

RESEARCH ARTICLE OPEN ACCESS

Continuous-Flow Conversion of Waste Polystyrene Into Styrene Monomers Utilizing the Microwave-Concentration Effect on Spherical Activated Carbon

 Naoya Sakurada¹  | Takanori Kitazono¹ | Madoka Ikawa² | Naoki Doi²  | Takashi Ikawa¹  | Hironao Sajiki^{1,3} 
¹Laboratory of Advanced Chemistry, Gifu Pharmaceutical University, Gifu, Japan | ²Laboratory of Pharmaceutical Physical Chemistry, Gifu Pharmaceutical University, Gifu, Japan | ³Faculty of Engineering, Department of Applied Chemistry, Aichi Institute of Technology, Toyota, Japan

Correspondence: Takashi Ikawa (ikawa-ta@gifu-pu.ac.jp) | Hironao Sajiki (sajiki@aitech.ac.jp)

Received: 27 April 2026 | **Revised:** 16 August 2026 | **Accepted:** 26 August 2026

Keywords: activated carbon beads | chemical recycling | continuous-flow reaction | microwave heating | monomer recovery | polystyrene depolymerization

ABSTRACT

Chemical recycling of polystyrene (PS) by high-temperature pyrolysis can recover styrene monomer, but conventional processes require substantial energy input and generate complex, nonrecyclable byproducts. Here, we report an additive-free continuous-flow depolymerization of PS using localized microwave (MW) heating. A toluene solution of PS was passed through a quartz cartridge packed with spherical activated carbon beads (CBs), which concentrate MW energy and create a confined high-temperature reaction zone. Using a temperature-controlled single-mode MW reactor, the effects of backpressure and feed delivery were examined with reagent-grade PS and postconsumer PS products, including takeout trays and containers. Backpressure was found to be essential for stable styrene production. Without backpressure, channel occlusion occurred and the styrene yield reached only 19% after 4 h, whereas 0.5 MPa backpressure enabled 70%–76% styrene yield after 24 h. Postconsumer PS feeds also afforded 67%–76% styrene yield, comparable to reagent-grade PS. The coproducts were mainly limited to dimers and trimers, supporting distillative styrene recovery. This cartridge-based MW-flow system provides a simple route for direct styrene recovery from diverse PS waste streams under low-power, localized heating conditions.

1 | Introduction

Polystyrene (PS) is widely used in packaging and constitutes a notable fraction of plastic waste streams; however, closed-loop mechanical recycling is often challenging because aging and reprocessing can deteriorate the appearance and mechanical performance, while contamination and legacy additives further compromise recycle quality [1–11]. The chemical recycling of styrene by high-temperature electric furnace pyrolysis has been demonstrated to be a viable method for monomer recovery. However, steep temperature gradients can promote undesirable processes, such as overcracking and char formation. Consequently, the reported monomer recovery typically plateaus at approximately 60 wt%, necessitating downstream distillation for further processing

[12–17]. Photothermal depolymerization using carbon black under concentrated sunlight has emerged as a promising alternative to conventional pyrolysis. Although this process demonstrates operational attractiveness, the reported conversions vary significantly (approximately 30%–80%) and remain sensitive to the feed composition [18]. More broadly, recent advances in plastic waste recycling and upcycling encompass diverse thermal and heterogeneous catalytic strategies, including photothermal, Joule heating, and microwave-assisted processes, highlighting the growing interest in alternative modes of energy delivery for efficient polymer conversion [19].

Microwave (MW) heating offers the advantages of compactness and rapid, on-demand energy delivery. In MW-assisted

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2026 The Author(s). *ChemSusChem* published by Wiley-VCH GmbH.

chemistry, powdered activated carbon (AC) is a prevalent susceptor; nevertheless, close particle–particle contacts can induce microarc discharges (“sparking”) under fixed-frequency irradiation, eroding the AC surface and abruptly terminating absorption, thereby complicating reproducibility and scaling up [20–23]. To address this issue, powdered AC was molded into spherical beads (CBs) with a diameter of approximately 0.3 mm as a fixed bed, and platinum-supported CBs (Pt/CBs) were used as the catalyst. This method combines the MW-susceptor role of the CBs with Pt catalytic sites. In this configuration, the desired outcomes of continuous hydrogen abstraction, cyclization, and hydrogenation were achieved under MW irradiation [24–27]. Subsequent experimentation based on the aforementioned platform presented a low-power, continuous-flow route to depolymerize PS solutions and recover the styrene monomer in a selective and locally MW-heated CB cartridge. As illustrated schematically in Figure 1, a metal-free CB fixed bed concentrates the MW energy within the beads, creating a confined hot zone (>300 °C) at <35 W. The systematic variation in backpressure delineates a practical operating window that reproducibly increases styrene monomer formation without high MW power and enables uninterrupted operation. The method was found to accommodate reagent-grade to postconsumer PS after simple preparation, which included the removal of non-PS parts (labels/adhesives), identification as PS, and dissolution into toluene with filtration of insoluble parts as needed and did not require

deashing, additive extraction, chemical cleaning, or thermal pre-treatment. Notably, the nonstyrene monomer fraction displays a narrow coproduct slate, predominantly composed of styrene dimers and trimers. This characteristic facilitates the distillative purification of styrene monomers, thereby retaining carbon in oligomers that are conducive to subsequent conversion processes. Collectively, these results define a cartridge-based approach that pairs MW heating with a continuous flow for monomer recovery from diverse PS streams and motivate further studies on solvent recycling, energy-intensity metrics, and valorization of the oligomer fraction.

2 | Results and Discussion

2.1 | Effect of Backpressure

To perform a preliminary assessment of backpressure in continuous-flow PS depolymerization, a CB-packed quartz cartridge (i.d.: 4.6 mm, length: 10 mm, and CBs: 80 mg) was used under MW-irradiated conditions. A solution of PS (**1a**, $M_w \approx 2.6 \times 10^5$; 0.05 M in toluene based on styrene monomer) was introduced at 0.5 mL min^{-1} , while the CB surface temperature was maintained at 350 °C by closed-loop MW power control ($\leq 35 \text{ W}$; IR thermography feedback). The yield of styrene monomer (**2**) is reported as a percentage of the GC yield and quantified by GC-FID using tetralin as the internal standard. The PS feed concentration (0.05 M) was established on a styrene-unit basis.

At an initial pressure of 0 MPa, the toluene underwent partial vaporization on the CB bed, resulting in the precipitation of **1a** and the subsequent clogging of the narrow flow channel (Figure 2). During the uninterrupted-flow interval, the profile attained 19% of **2** after 4 h.

To more precisely determine the pressure required for stable and efficient operation, additional experiments were conducted at 0.1 and 0.3 MPa. Although continuous operation was maintained under these conditions, the styrene yields remained relatively low and reached only 35% and 38%, respectively, after 12 h. In contrast, increasing the backpressure to 0.5 MPa produced a pronounced increase in styrene formation, affording 74% of **2** after 12 h.

Further increases in backpressure to 1.0 and 1.5 MPa afforded comparable yields of 71% and 70%, respectively, at 12 h. Thus, a clear increase in styrene formation was observed between 0.3 and 0.5 MPa, whereas no further improvement was obtained above 0.5 MPa. These results indicate that 0.5 MPa represents a practical threshold for the present flow system rather than an intrinsic optimum pressure for PS depolymerization.

We therefore attribute the effect of backpressure primarily to stabilization of the solvent/feed state within and immediately upstream of the locally heated CB bed. At insufficient backpressure, local vaporization of toluene can decrease liquid holdup and effective contact of the dissolved PS feed with the heated CB bed and, in the limiting case of 0 MPa, induce PS precipitation and channel clogging. Once a backpressure of 0.5 MPa is applied, these effects are sufficiently suppressed to maintain efficient and

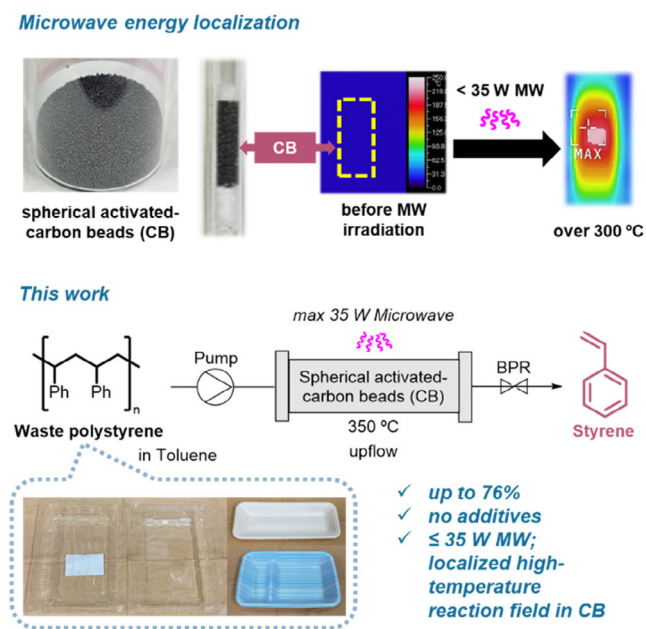


FIGURE 1 | Localized concentration effect of microwave energy on spherical activated carbon beads (CBs) and an overview of this study. Top: The CBs (average particle diameter: $0.50 \pm 0.05 \text{ mm}$) enclosed within the quartz cartridge selectively absorb MW and, as demonstrated in the thermographic images, generate a localized high-temperature reaction field (300 °C or higher) even under MW irradiation of 35 W or less within the flow channel. A conceptual diagram of the CB cartridge utilized in this study. PS solutions from reagent-grade and postconsumer sources are processed in a continuous flow without additives to recover styrene. The recovery process has been demonstrated to achieve up to 76% efficiency, with a relatively small amount and a narrow slate of byproducts dominated by styrene dimers/trimers.

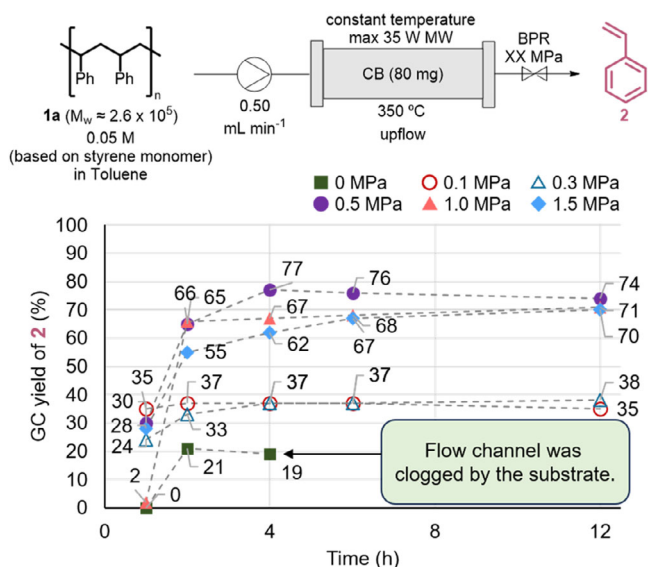


FIGURE 2 | Effect of backpressure on the formation of styrene (**2**) from polystyrene **1a** under continuous-flow conditions. In the absence of backpressure, partial solvent vaporization at the CB-bed inlet induced PS precipitation and eventual channel clogging. At 0.1 and 0.3 MPa, continuous operation was maintained, but the styrene yields remained 35% and 38%, respectively, at 12 h. Increasing the backpressure to 0.5 MPa markedly increased the styrene yield to 74% at 12 h, whereas further increases to 1.0 and 1.5 MPa afforded comparable yields of 71% and 70%, respectively. These results identify 0.5 MPa as the minimum practical backpressure for high-yielding and stable operation under the present conditions.

uninterrupted feed delivery. The absence of a systematic pressure dependence above 0.5 MPa provides no indication that further pressurization significantly alters the intrinsic depolymerization pathway under the present conditions. Accordingly, 0.5 MPa was employed as the minimum practical backpressure for subsequent experiments (Figure 3).

2.2 | Scope of Substrate for the Continuous-Flow Depolymerization of Polystyrene

In order to assess the versatility of the feedstock, in addition to **1a**, we examined reagent-grade PS ($M_w \approx 1.2 \times 10^5$; **1b**), a takeout food tray labeled “PS” ($M_w \approx 3.2 \times 10^5$; **1c**), and an expanded PS container ($M_w \approx 4.6 \times 10^5$; **1d**) after simple preparation (label removal, cutting, and dissolution). To better define the nature of these postconsumer feedstocks, samples **1a–1d** were characterized by ATR-FTIR spectroscopy, thermal analysis, elemental analysis, and GPC (see Section S4). The ATR-FTIR spectra of **1c** and **1d** exhibited the characteristic absorption bands of PS, while thermogravimetric analysis showed broadly similar major high-temperature weight-loss behavior for all four feedstocks. Elemental analysis further revealed differences among the feedstocks; in particular, **1c** showed lower carbon and hydrogen contents (C, 89.61 wt% and H, 7.37 wt%) than reagent-grade PS, whereas **1d** (C, 92.07 wt% and H, 7.75 wt%) was close to the theoretical composition of PS. Together with the thermal analysis and GPC results, these data confirm that **1c** and **1d** are PS-based post-consumer materials while also revealing feedstock-dependent

compositional and molecular-weight differences. Quantification was performed via GC-FID with tetralin as the internal standard. Unless otherwise noted, the values described below correspond to the product composition and GC yield determined for the reaction mixture sampled at the 24 h time point and do not represent the cumulative isolated yield of products collected over the entire 24 h operation. Two different metrics are presented in Figure 3. Figure 3A shows the GC-FID yield of styrene **2**, whereas Figure 3B shows the relative product distribution of the condensed organics normalized such that the sum of products **2–5** equals 100%.

At the 24 h time point, the GC-FID yields of **2** were 73%, 75%, 67%, and 76% for **1a–1d**, respectively (Figure 3A). The normalized product compositions are shown in Figure 3B. In all cases, styrene **2** was the major component of the condensed products, while α -methylstyrene **3**, styrene dimer **4**, and styrene trimer **5** accounted for the remaining identified products. Thus, the post-consumer PS samples **1c** and **1d** afforded styrene yields comparable to those obtained from reagent-grade PS samples **1a** and **1b** while maintaining a similarly narrow coproduct distribution. These data suggest that, within the current operating range, a product equivalent to reagent-grade styrene monomer can be obtained from spent PS. Furthermore, byproducts consisting primarily of relatively small amounts (35% or less) of the styrene dimer simplify the styrene monomer purification process (distillation of the toluene/**2** stream) while providing low-molecular-weight substances suitable for further chemical transformation as organic synthesis intermediates.

2.3 | Reusability and Stability of CBs

The spherical AC used throughout this study was A-BAC MP (Kureha Corp.), a petroleum-pitch-derived, binder-free spherical AC employed as the MW-absorbing material. According to the manufacturer, A-BAC MP has an average particle diameter of 0.50 ± 0.05 mm, and representative properties of the BAC product family include a BET surface area of $1100\text{--}1300$ m² g^{−1} and an ash content of $\leq 0.05\%$. The reusability of the CBs was evaluated over three consecutive 24 h runs under the standard conditions (Table 1). The styrene yields at 24 h were maintained at 75%, 75%, and 72% in the first, second, and third runs, respectively, indicating no substantial loss of performance upon reuse. SEM analysis of the CBs after 24 h of operation showed that the spherical morphology was largely retained, although localized surface deposits were observed. Elemental analysis revealed an increase in the hydrogen content from 0.26 wt% for the fresh CBs to 1.18 wt% for the spent CBs. Consistently, thermogravimetric analysis of the spent CBs showed a greater weight loss than that of the fresh CBs, together with a distinct thermal event at approximately 252 °C. These observations are consistent with the deposition of hydrogen-containing organic species derived from the reaction on the CB surface. The resonance frequency of the CB-packed bed showed only a negligible change from 2437.2 MHz before use to 2437.0 MHz after 24 h of operation. Overall, although localized surface deposition occurred during operation, no pronounced deactivation or macroscopic structural deterioration of the CBs was observed under the present conditions (see Section S5, Figures S10–S13, and Tables S5 and S6).

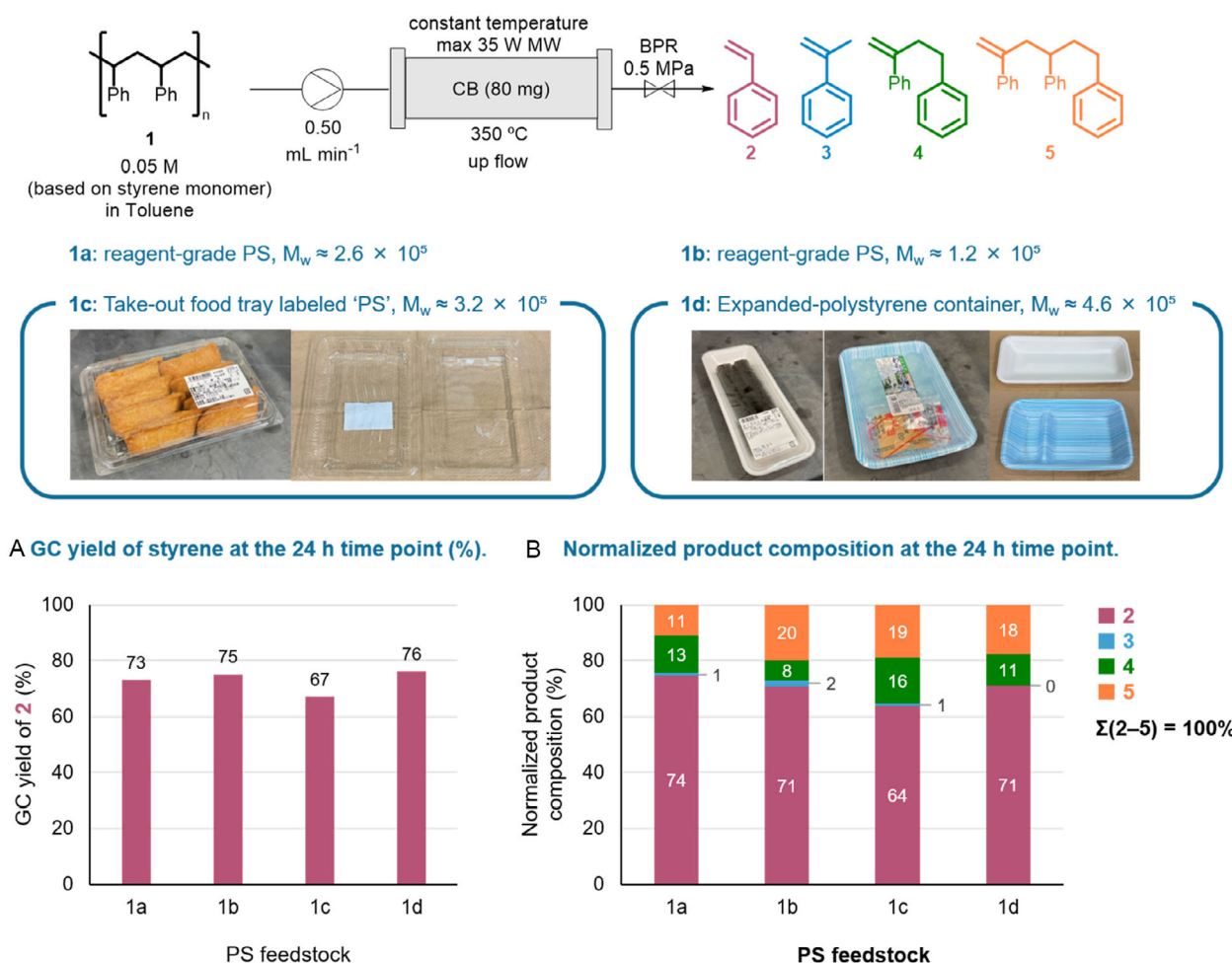


FIGURE 3 | The substrate composition ratios determined at the 24 h time point for the reaction of **1a–1d**. Data were obtained from the condensed organic fraction collected at the 24 h time point and do not represent cumulative yields over the entire 24 h operation. (A) GC-FID yield of styrene **2** determined using tetralin as an internal standard. (B) Product composition of the condensed organic fraction, calculated by normalizing the GC-FID-determined amounts of products **2–5** such that $\Sigma(2-5) = 100\%$.

TABLE 1 | Reusability of CBs in the continuous-flow depolymerization of polystyrene **1b**.

Run	GC-FID yield, % ^a (2 : 3 : 4 : 5)
1st	75:3:8:21
2nd	75:2:3:11
3rd	72:2:3:11

^aGC-FID yields at 24 h was determined by GC-FID using tetralin as an internal standard.

2.4 | Role of CBs and MW Heating

Control experiments were performed to clarify whether the CBs participate directly in PS depolymerization or primarily serve as a MW-absorbing heating medium. Variation of the A-BAC particle

size grade (SP, MP, and LP) and HCl pretreatment of A-BAC MP produced no substantial change in the styrene yield under MW conditions. Moreover, under conventional electric-furnace heating at 350 °C, similarly low styrene yields were obtained irrespective of the presence or type of bed material. Increasing the furnace temperature to 500 °C markedly increased the styrene yield to 63%, approaching the 67% yield obtained with the MW–CB system at 350 °C. These observations indicate that PS depolymerization is predominantly thermally driven and that a major catalytic contribution from the carbon surface is unlikely. Rather, the spherical CBs primarily serve as a MW-absorbing heating medium that provides an effective localized heating environment under MW irradiation (see Section S6 and Tables S7–S9).

2.5 | Proposed Reaction Mechanism

To examine whether nonvolatile components in the effluent remain convertible to **2**, the postreaction liquid from a 24 h standard run (with **1b** at 0.5 MPa, CB surface 350 °C, 0.5 mL min^{−1}, and 0.05 M in toluene) was concentrated under reduced pressure

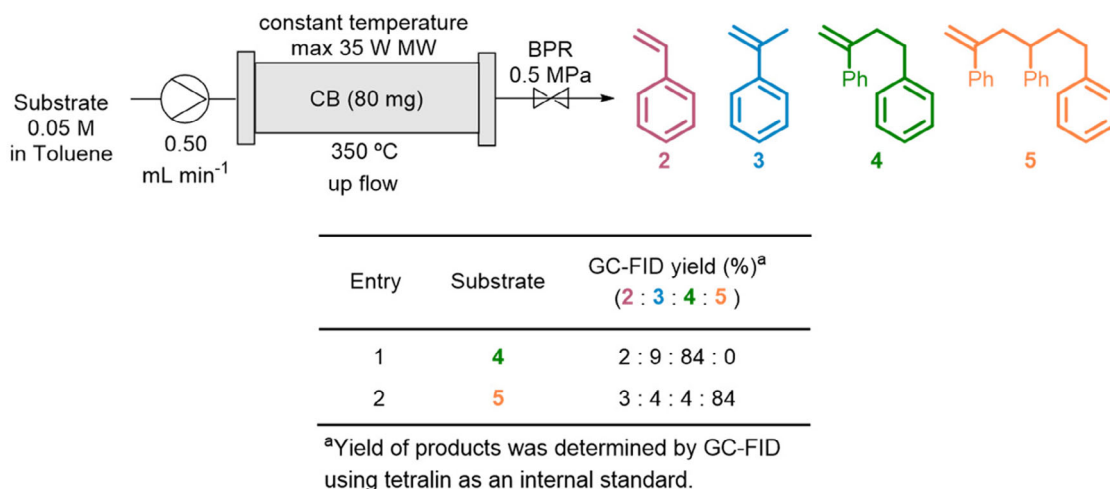
to remove toluene and **2**. To evaluate whether the major identified products could undergo further conversion under the reaction conditions, the reactivity of isolated **2** (styrene monomer), **4** (styrene dimer), and **5** (styrene trimer) was examined using the same MW-CB cartridge under otherwise identical conditions.

Figure 4A shows a synopsis of the results derived from the control experiments. When **2** was supplied, 96% of **2** was detected in the eluate after a 24 h continuous reaction. However, only trace amounts of low-boiling-point byproducts were present. When **4** or **5** was supplied, more than 80% of the respective substrate was

recovered, and small amounts of **2** and **3** were detected (GC-FID, tetralin as an internal standard). These observations indicate that **2**, **4**, and **5** are relatively stable under the present reaction conditions and are therefore consistent with their accumulation as major products rather than rapid secondary conversion.

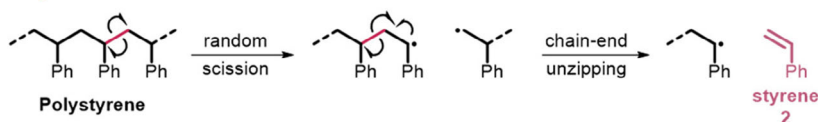
Additional radical-scavenger experiments were performed to probe the possible involvement of radical intermediates. Under the standard 6 h conditions, the styrene yield decreased from 67% in the absence of an additive to 45% in the presence of 1,1-diphenylethylene (DPE, 0.5 equiv) and to 33% in the presence

A Reactivity of isolated products (24 h, standard conditions).

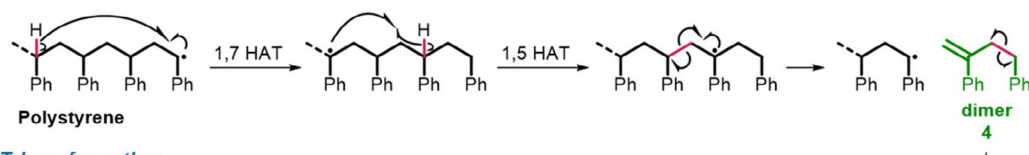


B Proposed pathways under MW heating.

Styrene formation



Dimer formation



Trimer formation

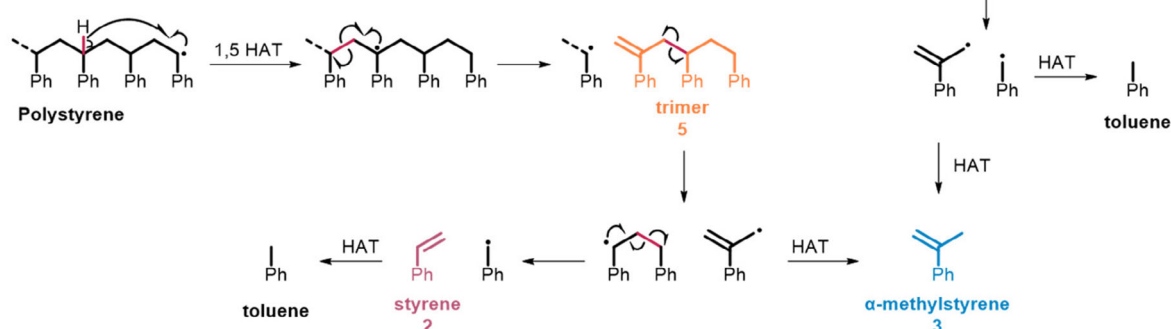


FIGURE 4 | Reactivity of each isolated product and the proposed mechanism. (A) In accordance with standard conditions, the incorporation of **2** led to a 96% recovery of **2** after a 24 h uninterrupted reaction. When **4** or **5** was introduced, recoveries of 80% or more were achieved in each case, and cracking was minimal (**2** and **3**; GC-FID, tetralin internal standard). (B) The proposed pathways under MW heating include random scission, followed by chain-end unzipping to **2**. Intramolecular H-atom transfer (1,7- or 1,5-HAT) during depropagation accounts for **4** and **5**, respectively. Notably, within the confines of the present window, **4** and **5** function as kinetic endpoints.

of galvinoxyl free radical (0.5 equiv). The product distribution was also perturbed; for example, the trimer yield increased from 6% to 11% in the presence of DPE. Although unambiguous radical-trapping adducts were not detected by mass spectrometry, the pronounced suppression of styrene formation by two different radical scavengers is consistent with the involvement of radical intermediates in the depolymerization network (see Section S7 and Table S10).

In light of these controls and considering the prior precedent for PS depolymerization, Figure 4B delineates a plausible working hypothesis: random backbone scission followed by chain-end unzipping to **2** [28, 29], with intramolecular H-atom transfer (1,7-/1,5-HAT) during depolymerization accounting for the formation of **4** and **5** [30, 31]. The restricted coproduct distribution, the persistence of **4** and **5** under matched reaction conditions, and the perturbation of the product distribution by radical scavengers are consistent with a radical-mediated depolymerization pathway involving chain scission, unzipping, and H-atom transfer. However, because the trapping adducts could not be directly identified under the present high-temperature conditions, Figure 4B should be regarded as a mechanistic model consistent with the available experimental evidence rather than a definitive elementary-step mechanism. Direct characterization of transient intermediates by time-resolved and/or in situ methods will be required for further mechanistic verification.

3 | Conclusion

A cartridge-based, microwave-driven flow platform was established in which a CB-packed bed enabled the continuous depolymerization of PS solutions into styrene monomers. A notable feature of this MW cartridge is its absorption of MW energy locally, creating a high-temperature zone (300 °C or higher) exclusively in the CB region at power levels of 35 W or less; this enables efficient depolymerization reactions within a compact flow channel. A systematic variation of the backpressure was employed, which revealed a moderate operating window that reproducibly formed styrene. However, further increases yielded little additional benefit under otherwise fixed setpoints. This approach has the capacity to accommodate both reagent-grade and postconsumer feeds with simple preparation, which involves the removal of non-PS components, such as paper labels on products, and identity confirmation. Across various feeds, the nonmonomer fraction was characterized by a narrow distribution, with a predominance of dimers (**4**) and trimers (**5**). This configuration facilitated the distillative purification of **2** and preserved carbon as a small-molecule byproduct conducive to subsequent conversion processes. The stability and uninterrupted operation of the system are attributed to localized MW absorption within the CB bed at low power rather than to bulk resistive heating. The protocol utilizes standard hardware, straightforward separation (distillation of the toluene/styrene stream), and a fixed-bed geometry that can be scaled up by numbering up. These collective features delineate the innovation and pragmatic efficacy of integrating CB-mediated localized MW heating effects with a continuous flow for monomer retrieval from a variety of PS streams. This integration provides a foundation for subsequent studies, including solvent recycling, energy-intensity benchmarking,

and valorization of the small-molecule fraction. In addition, the integration of these processes with downstream repolymerization is facilitated.

4 | Experimental

4.1 | Instrumentation and Materials

The substrates and solvents were purchased from commercial sources and used without further purification unless otherwise noted. ^1H NMR and ^{13}C NMR spectra were recorded using JEOL JNM ECA-500 (500 MHz for ^1H NMR and 125 MHz for ^{13}C NMR) and ECZ-400 (400 MHz for ^1H NMR and 100 MHz for ^{13}C NMR) spectrometers. CDCl_3 was used as the solvent for the NMR measurements. The chemical shifts (δ) are expressed in parts per million and internally referenced (0.00 ppm for tetramethylsilane and 77.0 ppm for CDCl_3 in ^{13}C NMR). The continuous-flow MW reactor (EYELA, MR-2G-100) was developed by Tokyo Rikakikai Co., Ltd., Tokyo, Japan; see the product URL: <https://eyela.actibookone.com/content/detail?param=eyJjb250ZW50TnVtIjoyMTY4MX0=&detailFlg=1&pNo=44>. Straight glass and quartz tubes used as the CB cartridges were obtained from Saida FDS Inc. and Tokyo Rikakikai Co., Ltd. An LC-20AD (Shimadzu Co., Kyoto, Japan) was used to flow the reaction solution. A backpressure regulator (BPR-1000A, EYELA, Tokyo Rikakikai Co., Ltd.) was used to maintain the system pressure during the flow reactions. Conventional heating control experiments were performed using an economy tubular electric furnace (ROM-500P, AS ONE Corp., Japan). The GC-FID analyses were performed on a SHIMADZU GC-2010 system (Kyoto, Japan) equipped with a flame ionization detector (FID) and an InertCap 5 capillary column (0.18 mm i.d., 20 m in length, 0.28 μm df; GL Science, Tokyo, Japan). The spherical AC used as the standard MW-absorbing material was A-BAC MP (Kureha Corp., Japan), supplied by N.E. CHEMCAT Co. (Tokyo, Japan).

PS (atactic, flakes; $M_w \approx 1.2 \times 10^5$ according to the supplier; Polysciences, Inc., Warrington, PA, USA; Cat. No. 23637; CAS registry number 9003-53-6) was utilized in its original state without undergoing additional purification. The supplier has reported that the polymer has a refractive index of 1.59 and a softening point of approximately 125 °C. In addition, the polymer is soluble in toluene, MEK, dioxane, and xylene. PS (atactic, white beads; average $M_w \approx 2.6 \times 10^5 \text{ g mol}^{-1}$ by GPC; Sigma-Aldrich, Cat. No. 182427; CAS registry number 9003-53-6) was used in its original state without undergoing additional purification processes. According to the supplier, the polymer is amorphous, with a glass-transition temperature of approximately 100 °C, a density of 1.05 g cm^{-3} , and a refractive index of 1.59. The polymer is soluble in toluene, chloroform, and tetrahydrofuran but insoluble in alcohol and water.

The spherical activated carbon beads (CBs) used throughout this study were A-BAC MP (Kureha Corp., Japan; average particle diameter: $0.50 \pm 0.05 \text{ mm}$, manufacturer-reported representative value), hereafter referred to as CBs. A-BAC MP, a petroleum-pitch-derived spherical AC manufactured by Kureha Corp., was used as the standard MW susceptor. According to the manufacturer, A-BAC MP has an average particle diameter of

0.50 ± 0.05 mm; representative properties of the BAC product family include a BET surface area of 1100–1300 m² g^{−1} and an ash content of ≤0.05%.

4.2 | General Procedure

4.2.1 | Condition A (Figure 2)

The entire flow path was fitted with the CB (80.0 mg)-packed EYELA reaction tube and filled with toluene. The solvent was pumped through the reaction tube at a constant flow rate and temperature under a maximum MW irradiation of 35 W for 5 min. A constant back pressure was applied using a backpressure regulator. PS ($M_w \approx 2.6 \times 10^5$) 1, dissolved in toluene (0.05 M) and then pumped into the reaction tube for 12 h. The MW irradiation was stopped, and ethyl acetate/toluene (1/1, 40 mL) or dichloromethane (40 mL) was pumped to further wash the entire flow path. The whole reaction mixture and washing solution were collected and analyzed by GC-FID using tetralin (55.1 μL, 0.4 mmol) as an internal standard.

4.2.2 | Condition B (Figure 3)

The flow system was assembled with an EYELA reaction tube packed with CBs (CB, 80.0 mg), and the entire flow path was primed with toluene. Toluene was first pumped through the reactor at the prescribed flow rate and reaction temperature while the CB bed was irradiated with MWs (maximum output, 35 W) for 5 min. A toluene solution of PS feedstock **1a–1d** (0.05 M based on the styrene repeating unit) was then introduced into the reactor under constant back pressure and continuously processed for 24 h under MW irradiation. At the 24 h time point, the condensed organic fraction was sampled and analyzed by GC-FID using tetralin (55.1 μL, 0.40 mmol) as an internal standard to determine the GC yield of **2**. The product composition of the condensed organics was normalized to $\Sigma = 100\%$ for **2–5**. These data represent the product distribution and GC yield at the 24 h time point and do not correspond to the cumulative yield of materials collected over the entire 24 h flow operation. After completion of the run, the flow path was additionally washed with EtOAc/toluene (1:1, 40 mL) and CH₂Cl₂ (40 mL).

4.2.3 | Condition C (Table 1)

The flow system was assembled with an EYELA reaction tube packed with CBs (CBs, 80.0 mg), and the entire flow path was primed with toluene. Toluene was first pumped through the reactor at 0.50 mL min^{−1} and 350 °C, while the CB bed was irradiated with MWs (maximum output, 35 W) for 5 min. A toluene solution of PS **1b** (0.05 M based on the styrene repeating unit) was then introduced into the reactor at 0.50 mL min^{−1} under a constant backpressure of 0.5 MPa and continuously processed for 24 h under MW irradiation. At the 24 h time point, the condensed organic fraction was collected and analyzed by GC-FID using tetralin as an internal standard to determine the GC yields of **2–5**. The reported yields correspond to the fraction collected at the 24 h time point and do not represent cumulative yields over the entire 24 h operation. After completion of each run, the flow path and CB bed were washed with EtOAc/toluene (1:1, 40 mL) and CH₂Cl₂ (40 mL), and the same CB bed was subsequently

reused under otherwise identical conditions. This procedure was repeated for three consecutive 24 h runs.

Acknowledgments

This study was partially funded by grants for a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO, Project Code: P19004), the 2025 Aichi Institute of Technology Special Grant for Education and Research, a Sasakawa Scientific Research Grant from the Japan Science Society (Number 2420-3005) to N.S., and the Japan Science and Technology Agency (JST), Support for Pioneering Research Initiated by the Next Generation (SPRING) Program (Number JPMJSP2142) to N.S. Additionally, we extend our appreciation to N.E. CHEMCAT Co. for providing CBs and to Editage (www.editage.jp) for the English language editing services.

Funding

This study was supported by New Energy and Industrial Technology Development Organization (Grant P19004), Japan Science and Technology Agency (Grant JPMJSP2142), N.E. CHEMCAT Co.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supporting information of this article.

References

1. A. Marek, L. Kaprálková, P. Schmidt, et al., “Spatial Resolution of Degradation in Stabilized Polystyrene and Polypropylene Plaques Exposed to Accelerated Photodegradation or Heat Aging,” *Polymer Degradation and Stability* 91 (2006): 444.
2. K. Ragaert, L. Delva, and K. Van Geem, “Mechanical and Chemical Recycling of Solid Plastic Waste,” *Waste Management* 69 (2017): 24.
3. C. Signoret, M. Edo, D. Lafon, et al., “Degradation of Styrenic Plastics During Recycling: Impact of Reprocessing Photodegraded Material on Aspect and Mechanical Properties,” *Journal of Polymers and the Environment* 28 (2020): 2055.
4. Z. O. G. Schyns and M. P. Shaver, “Mechanical Recycling of Packaging Plastics: A Review,” *Macromolecular Rapid Communications* 42 (2021): 2000415.
5. N. Meides, T. Menzel, B. Poetzschner, et al., “Reconstructing the Environmental Degradation of Polystyrene by Accelerated Weathering,” *Environmental Science & Technology* 55 (2021): 7930.
6. M. Bachmann, C. Zibunas, J. Hartmann, et al., “Towards Circular Plastics Within Planetary Boundaries,” *Nature Sustainability* 6 (2023): 599.
7. N. Singh and T. R. Walker, “Plastic Recycling: A Panacea or Environmental Pollution Problem,” *Npj Materials Sustainability* 2 (2024): 17.
8. Z. Xu, D. Sun, J. Xu, R. Yang, J. D. Russell, and G. Liu, “Progress and Challenges in Polystyrene Recycling and Upcycling,” *ChemSusChem* 17 (2024): e202400474.
9. L. Monclús, H. P. H. Arp, K. J. Groh, et al., “Mapping the Chemical Complexity of Plastics,” *Nature* 643 (2025): 349.
10. H. Moon, J. S. DesVeaux, E. C. Van Roijen, et al., “Upcycling Waste Polystyrene to Adipic Acid Through a Hybrid Chemical and Biological Process,” *Nature Communications* 16 (2025): 9543.

11. J.-P. Laviolette, A. Eslami, and J. Doucet, "Membrane-Based Nanopurification for Plastic Recycling," *Communications Chemistry* 8 (2025): 319.
12. Y. Liu, J. Qian, and J. Wang, "Pyrolysis of Polystyrene Waste in a Fluidized-Bed Reactor to Obtain Styrene Monomer and Gasoline Fraction," *Fuel Processing Technology* 63 (2000): 45.
13. J. J. Park, K. Park, J.-S. Kim, et al., "Characterization of Styrene Recovery From the Pyrolysis of Waste Expandable Polystyrene," *Energy & Fuels* 17 (2003): 1576.
14. Y. Mo, L. Zhao, Z. Wang, C.-L. Chen, G.-Y. A. Tan, and J.-Y. Wang, "Enhanced Styrene Recovery From Waste Polystyrene Pyrolysis Using Response Surface Methodology Coupled With Box-Behnken Design," *Waste Management* 34 (2014): 763.
15. R. Dahal, P. Uusi-Kyyny, J.-P. Pokki, T. Ohra-aho, and V. Alopaeus, "Conceptual Design of a Distillation Process for the Separation of Styrene Monomer From Polystyrene Pyrolysis Oil: Experiment and Simulation," *Chemical Engineering Research and Design* 195 (2023): 65.
16. M. Holtkamp, M. Renner, K. Matthiesen, M. Wald, G. A. Luinstra, and P. Biessey, "Robust Downstream Technologies in Polystyrene Waste Pyrolysis: Design and Prospective Life-Cycle Assessment of Pyrolysis Oil Reintegration Pathways," *Resources, Conservation, and Recycling* 205 (2024): 107558.
17. M. R. Reed, E. R. Belden, N. K. Kazantzis, M. T. Timko, and B. Castro-Dominguez, "Thermodynamic and Economic Analysis of a Deployable and Scalable Process to Recover Monomer-Grade Styrene From Waste Polystyrene," *Chemical Engineering Journal* 492 (2024): 152079.
18. S. Oh, H. Jiang, L. H. Kugelmass, and E. E. Stache, "Recycling of Post-Consumer Waste Polystyrene Using Commercial Plastic Additives," *ACS Central Science* 11 (2025): 57.
19. C.-J. Yang, X.-Y. Wang, M.-Q. Zhu, et al., "A Panoramic View on Plastic Waste Recycling and Upcycling: Heterogeneous Catalytic Strategies for Diverse Plastics and Multiple Pathways," *Advanced Materials* 38 (2026): e21912.
20. S. Horikoshi, A. Osawa, M. Abe, and N. Serpone, "On the Generation of Hot-Spots by Microwave Electric and Magnetic Fields and Their Impact on a Microwave-Assisted Heterogeneous Reaction in the Presence of Metallic Pd Nanoparticles on an Activated Carbon Support," *Journal of Physical Chemistry C* 115 (2011): 23030.
21. S. Horikoshi, A. Osawa, S. Sakamoto, and N. Serpone, "Control of Microwave-Generated Hot Spots. Part V. Mechanisms of Hot-Spot Generation and Aggregation of Catalyst in a Microwave-Assisted Reaction in Toluene Catalyzed by Pd-Loaded AC Particulates," *Applied Catalysis A: General* 460–461 (2013): 52.
22. S. Horikoshi and N. Serpone, "Role of Microwaves in Heterogeneous Catalytic Systems," *Catalysis Science & Technology* 4 (2014): 1197.
23. S. Horikoshi, Y. Arai, I. Ahmad, et al., "Application of Variable Frequency Microwaves in Microwave-Assisted Chemistry: Relevance and Suppression of Arc Discharges on Conductive Catalysts," *Catalysts* 10 (2020): 777.
24. T. Ichikawa, T. Matsuo, T. Tachikawa, et al., "Microwave-Mediated Site-Selective Heating of Spherical-Carbon-Bead-Supported Platinum for the Continuous, Efficient Catalytic Dehydrogenative Aromatization of Saturated Cyclic Hydrocarbons," *ACS Sustainable Chemistry & Engineering* 7 (2019): 3052.
25. T. Ichikawa, T. Matsuo, T. Tachikawa, et al., "Microwave-Mediated Continuous Hydrogen Abstraction Reaction From 2-PrOH Catalyzed by Platinum on Carbon Bead," *Catalysts* 9 (2019): 655.
26. T. Yamada, W. Teranishi, N. Sakurada, et al., "Microwave-Assisted C–C Bond Formation of Diarylacetylenes and Aromatic Hydrocarbons on Carbon Beads Under Continuous-Flow Conditions," *Communications Chemistry* 6 (2023): 78.
27. N. Sakurada, T. Kitazono, T. Ikawa, T. Yamada, and H. Sajiki, "Pt/CB-Catalyzed Chemoselective Hydrogenation Using In Situ-Generated Hydrogen by Microwave-Mediated Dehydrogenation of Methylcyclohexane Under Continuous-Flow Conditions," *Catalysts* 14 (2024): 384.
28. G. Madras, J. M. Smith, and B. J. McCoy, "Thermal Degradation Kinetics of Polystyrene in Solution," *Polymer Degradation and Stability* 58 (1997): 131.
29. S. E. Levine and L. J. Broadbelt, "Reaction Pathways to Dimer in Polystyrene Pyrolysis: A Mechanistic Modeling Study," *Polymer Degradation and Stability* 93 (2008): 941.
30. Z. Deng and E. R. Gillies, "Emerging Trends in the Chemistry of End-to-End Depolymerization," *JACS Au* 3 (2023): 2436.
31. V. Lohmann, G. R. Jones, N. P. Truong, and A. Anastasaki, "The Thermodynamics and Kinetics of Depolymerization: What Makes Vinyl Monomer Regeneration Feasible?," *Chemical Science* 15 (2024): 832.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.