revised: June 25, 2026

Accepted: June 30, 2026

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<https://doi.org/10.26599/CF.2026.9200082>



清华大学出版社
Tsinghua University Press

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requires high temperatures ($> 400\text{ }^{\circ}\text{C}$) and is prone to coking, resulting in poor catalyst durability¹⁵. Recently, other emerging techniques such as plasma-assisted catalysis, photothermal catalysis, and enzymatic recycling have offered new routes for waste plastic recovery^{16–18}. However, plasma-assisted processes suffer from high energy consumption and poor product selectivity. Photothermal methods are limited by shallow light penetration, making them ineffective for opaque or large-sized waste. Enzymatic recycling, despite its high selectivity, is hindered by slow reaction rates and impurity tolerance, failing to handle complex mixed waste plastics. In contrast, microwave catalysis utilizes dielectric heating to achieve rapid and uniform energy transfer, thereby shortening reaction time and reducing energy consumption. Simultaneously, with this unique heating mode, microwave catalysis can precisely tune the selectivity toward high-value chemical products, thereby showing significant suitability for complex mixed plastic waste^{19–22}. Therefore, in recent years, microwave catalysis has been widely applied to the thermochemical conversion of various plastic wastes^{23–25}.

This review summarizes recent advances in microwave-driven upcycling of waste plastics. It first introduces the basic principles of microwave-catalyzed plastic conversion. Then, it describes conversion systems for different plastic types (PE, PP, PS, and PET, etc.). Key catalysts such as carbon materials, metal oxides, and zeolites are discussed. Meanwhile, their mechanisms and structure-activity relationships are highlighted. In addition, their effects on product distribution are analyzed. Moreover, current challenges have been clarified, which include reactor scale-up, catalyst deactivation, and understanding non-thermal effects. Finally, the future directions are proposed, including rational catalyst design, continuous-flow reactors, and life-cycle assessment. This review aims to provide insights into waste plastic valorization toward a circular economy.

2 Microwave catalytic plastic conversion

2.1 The mechanism of microwave heating

Microwave is an electromagnetic wave with frequencies of 300 MHz to 300 GHz and the most common frequency for plastic recycling is 2.45 GHz²⁶. Microwave heating works through dielectric heating, so polar molecules or lossy materials absorb microwave energy and convert it into heat via molecular friction²⁷. The efficiency is measured by the dielectric loss tangent ($\tan\delta$), but most plastics have a low $\tan\delta$ and are hard to heat directly.

Therefore, high-loss materials like activated carbon, silicon carbide, and metal oxides are added as susceptors or catalyst supports. This allows microwaves and catalysts to work together and improve plastic conversion. In this way, the localized “hot spots” on catalyst surfaces lower the activation energy for polymer bond breaking. Meanwhile, microwave-catalyst interactions actively steer reaction pathways to increase product selectivity, and they also suppress unwanted side reactions such as excessive charring or gas formation²¹. As a result, the overall depolymerization process becomes cleaner and more efficient, which is a clear advantage over conventional heating methods (Fig. 1).

2.2 Recent advances in microwave catalytic plastic conversion

Polyester (PET and PLA) contains polar ester bonds and is easily activated by microwave, so it can achieve closed-loop recovery of high-purity monomers through main pathways such as ester exchange, ammonolysis, and hydrolysis. Polyolefins possess inert saturated backbones and thus need strong microwave absorbers and catalysts, with conversion targets of fuels and carbon materials. Other plastics such as PS and PVC face unique challenges in microwave-assisted recycling processes. For example, PS needs to recover styrene monomers through highly selective depolymerization, rather than complex aromatic mixtures. And PVC must achieve efficient dehydrochlorination to prevent catalyst poisoning. This section reviews reaction paths, catalyst design, and products for each plastic type.

2.2.1 Microwave catalytic conversion of polyesters

Due to the presence of polar ester bonds in its molecular structure, polyester stands out as the optimal target for microwave catalytic closed-loop recycling. As the most representative polyesters, PET and PLA conversion cases are highlighted below.

2.2.1.1 PET conversion

Recently, microwave glycolysis of PET has attracted much attention due to significantly reduced reaction times. Selvam et al. found that reducing the particle size or selectively exposing the polar (001) facets of ZnO enhances its catalytic activity (Fig. 2a)²⁸. Under microwave irradiation, a bis(2-hydroxyethyl) terephthalate (BHET) yield of over 95% was achieved at $210\text{ }^{\circ}\text{C}$ within 45 min. Achilias et al. demonstrated that complete depolymerization occurs within 5 min at $180\text{ }^{\circ}\text{C}$ under microwave conditions, whereas conventional heating requires over 4 h²⁹. Meanwhile, we developed a

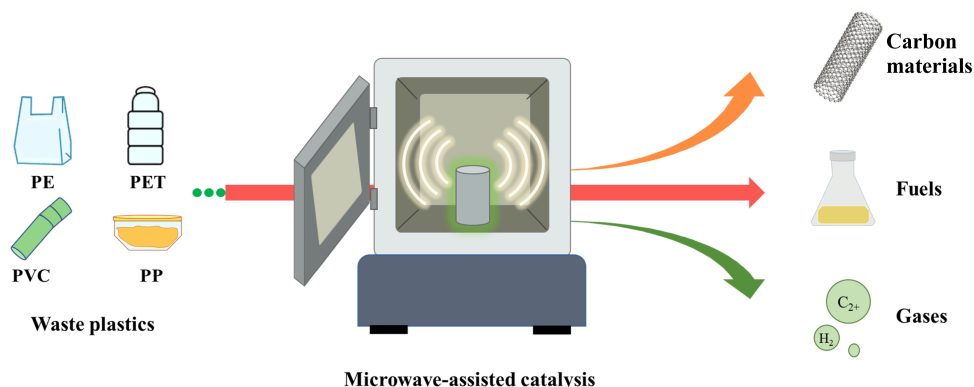


Fig. 1. Schematic diagram of microwave catalytic conversion of plastic waste into high value-added chemicals

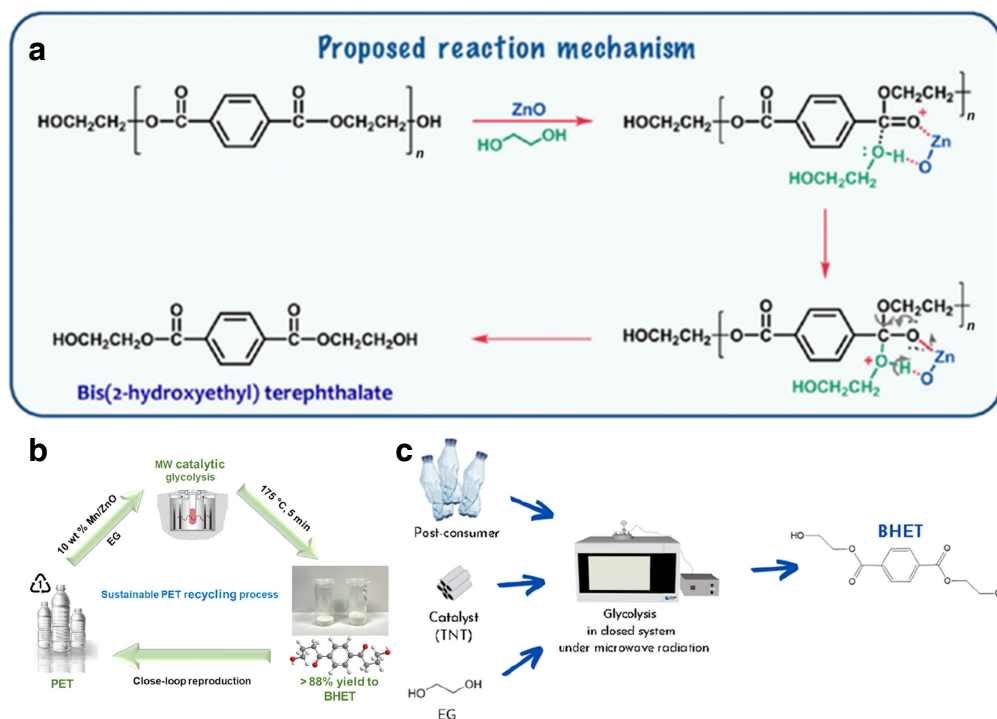


Fig. 2. The conversion of PET. **a**, Proposed reaction mechanism for glycolysis of PET over ZnO. Reproduced with permission from Ref.²⁸, © Elsevier B.V. 2023. **b**, Schematic illustration of the sustainable PET recycling process via microwave catalytic glycolysis over Mn₃O₄/ZnO catalyst. Reproduced with permission from Ref.³⁰, © Chinese Chemical Society 2023. **c**, Schematic diagram of chemical recycling of virgin PET and post-consumer PET over titanate nanotube catalysts. Reproduced with permission from Ref.³¹, © Stigger, A. R. D. N. et, al.

Mn₃O₄/ZnO composite catalyst, in which the incorporation of Mn₃O₄ enhances both microwave absorption and Lewis acidity. (Fig. 2b)³⁰. Complete PET conversion was achieved at 175 °C in just 5 min, with a bis-hydroxyethyl terephthalate monomers selectivity of 88%. The superior performance of the Mn₃O₄/ZnO composite catalyst over pure ZnO can be attributed to two primary factors. First, Mn₃O₄ provides additional Lewis acid sites, which effectively activate the ester bonds of PET and facilitate their cleavage. Second, the irregular morphology and heterogeneous interfaces of the composite lead to enhanced dielectric loss, thereby generating localized “hot spots” under microwave irradiation and enabling rapid volumetric heating. Additionally, Stigger et al. used titanate nanotubes as a catalyst³¹. A BHET yield of about 80% was obtained at 196 °C within 60 min, reducing the reaction time by two thirds relative to conventional heating (Fig. 2c). Recently, Jose et al. prepared a particulate, metal-free, basic carbon-based catalyst by carbonizing soybean flour (as nitrogen source) together with a urea-glucose system and ZnO hard template at 1223 K³². The resulting material has a specific surface area of 707 m²/g and a microporous-mesoporous hierarchical structure. In catalytic tests at 468 K for 1 hour for catalyst/PET and ethylene glycol/PET with mass ratios of 0.1 and 8.6 respectively, the BHET yield from pure PET alcoholysis reached 76.3 mol%. In addition, this catalyst can be recycled multiple times and also shows excellent depolymerization performance on real PET waste.

2.2.1.2 PLA conversion

In recent years, microwave chemical recycling of PLA has attracted attention due to significantly reduced reaction times. Nim et al. employed microwave alcoholysis using tetrabutyl orthotitanate as a catalyst³³. They investigated the effects of diols with different chain

lengths on PLA depolymerization. Under the conditions of 240 °C and 10 min, short-chain diols gave a monomer yield of around 90%. The products could be used as polyol precursors for the synthesis of lactate-based polyurethanes. On this basis, Breen et al. designed a metal-free catalytic system³⁴. They covalently grafted a cyanoguanidine ligand onto mesoporous SiO₂ for microwave methanolysis of PLA. At 130 °C and 4 h, a high yield of methyl lactate was obtained, and the catalyst was easily recyclable. Density functional theory calculations revealed that the guanidine group activates the ester bond via hydrogen bonding. Moreover, methanol molecules further participate in proton transfer, thereby lowering the energy barrier. Different from the alcoholysis route, Siddiqui et al. used microwave alkaline hydrolysis PLA with hexadecyltrimethylammonium bromide as a phase transfer catalyst³⁵. Under mild conditions of 100 °C and 10 min, the PLA degradation rate exceeded 90%. The main products were lactic acid and its sodium salt.

2.2.2 Microwave catalytic conversion of polyolefin

Microwave catalysis lowers the reaction energy barrier for polyolefin (low density PE (LDPE), high density PE (HDPE), and PP) upcycling by selectively heating catalysts to generate localized hot spots. Cao et al. employed Ti₃AlC₂ as both a microwave receptor and catalyst, achieving one-step conversion into high-purity hydrogen (> 75 vol%) and highly graphitic carbon nanofibers (Fig. 3a)³⁶. In this system, Ti₃AlC₂ decomposes into TiC and TiAl, synergistically promoting C–H bond cleavage and carbon nanostructure growth. Qiao et al. introduced trace Pt into a Fe/Ni bimetallic catalyst, raising hydrogen yield to 53.9 mmol/g and selectivity to 90% (Fig. 3b)²¹. Density functional theory (DFT) calculations revealed that Pt lowers the oxygen vacancy formation

energy and increases strong acid site density by 3.3-fold, thereby accelerating terminal C–H bond scission and deep dehydrogenation of alkanes. Similarly, Luong et al. found that in LDPE/PS mixtures, HZSM-5 zeolite lowers the activation energy from 38.3 to 20.3 kJ/mol. Moreover, hydrogen radicals released from LDPE suppress coke formation derived from PS and provide alkyl side chains that enhance BTX production.³⁷ In addition, we developed a hybrid Zn/b-ZnO catalyst for ambient-pressure plastic upgrading without H₂ (Fig. 3c).³⁸ In this system, the bifunctional ZnO serves as both a microwave absorber and a catalytic substrate, while in-situ formed Zn clusters facilitate C–C bond cleavage. This approach upcycles nearly 100% of mixed landfill plastics into lubricant base oil precursors and monomers. Zeng et al. employed HZSM-5 as a catalyst in the microwave catalytic of waste edible oil and LDPE.²² At a mass ratio of 1:3, the process produced light aromatic hydrocarbons dominated by benzene, toluene, ethylbenzene, and xylene (BTEX). The relative content of monocyclic aromatic hydrocarbons exceeding 80% and that of BTEX approaching 70%. Majd et al. prepared a high-sulfur (7.9 wt%) metal-free acidic carbon-based catalyst using sodium lignosulfonate, a byproduct of papermaking, as a raw material.³⁹ Under normal pressure and nitrogen atmosphere, this catalyst can efficiently pyrolyze waste PE plastics to produce straight-chain alkanes and olefins without the need for external hydrogen. The results showed that increasing the temperature or extending the reaction time can increase the liquid oil yield (up to 65%).

Catalytic hydrocracking and hydrogenolysis of polyolefin waste are important technological pathways for achieving high-value recycling of plastics. Vlachos et al. constructed a tandem catalytic system combining Pt/WO₃/ZrO₂ and HY molecular sieves.⁴⁰ This bifunctional catalyst can directionally convert various waste raw materials such as PP, PE, and mixed polyolefins into liquid hydrocarbon fuels under mild hydrogenation conditions. Meanwhile, Julie E. Rorrer et al. conducted a series of studies on the catalytic conversion of plastics using ruthenium-based catalysts. They first used a Ru/C catalyst to achieve low-temperature hydrogenolysis of polyolefins.⁴¹ This catalyst showed good cycle stability, but the reaction process was prone to carbon chain end-position breakage, generating low-value gaseous byproducts such as methane. Subsequently, they further introduced acidic molecular sieves such as octahedral zeolite and β -zeolite as supports to prepare ruthenium-based bifunctional catalysts.⁴² During the catalytic process, the synergistic effect of the metal active sites and acidic sites optimized the reaction pathway, effectively suppressing methane formation and improving the selectivity and yield of liquid alkanes.

Compared to reactions without hydrogen participation, the above-mentioned hydrocracking and hydrolysis methods require external hydrogen and have higher equipment requirements, but the product yield and oil quality are better.

2.2.3 Microwave catalytic conversion of other plastics

In the field of microwave catalytic conversion, besides polyesters and polyolefins, PS waste has also received extensive attention. Terapalli et al. introduced KOH catalyst into the microwave pyrolysis of PS and optimized the experiments using machine learning.⁴³ The results showed that when the mass ratio of PS to KOH was 27.5:7.5, the oil yield reached 95 wt%. The addition of KOH shifted the product composition significantly, from styrene-dominated aromatics (about 96%) to long-chain olefins and cycloalkanes. Zhang et al. designed a Zn/b-ZnO catalyst system, in which they utilized microwave induction to *in-situ* form Zn species (Figs. 4a and 4b).⁴⁴ At 270 °C, nearly 100% conversion of PS was achieved, with a styrene monomer yield of 0.8 g. Density functional theory calculations showed that Zn sites reduced the C–H bond cleavage energy from 2.19 to 1.36 eV. The obtained monomer could be repolymerized, achieving about 80 wt% closed-loop recycling of PS. Moreover, the energy consumption was only 63% of that in conventional thermal catalysis. In addition, we developed an *in-situ* constructed FeNi/Ni/C catalyst for rapid microwave conversion of mixed plastic waste into H₂ and CNTs (Fig. 4c).⁴⁵ This process achieves near-perfect atom economy, with H₂ yield exceeding 922 mmol·g⁻¹_{catalyst} and CNT yield over 10600 mg·g⁻¹_{catalyst}. Mechanistic studies show that in the FeNi/Ni/C catalyst, Ni helps break the C–H bonds in plastic molecules, producing hydrogen intermediates that eventually turn into H₂. Fe, on the other hand, promotes the formation and growth of CNTs from the decomposed plastic. In addition, chloride ions (Cl⁻) from PVC and fluoride ions (F⁻) from PTFE help regenerate the active sites.

In addition, Li et al. employed microwave catalytic technology with a Ni–Al–Fe multimetal catalyst to investigate H₂ production from mixed waste plastics, including PE, PP, PET, and PVC.⁴⁶ The study revealed that hydrocarbon plastics enable efficient and stable hydrogen generation. However, hydrogen chloride (HCl) released during PVC pyrolysis corrodes the catalyst, leading to the migration and sintering of active components, as well as deactivation of active sites. To address this issue, they modified the catalyst using in-situ generated CNTs during the reaction, producing a Ni–Al–Fe–CNTs composite. The CNTs can adsorb chlorine species, protect the catalyst structure and construct oxygen vacancies and

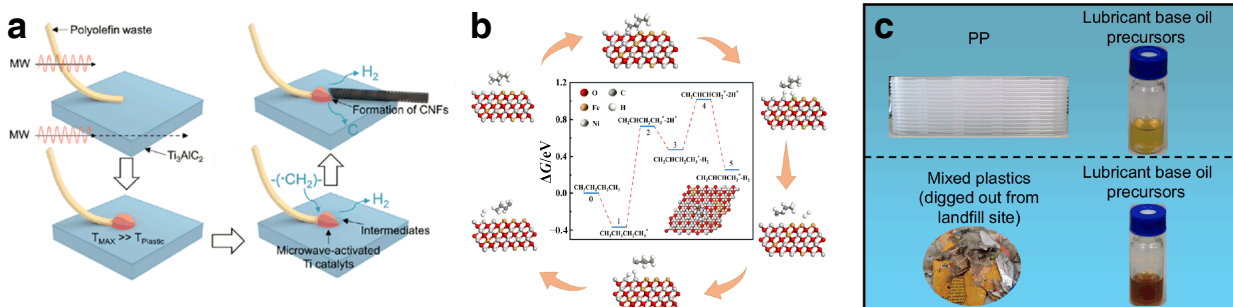


Fig. 3. The conversion of polyolefin. **a**, Schematic diagram for the upcycling mechanism of polyolefin plastic wastes over Ti₃AlC₂ MAX catalyst. Reproduced with permission from Ref³⁶, © Elsevier B.V. 2022. **b**, Relative energy pathway for the stepwise dehydrogenation of LDPE on FeNO under microwave irradiation, calculated via DFT. Atom colors: gray for C, white for H, yellow for Fe, silver for Ni, and red for O. Reproduced with permission from Ref²¹, © Elsevier B.V. 2025. **c**, The process for microwave-assisted catalytic depolymerization of LDPE. Reproduced with permission from Ref³⁸, © Zhao, J. et, al. 2025.

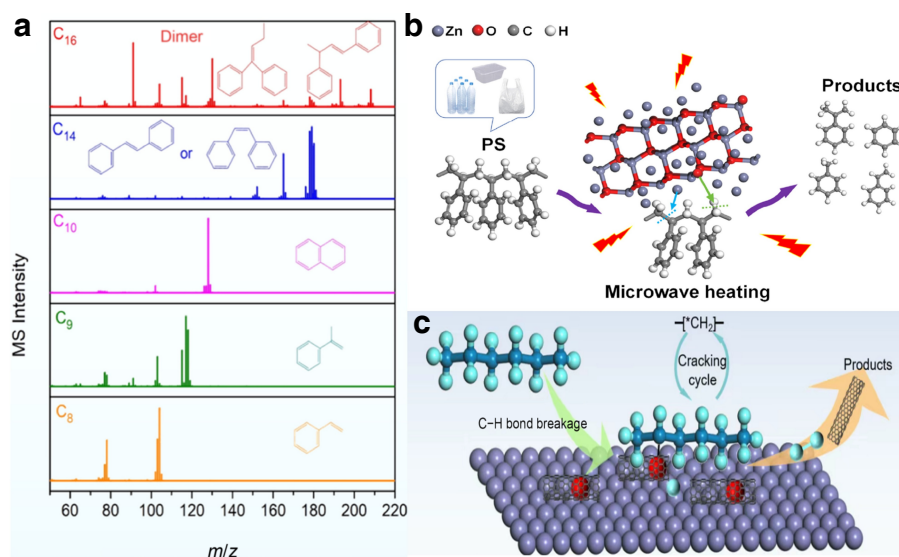


Fig. 4. The conversion of other plastics. **a**, Mass spectrometric determination of solid products from successive cycles of microwave catalytic depolymerization of PS over Zn/b-ZnO. **b**, The schematic presentation of the catalytic mechanism for PS depolymerization over Zn/b-ZnO. Reproduced with permission from Ref^[44], © Elsevier Ltd. 2026. **c**, Mechanism diagram of FeNi/Ni/C catalyst for converting plastic waste into high-value-added products. Reproduced with permission from Ref^[45], © Zhao, J. et, al. 2026.

heterojunctions, thereby enhancing catalytic performance. Experimental results show that the modified catalyst increases the hydrogen yield from PVC-containing plastic systems by 35%.

3 Challenges and future prospects

3.1 Major challenges

3.1.1 The interaction mechanism between microwaves and materials remains unclear

Fig. 5 summarizes the main challenges currently faced by microwave-catalyzed plastic upcycling. Most waste plastics (e.g., PP and PE) have low dielectric loss and absorb microwaves poorly, so microwave absorbers (such as silicon carbide and activated carbon) must be added during pyrolysis. Thus, high-efficiency microwave absorbers are essential for microwave catalytic conversion of plastics. Representative candidates include carbon-based materials, SiC, and metal oxides, which improve microwave energy utilization. Carbon materials such as activated carbon and carbon nanotubes possess high dielectric loss and large specific surface areas for efficient microwave-to-heat conversion. Silicon carbide exhibits outstanding thermal conductivity, high-temperature resistance, and stable microwave absorption under harsh conditions. On the other hand, metal oxides including ZnO, Mn₃O₄ and iron-based oxides can generate localized hot spots via microwave absorption and provide catalytic sites to accelerate plastic degradation. However, the introduction of absorbers brings problems such as uneven mixing, high-temperature sintering or coking, and product contamination. In addition, the interaction mechanism between microwaves and various functional materials has not been fully elucidated, which limits the rational design and performance optimization of microwave absorbers and catalysts.

3.1.2 Catalyst performance and stability are insufficient

Although advanced catalysts (e.g., liquid metals and bifunctional catalysts) can improve product selectivity and quality, they suffer

from high cost, poor stability, and sensitivity to impurities. Meanwhile, under microwave irradiation, localized high temperatures accelerate carbon deposition on the catalyst surface. For example, the acid sites of ZSM-5 zeolites are deactivated by coke formation. Meanwhile, the unclear mechanism of non-thermal effects also makes targeted catalyst optimization difficult.

3.1.3 Scaling-up faces engineering challenges

Enlarging the reactor volume often leads to uneven electromagnetic field distribution, resulting in localized overheating or insufficient heating. Currently, industrial-scale continuous microwave reactors capable of long-term stable operation are still extremely rare. Furthermore, accurate temperature measurement has always been a technical challenge.

3.2 Future prospects

3.2.1 Further explore reaction mechanisms and establish multiscale simulation models

Multi-scale simulations and advanced characterization techniques should be used to reveal the complex interactions among the microwave field, catalysts, and plastic intermediates. Meanwhile, statistical tools such as response surface methodology can be employed to systematically investigate the interactive effects of parameters such as microwave power, temperature, absorbers, catalysts, and feedstocks.

3.2.2 Develop efficient and stable catalysts and absorbers

To design novel catalysts that combine good microwave absorption, high selectivity, and long life, we need to overcome some challenge. First, deactivation can be effectively slowed down by increasing the number of active sites and improving resistance to coking and sintering. Meanwhile, corresponding catalyst regeneration technologies should be developed. In addition, due to the poor microwave absorption ability of plastics, it is necessary to develop more efficient microwave absorbers before conducting microwave catalysis research.

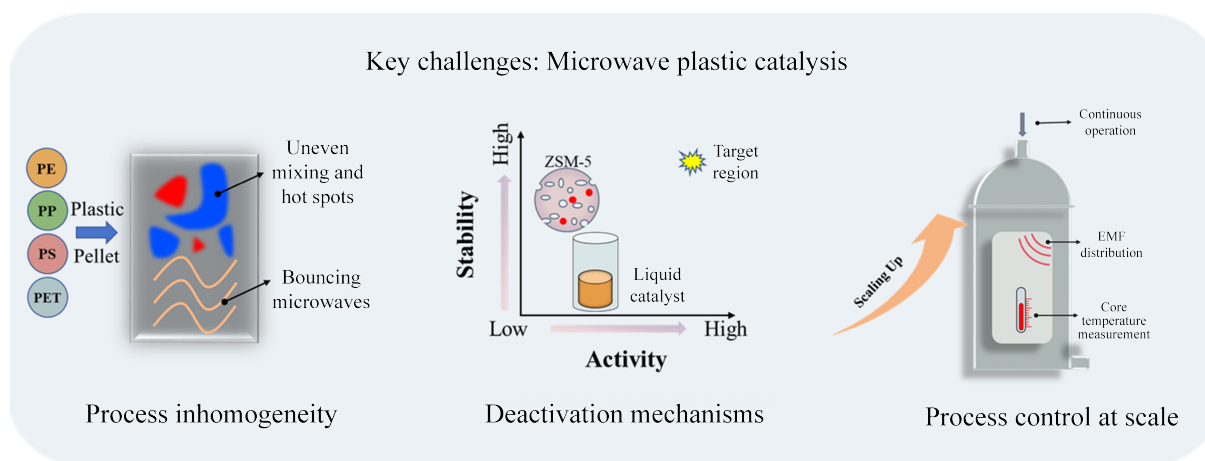


Fig. 5. Key challenges in scaling microwave-catalytic plastic valorization: Process inhomogeneity, catalyst deactivation, and process control.

3.2.3 Innovate reactor design and advance engineering scale-up

First, researchers should enhance the safety design of the reactor to effectively prevent risks such as leakage, overheating, and overpressure, with special attention to monitoring systems and emergency protocols to ensure reliable operation under industrial conditions. Second, it is necessary to systematically evaluate material performance under large-scale conditions, including high-temperature resistance, corrosion resistance, and stability of microwave absorption capacity. Third, scaling-up is more forward-looking, and continuous-flow microwave reactors and modular designs should be considered as these approaches can improve process controllability, facilitate integration into industrial systems, and provide flexibility for different feedstocks and operating conditions.

3.2.4 Strengthen life cycle and techno-economic assessments

To achieve industrial feasibility of the technology, a life cycle assessment and cost analysis should be conducted from feedstock acquisition to end-of-life disposal. This helps verify the reliability and accuracy of key parameters and provides a basis for industrial planning. In such an assessment, full consideration should be given to the degradation characteristics of different polymers, the difficulty of degrading mixed plastic waste, and the cost of catalysts.

3.2.5 Artificial intelligence (AI)-assisted catalyst screening

Combining machine learning, high-throughput experimentation and large language models, AI enables rapid screening and rational design of catalysts. Future work should focus on developing AI-driven bifunctional catalysts discovery, exploring in-depth reaction mechanisms and designing dedicated microwave reactors.

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Data availability

Not applicable.

Acknowledgements

All authors thank the financial support from the S&T Program of Energy Shaanxi Laboratory (No. ESLB202407), the National Natural Science Foundation of China (No. U23B20162) and the Beijing Natural Science Foundation (No. F251045).

Author contributions

J. B. Q. and J. L. Y.: Writing of original draft. J. W. T.: Review and editing of the content.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article. Author Junwang Tang is the associate editor of this journal, but he is not involved in the peer review or decision of this article.

Use of AI statement

None.



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