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Luo et al. report an alternating-magnetic-field-initiated catalytic process to rapidly decompose disposable syringe plastic into hydrogen-rich gases and high-value graphite. Beyond disposable syringes, this strategy could help to address this emerging issue for other types of medical waste disposal—for example, masks and protective clothing.
Alternating magnetic field initiated catalytic deconstruction of medical waste to produce hydrogen-rich gases and graphite

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SUMMARY

During the coronavirus 2019 (COVID-19) pandemic, there has been a dramatic increase in the use of medical products and personal protective equipment, such as masks, gowns, and disposable syringes, to treat patients or administer vaccines. However, this may lead to generation of large quantities of biohazardous medical waste. Here, an alternating-magnetic-field-initiated catalytic strategy is proposed to convert disposable syringes into hydrogen-rich gases and high-value graphite. Specifically, in addition to selecting heavy fraction of bio-oil as initiator, disposable syringe needles are used as radio frequency electromagnetic wave receptors to initiate the deconstruction of disposable syringe plastic. The highest H2 yield of 39.9 mmol g⁻¹ is achieved, and 30.1 mmol g⁻¹ is maintained after 10 cycles. Moreover, a high carbon yield of 286 mg g⁻¹ can be obtained. Beyond disposable syringes, this strategy could help to solve the emerging issue for other types of medical waste (e.g., mask and protective clothing) disposal.

INTRODUCTION

The unpredictable outbreak of the coronavirus 2019 (COVID-19) pandemic has driven increased medical supplies to minimize exposure and transmission of novel coronaviruses.1,2 As patient numbers surge and vaccination campaigns begin, the demand for single-use medical (SUM) products (mask, disposable syringe, etc.) has increased to a million tons.3,4 These generated medical waste will pose a massive threat to humans and the ecosystem if they are not processed in time.5,6 Indeed, SUM products are mainly composed of polyolefin plastics (e.g., polyethylene [PE], polypropylene [PP], and polystyrene [PS]) and metals (e.g., 304 stainless steel).5,6 To address the issue of burgeoning medical-waste quantities, various thermochemical-conversion technologies have been successfully implemented in recent years to treat these waste in a harmless manner.10–14 Thereinto, incineration15–17 is a simple and fast practice, but there are still three main problems to be solved: (1) emission of large quantities of CO2, (2) the release of a huge amount of toxic gases due to an unreasonable air-fuel ratio, and (3) only heat is used efficiently (Figure 1A). Gasification18–20 is another important method of medical-waste treatment to generate synthetic gas streams for further energy or synthesis purposes. The high-molecular weight (commonly 5,000–5,000,000 g mol⁻¹) polyolefin plastic in medical waste contains 8%–14% hydrogen and can be used as hydrogen-rich energy feedstock for H2 production.10–12,18 Jung et al.21 and others22–24 have reported a novel two-step heterogeneous catalytic approach for thermal decomposition of medical waste to obtain hydrogen-rich gases. In this two-stage process (Figure 1B), the...
plastic polymer in medical waste is first decomposed into vapor/gas mixture (small hydrocarbons) via high-temperature pyrolysis, and then the vapor/gas mixture is further catalytically cracked (>750°C for C_{14}C) for syngas production (e.g., H_{2}, CH_{4}, and C_{2}H_{4}). This represents a tremendous advance, but low conversion efficiency accompanied by the rapid catalyst deactivation seems unavoidable. Moreover, this two-stage process consumes massive energy by virtue of the whole reactor needing to be heated at the same temperature. Therefore, it remains a challenge to efficiently convert medical waste into hydrogen-rich gases with the additional purpose of minimizing the energy consumption of the reaction system.

To tackle the above problems, we fully considered the advantage of carbon deposition to effectively absorb high radio-frequency (RF) electromagnetic waves. Our intention is not to avoid or reduce carbon deposition but to make full use of them. In addition, only localized heating between reactant and catalyst is desired to reduce unnecessary energetic cost. Magnetic hyperthermia is a method of localizing intense heating near magnetic nanoparticles (MNPs) under high-frequency alternating magnetic field (AMF) excitation. So far, this eddy thermal effect has been primarily used in the treatment of cancer, in which the generated eddy heat destroys cancer cells for therapeutic purposes. Previous experiments have proved that the temperature reached on the surface of excited MNPs is several orders of magnitude larger than that of a simple thermal-diffusion equation. Beyond magnetic...
hyperthermia, this AMF-driven strategy has been successfully applied to the field of water splitting; encouragingly, the water splitting close equilibrium voltage at room temperature is achieved, which is out of reach in current classic methods.

Here, an AMF-initiated catalytic strategy is applied in the deconstruction of medical waste. Specifically, in addition to choosing heavy fraction of bio-oil (HB) as initiator, we use catalytically active disposable syringe needles to continuously convert disposable syringe plastic into hydrogen-rich gases and high-value graphite under AMF excitation. The disposable syringe needle can be used as magnetic-response catalyst by simply shaping it into a chain. This approach enables complete treatment of the disposable syringe, which is significantly different from the conventional thermal catalytic process. From start of the AMF-initiated catalytic process, H2 selectivity in the evolved gases can reach nearly 63 vol % with a high H2 yield of 39.9 mmol g⁻¹ obtained, leaving a residue of carbon material, most of which is identified as layered graphite. In addition, the H2 yield can still remain at 30.1 mmol g⁻¹ even after 10 cycles.

RESULTS AND DISCUSSION

PP deconstruction under AMF excitation

The one-step AMF-initiation catalytic process significantly simplifies approaches to deconstruction of medical waste (Figures 1C and S1), which rapidly converts disposable syringe plastic (PP) into hydrogen-rich gases and high-value graphite using a disposable syringe needle as a magnetic-response catalyst (Figures 1D; Video S1).

The chain-shaped magnetic response catalyst was prepared by joining 10 bent needles together (unless otherwise noted) (Figure 2A). The selectivity was defined through the volume percentage of gas components obtained in gas chromatography (GC) analysis. The mass of gas product was acquired according to the volume of gas produced and the composition analysis from GC. The yields of gas, oil, and solid (carbon) were therefore defined as their respective mass fractions in the total weight of HB or PP. The H2 efficiency was considered to be the ratio of total mass of hydrogen in all gas products to the theoretical amount of hydrogen in initial HB/PP. (see Equations 1, 2, 3, 4, and 5 in the experimental procedures).

The ferromagnetism of a needle at varied angles and temperatures was performed by magnetometer (vibrating-sample magnetometer [VSM]) measurements (Figure S3). The needle had highest saturation magnetization (80.4 emu g⁻¹) at an angle of 0° to the magnetic-field direction. Moreover, the saturation magnetization decreased gradually from 75.3 to 0.3 emu g⁻¹ with an increasing temperature. Such high ferrimagnetism and temperature dependence of needle were conducive to achieve efficient thermal conversion under AMF excitation.

To maximize the magnetic thermal properties of needle, we measured thermal maps of different needle shapes with a magnetic field strength of 10.4 mT (Figures 2B and S4). The shape of needle in the form of a chain proved to be the most effective, with a maximum temperature of about 600°C compared with other shapes, all of which gave less than 600°C. As shown in Figure 2C, the maximum temperature of the chain-shaped needle revealed a magnetic field-strength-dependent magneto-thermal effect under AMF excitation. The maximum temperature measured was ~600°C at 10.4 mT, ~400°C at 7.7 mT, 220°C at 5.8 mT, and ~150°C at 1.2 mT. Notably, the maximum temperature of the chain-shaped needle increased quickly to over 500°C within just 9 s, which was beneficial for rapidly disposing of subsequent medical waste.
Unlike conventional thermal catalytic processes where the catalyst and feedstock must be heated simultaneously, the AMF-initiation catalytic approach enables heat to be generated only inside a magnetic-response catalyst (here, a chain-shaped needle), while the temperature of surrounding it (here, HB/PP) remains essentially constant (room temperature). In a sense, this method is, in principle, fundamentally different from traditional thermal catalytic processes where the entire plastic must be heated externally, and then the catalyst is finally heated and activated via diffusion heat transfer and thermal convection. In addition, we have found that this AMF-initiation catalytic method can decompose disposable syringes rapidly and achieves excellent yields of H₂ production without any other specific catalyst added.

A maximum temperature difference of over 550°C was observed in a tentative comparison of HB-1 and PP separately under AMF excitation (Figure 2D). The maximum temperature of the mixed sample (HB-1PP) was determined to be ~650°C by an in situ infrared pyrometer during AMF excitation. Therefore, heat is one move away from HB-1 into the bulk of the PP host. Figure 2E illustrates the data for continuous cycles of deconstruction of PP. The temperature of the reaction system was typically between 533°C and 1,221°C and gradually increased throughout cyclic tests due to

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**Figure 2. Schematic diagram**
(A) Schematic illustration of AMF-initiation catalytic process.
(B) The thermal maps of different needle shapes at 10.4 mT.
(C) Time-temperature graph of chain-shaped needle reacted under different AMF strengths.
(D) Time-temperature graph of HB, PP, chain-shaped needle, and a mixed sample at 10.4 mT.
(E) Time-temperature graph for continuous addition of PP at 10.4 mT.
generation of highly RF-electromagnetic-wave-absorbing carbon, which would be confirmed in our subsequent simulated in situ characterization.

As presented in Figure 3A, the typical strong bands of PP at 2,916 and 2,849 cm\(^{-1}\), corresponding to CH\(_2\) asymmetric stretching of PP, decreased dramatically until disappearance from PP to HB-1PP. In the absence of initiator HB, the Fourier-transform infrared (FTIR) spectrum of 10PP remained almost unchanged after the reaction. Notably, no visible CH\(_2\) asymmetric stretching of PP was shown in FTIR spectrum after 10 cycles (HB-10PP).

X-ray diffraction (XRD) patterns on magnetic-response catalyst both before and after AMF-excitation treatment showed that the initial needle mainly contained Fe\(_3\)O\(_4\) and Cr\(_7\)C\(_3\) (Figure 3B). The absence of XRD peaks for Ni, Co, and Mn might be due to the existence of these substances in amorphous form. Significantly, Fe\(_3\)C was detected for both HB-1 and HB-nPP (n = 1, 5, 8, or 10), while no significant changes were revealed between 10PP and PP. The typical diffraction peaks of PP at angles (2\(\theta\)) of 14.44, 17.13, 18.84, and 22.13 were found to disappear under the first AMF excitation, which corresponded to the degradation of PP to produce elemental carbon and thus Fe\(_3\)C. The relative intensity of Fe\(_3\)O\(_4\) peaks decreased sharply after reaction, and two broad peaks were detected at 26.69\(^\circ\) and 54.82\(^\circ\), indicating the formation of graphite.

Raman spectra was provided to investigate the evolution of graphitization degree. In Figure 3C, HB-1 had largest I\(_D\)/I\(_G\) (D and G bands, respectively) ratio, implying a
higher defect concentration. Apparently, this temperature (about 590°C) was not able to completely transform HB to form a graphite structure. Afterwards, the I₀/I₂ value of HB-nPP (n = 1, 2, 5, 8, or 10) decreased gradually from 0.965 to 0.174 with the continuous addition of PP. Interestingly, a two-dimensional (2D) bond was clearly visible in the second cycle (HB-2PP), which was attributed to the increasing temperature (about 845°C) of the reaction system. In addition, the I₂ of HB-10PP displayed a visible redshift compared with those of HB-1 due to the generation of graphite.

X-ray photoelectron spectroscopy (XPS) was used to reveal the evolution of the electronic structure (Figure 3D). The high-resolution C1s spectra can be fitted by components corresponding to sp² carbon atoms (284.7 eV, marked as C₁), sp³ carbon atoms (285.1 eV, marked as C₂), alpha carbon (285.7 eV, marked as C₃), C–O (287.1 eV, marked as C₄), and shake up (290.9 eV, marked as C₅). The initial PP was mainly composed of C₁, C₂, C₃, and C₄. The intensity of C₃ in HB-nPP (n = 1, 5, 8 or 10) noticeably increased and was accompanied by a transformation of C₂ to C₁ with the constant addition of PP. Interestingly, the distribution of each carbon type in the solid remained steady after the fifth cycles (Table S3).

**Parametric studies of AMF-initiated catalytic process**

Now, it is interesting to estimate what the cycle performance of magnetic-responsive catalyst could be under AMF excitation if operated in a reaction system optimized both in terms of shape (chain shaped) and magnetic field strength (10.4 mT). Figure 4A shows time-on-stream experimental data for dehydrogenation of PP using a chain-shaped needle. The evolved gas volume increased dramatically to ~400 mL in 50 s from the onset of the AMF-initiated catalytic process, and the final volume of evolved gas reached up to 460 mL. Combined with the results of in situ infrared pyrometer (Figure 2E), the eddy current originated from the electro-magnetic induction brought PP to temperatures higher than 1,000°C in less than 32 s, effectively transforming PP to solid (carbon), oil, and gas.

The H₂ yield of PP was typically between 2.8 and 39.9 mmol g⁻¹ (Figure 4B) and increased gradually (first 5 cycles) at first and then maintained steady (6–10 cycles) throughout the cyclic tests. Remarkably, the H₂ yield of PP could still remain at 30.1 mmol g⁻¹ after 10 cycles at 10.4 mT, which is far superior to or at least comparable with that previously reported for other conventional thermal catalytic processes and microwave-initiated technology. Furthermore, over 76.4%–98.5% (except cycle 1, 17.9%) of the theoretical mass of hydrogen contained in PP was quickly extracted under AMF excitation, leaving solid (carbon) and oil. The gas yield first rapidly increased (first 5 cycles) and then progressively decreased (6–10 cycles), while the oil yield had the opposite trend. This was due to the fact that the degree of graphitization of solid (carbon) was low before the 5th cycle test, which was unable to effectively absorb and convert the energy of AMF into heat. After that, the degree of graphitization of solid (carbon) increased with the continuous addition of PP, resulting in a further rise in the temperature of the reaction system to above 1,000°C (Figures 2E and 3).

In Figure 4C, we display a ten-cycle test on cumulative gas/carbon production. The carbon yield just fluctuated between 26.1 and 28.4 wt % in each test cycle (except for the first 5 cycles), and the gradual increase in carbon yield from cycle 1 to 5 was attributed to the low temperature of the reaction system. After ten consecutive test cycles, around 1,024 mg of carbon (including carbon formed by HB and PP) was eventually deposited on the chain-shaped needle, thus the total carbon yield
in this process was ~286 mg C g⁻¹. In addition, the cumulative gas production was about 3,024 mL, and the highest H₂ yield was achieved in the fifth cycle (291 mL). Meanwhile, GC with both flame ionization and thermal conductivity (GC-FID/TCD) detected the signal peak of CO, which was due to the unavoidable extraneous oxygen contained in HB (Table S1). Remarkably, the gas retained a high yield of about 340 mL after 10 cycles, highlighting the excellent cyclic stability.

The H₂ selectivity in evolved gases first increased gradually from 37 to 63 vol % (cycles 1–5) and then remained steady at ~55–65 vol % (cycles 5–10) (Figures 4D; Table S4). Because of the high molecular weight of polymer molecules that constitute medical plastic (typically 5,000–5,000,000 g mol⁻¹), the low conversion efficiency by virtue of carbon deposited on catalyst surface in conventional thermal catalytic processes seems to be inevitable throughout the cyclic tests. This work takes full advantage of the property of carbon deposition as an excellent RF-electromagnetic-wave absorber to maintain favorable H₂ production performance even after 10 cycles. In addition, this process of treating medical waste is greatly simplified by the AMF-initiated catalytic strategy. It not only treats the whole disposable syringe but also selectively obtains H₂ and high-value graphite in a one-step reaction. (A comparison of the performance of H₂ production with other literature is listed in Table S5.)

**The characterization of carbon products**

Graphite is an important solid product of the AMF-initiated catalytic process. These solid materials have received widespread attention for their high economic value and multiple applications, including in aerospace, graphite electrode, and machinery industries. This work thus presents an AMF-initiated catalytic process for
completely converting medical waste into hydrogen-rich gases and high-value graphite without additional catalyst.40,41

Thermogravimetric analysis (TGA) revealed the mechanism of graphite formation on the chain-shaped needle (Figures 5A and 5B), whereby HB-1 gave two peaks at 408°C and 440°C, associated with amorphous carbon.42 Only one peak at 580°C (corresponding to graphite) was observed in HB-1PP, which was attributed to the highly RF-electromagnetic-wave-absorbing carbon deposited on the surface of the chain-shaped needle to increase the temperature of the reaction system. These peaks moved to higher temperatures throughout the continuous cycle test, and the peaks detected at lower temperatures were usually merged with peaks at higher temperatures. Notably, the spent sample after five cycles consisted of nearly 53.6 wt % of graphite, and then the residue after ten cycles was comprised of 67.8 wt % of graphite.

The field-emission scanning electron microscopy (SEM) images of HB-10PP confirmed the growth of a large amount of flaky carbon (Figures 5C and S5A–SSD). Only a strong carbon signal was observed by energy-dispersive X-ray spectroscopy (EDS) (Figures S5E and S5F), indicating a lack of defects in HB-10PP. High-resolution field-emission transmission electron microscopy (HRTEM) indicated that HB-10PP consisted of 7 layers of graphite sheets, and its lattice structure was perfect with few defects (Figures 5D and S6), in good concordance with the Raman
results discussed above. Its corresponding selected-area electron diffraction (SAED) spots also exhibited a typical hexagonal array of spots, demonstrating high quality.

**Proposed preliminary reaction mechanism**

Although magneto-thermal has a wide range of applications in several key technical fields (e.g., metallurgy, magnetic hyperthermia, and water electrolysis), its development in the field of heterogeneous catalysis is relatively recent, and the fundamental properties regarding the interaction of RF electromagnetic waves with chemicals and materials remain controversial.32,40,43

What we have in this existing system is the initiation or activation of an RF electromagnetic wave multiphase catalyst (needle). The starting objects are apparently inhomogeneous multiphase systems that undergo catalysis under AMF excitation. Despite the controversy over the relative importance of thermal and non-thermal effects under AMF excitation, we present here a preliminary mechanistic model of RF-electromagnetic-wave-initiated solid-solid reactions using a chain-shaped needle for hydrogen-rich gases and graphite production from medical waste (Figure 6).

The fundamental advantage of using AMF excitation is due to the fact that the chain-shaped needle plays two parts in this process at the same time. First, an effective energy absorption transfers from the incoming RF electromagnetic wave to initiate the physical heating process (driving force) of the chain-shaped needle (catalyst). Second, the subsequent catalytic reaction between the chain-shaped needle and HB/PP interface occurs when the chain-shaped needle reaches the necessary temperature.

When RF electromagnetic waves interact with the chain-shaped needle, eddy-current loss and magnetic hysteresis loss are rapidly generated on the chain-shaped needle’s surface.44,45 The heating mechanism associated with eddy currents can be understood in terms of the power loss dissipation caused by the change in magnetization, which increases proportionally to square root of frequency according to Equation 6. On the other hand, the magnetic field generated by eddy currents always opposes the variation in magnetization so that the latter is decayed inside the chain-shaped needle, and if the frequency is high enough (here, 256 kHz), the eddy-current losses become important. The skin effect also causes an increase in the effective resistance of the chain-shaped needle to the passage of currents, which improves heating efficiency greatly. In addition, the repeated magnetization and demagnetization of AMF causes significant friction and heating inside the chain-shaped needle. This heating effect is named hysteresis loss, and it is directly associated with the area of M–H hysteresis loops (Figure 3A). Notably, as magneto-thermal itself is a function of the electro kinetic properties of catalyst (i.e., the charge dynamics correlated with the susceptibility of catalyst), magneto-thermal is closely related to material properties, which determine heating rate.

In contrast, it is important to note that HB/PP is essentially completely transparent to incoming RF electromagnetic waves and will initially maintain room temperature (Figures 6A–6D). As shown in Figure 2D, the temperature gap between the chain-shaped needle and HB/PP can exceed 550°C. Thus, heat is selectively produced at the chain-shaped needle and subsequently transferred to HB/PP (reactants). This is an important fundamental difference because the heat flux (flow) is apparently directed from the surface of catalyst and the mass transfer clearly occurs in the same direction. As described in Equations 7 and 8, the AMF-initiated catalytic approach involves not only heat transfer (conventional thermal catalytic process) caused by
temperature gradient but also heat energy generated by polarization relaxation and magnetization relaxation.

In view of the fact that HB/PP will certainly melt in the vicinity of a continuously heated chain-shaped needle, the reactant molecules will have a large enough kinetic energy to produce a high frequency of collisions on the active site of the chain-shaped needle, which will obviously lead to an enlargement in the key factors in Arrhenius reaction equation: 

\[ k = A e^{-E_a/RT} \]

where \( k \) is the number of species that can overcome the activation energy barrier, \( A \) is the frequency of collisions between reactant (HB/PP) molecules and the active site of catalyst (chain-shaped needle), \( E_a \) is the apparent activation energy, \( R \) is the molar gas constant, and \( T \) is the temperature.

In Figures 6E and 6F, we display a finite element simulation model mapping of current density and heating rate at the interface of the chain-shaped needle with HB/PP based on a domain-steady state numerical solution (see experimental procedures for details). From these simulation results, the current density and heating rate at the interface increase sharply due to the skin effect and interfacial polarization.
The current density at the interface is over six orders of magnitude higher than that of HB. Notably, after the reaction between HB and the needle is completed, the highly RF-electromagnetic-wave-absorbing carbon is deposited on the surface of the chain-shaped needle, which will further enhance current density at the interface.

In AMF-initiated solid-solid reactions, the heating rate \( \dot{P} \) (in joules per second) is calculated as Equation 9. The heating rate is determined by three parts: conductivity loss, polarization loss, and magnetization loss. Since the heating rate is linearly related to the square of electric and magnetic field strength, the electromagnetic field strength at the chain-shaped needle-HB/PP interface is locally increased due to the skin effect and interfacial polarization, resulting in a dramatic enhancement of the interfacial heating rate. In addition, the heating rate with a highly RF-electromagnetic-wave-absorbing carbon (HB-1PP) will be an order of magnitude larger than that of HB, indicating the necessity of adding HB as an initiator in the initial reaction.

In summary, the AMF-initiated catalytic process takes place only at the interface (Figure 6C) between the hot chain-shaped needle and initially cold HB/PP under AMF excitation. Firstly, the chain-shaped-needle-catalyzed HB undergoes decomposition to generate \( \text{H}_2 \), \( \text{CH}_4 \), and other gases, accompanied by the formation of Fe\(_3\)C and high RF-electromagnetic-wave-absorbing carbon, which will promote the subsequent reaction system to increase the temperature. After that, the graphitization of carbon material increases with the continuous addition of PP, which has a positive impact on the subsequent deconstruction of a disposable syringe, and eventually, a high \( \text{H}_2 \) yield of 30.1 mmol g\(^{-1}\) is maintained even after 10 consecutive cycles of testing. This is apparently an incredibly unusual and complex magneto-thermal catalytic process, and further research is underway to determine more precise magneto-thermal catalytic mechanisms at the interface.

In this work, we have presented a simple one-step AMF-initiated catalytic process for quickly decomposing medical waste into hydrogen-rich gases and high-value graphite. HB and a chain-shaped needle are used as initiators and RF-electromagnetic-wave receptors, respectively. This process can quickly extract nearly 76.4%–98.5% (except cycle 1, 17.9%) theoretical mass of hydrogen from PP. A high \( \text{H}_2 \) yield of 39.9 mmol g\(^{-1}\) is obtained, and the \( \text{H}_2 \) selectivity in the evolved gases is approximately 63 vol%. Notably, the \( \text{H}_2 \) yield can still maintain 30.1 mmol g\(^{-1}\) even after 10 cycles at 10.4 mT. Through continuous addition of PP, around 1,024 mg of carbon is ultimately deposited on the chain-shaped needle, and the spent sample contains nearly 67.8 wt % of graphite.

The production of hydrogen-rich gases and graphite so rapidly from the deconstruction of syringe disposal reveals a potential way to help tackle the emerging issue of medical waste. Beyond disposable syringes, these results may help to address the burgeoning problems for other types of medical waste (e.g., mask and protective clothing) disposal by accelerating the decomposition reaction via local and extremely intense heating of catalytic metal (e.g., needle and steel bead) only, which do not require additional synthetic catalyst and consume less energy compared with heating the whole reactor simultaneously.

**EXPERIMENTAL PROCEDURES**

**Resource availability**

**Lead contact**

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Xifeng Zhu (xfzhu@ustc.edu.cn).
Materials availability
This study did not generate unique materials.

Data and code availability
All of the data associated with the study are included in the article and the supplemental information. Additional information is available from the lead contact upon reasonable request.

Materials
HB is the by-product of a pilot biomass pyrolysis liquefaction unit (pyrolysis temperature, 550°C; condensing temperature, 120°C).\textsuperscript{46,47} A disposable syringe (volume, 5 mL) was supplied by a local hospital (Hefei, China).

Experimental setup and high-frequency induction reactor
The high-frequency induction heating (IH) reactor setup is given in Figures 1E and S1. The system consists of alternating current (AC) input, electromagnetic interference (EMC) filter, AC-direct current (AC-DC) converter, filter, DC-AC converter, and IH load.

Firstly, an EMC filter makes the power converter meet with the electromagnetic codes. Then, an AC-DC converter delivers the dc-bus to feed the inverter block. Finally, a DC-AC converter provides an ultra-high frequency of 256 kHz to ensure that the IH load can be heated quickly. The magnetic induction coil is comprised of four loops (inner diameter, 30 mm; outer diameter, 40 mm), which is cooled by water (25°C) to eliminate the self-generated heat effect.

Experimental procedures
The real-world medical waste of disposable syringes mainly consists of the plastic part (core pin and outer shell, PP) and the metal part (needle, 304 stainless steel) (Figures 2A and S2; Table S1). Prior to use, plastics were crushed into small pieces (<5 mm) using a shredder. The needle was bent into a ring (like the Greek letter \( \theta \)) by a special tool (Figure S4). Immediately after, every 10 rings were connected one by one to form a chain shape.

Compared with low fixed carbon content of PP (0.12%), HB was selected as an initiator due to its higher fixed carbon content (34.70%) (Table S2). Typically, 320–340 mg of HB was then physically mixed with the chain-shaped needle in a typical weight ratio of 1:1. Thereafter, the mixture sample (HB + needle) was positioned in a quartz tube (inner diameter, 15 mm; outer diameter, 18 mm), with specific volumes of about 1.42 cm\(^3\) and heights of approximately 0.8 cm, which is to ensure that the sample was fully exposed to the axial AMF (2 cm long). Immediately after, the filled quartz tube was placed axially in the center of the coil in order to allow the sample to cut more magnetic induction lines. Before starting AMF excitation, the sample was first purged with an argon (Ar) flow at a rate of 50 mL min\(^{-1}\) for 5 min. The sample was then excited at 10.4 mT (unless stated otherwise) for 3–30 min. A cold trap (condensing temperature, 0°C) was set up to obtain oil products.

When the above experiment was completed, highly RF-electromagnetic-wave-absorbing carbon was generated (named HB-1), which could dramatically increase the temperature of reaction system. After that, continuous additions of PP (320–340 mg) were added, with no more HB or chain-shaped needle, 10 times. The PP-treatment experiments followed the same procedure as the above experiment. According to the different cycles, the solids obtained were termed HB-nPP (n = 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10). For comparison purposes, 10PP was prepared in the absence of HB.
The mass of each gas product was calculated based on the volume of gas generated and the composition analysis by GC. The H\textsubscript{2} yield, hydrogen efficiency, gas yield, solid (carbon) yield, and oil yield were obtained according to the following:

**H\textsubscript{2} yield**

\[
\text{H}_2 \text{ yield} = \frac{\text{Mole of } \text{H}_2 \text{ produced}}{\text{Mass of HB/PP}} \text{ (mmol g}^{-1})
\] (Equation 1)

**Hydrogen efficiency**

\[
\text{Hydrogen efficiency} = \frac{\text{Total mass of } \text{H} \text{ contained in all gas products (g)}}{\text{Theoretical mass of } \text{H} \text{ in HB/PP (g)}} \times 100\% \text{ (wt%)},
\] (Equation 2)

**Gas yield**

\[
\text{Gas yield} = \frac{\text{Mass of gas}}{\text{Mass of HB/PP}} \text{ (wt%)},
\] (Equation 3)

**Solid (carbon) yield**

\[
\text{Solid (carbon) yield} = \frac{\text{Mass of spent needle} - \text{mass of fresh needle}}{\text{Mass of HB/PP}} \times 100\% \text{ (wt%)}, \text{ and }
\] (Equation 4)

**Oil yield**

\[
\text{Oil yield} = 100\% - \text{Gas yield} - \text{Solid (carbon) yield} \text{ (wt%)}. \quad \text{(Equation 5)}
\]

**Characterization techniques**

The proximate analysis of HB and PP was determined in accordance with Standard GB/T 28731-2012. Carbon (C), hydrogen (H), and nitrogen (N) contents of the sample were conducted by an elemental analyzer (Vario EL III, Elementar Analyse systeme GmbH, Langenselbold, Germany). The oxygen (O) content was obtained by difference. The elemental analysis of the needle was carried out in inductively coupled plasma and atomic emission spectroscopy (ICP-AES; Thermo-Jarrell Ash, Waltham, MA, USA). The magnetic properties of the needle were measured by a physical property measurement system (PPMS DynaCool, Quantum Design, San Diego, CA, USA) equipped with a VSM. TGA was used to characterize carbon produced in the spent sample. Typically, the sample was heated from 25°C to 1,000°C at 20°C/min heating rate under air atmosphere (flow rate, 100 mL min\textsuperscript{-1}).

FTIR spectra were acquired using a Thermo Nicolet 8700 spectrometer (USA). XRD was performed using a D8 ADVANCE A25 X-ray powder diffractometer (Germany). Raman spectra were conducted from a 769G05 laser Raman spectrometer (UK). XPS (Thermo ESCALAB 250, USA) was used to characterize the surface functional groups of samples. The surface morphologies of HB-10PP were examined by field-emission SEM (Sirion 200, FEI Electron Optics) and field-emission TEM (JEM-2100F, Japan Electronics) with HRTEM. The evolved gases were analyzed by GC (GCSP689, TCD/FID detectors, Shandonglunan, Shandong, China).

**Modeling of current density and heating rate**

COMSOL Multiphysics 5.6 Modeling Software (COMSOL) was used to estimate electromagnetic thermal coupling of the reaction system. Although these simulations were quasi-quantitative and do not take into account the 3D structure of actual carbon accumulation or temperature dependency of magnetic and electrical permeability, they provided information about the current density between the chain-shaped needle and HB/PP interface as well as an approximation of their distribution, electromagnetic field strength, and heating rate. The simulations were used to adjust the electromagnetic field strength near the chain-shaped needle and HB/PP interface to build a desired actuator-body connection. Simulations were performed by solving Maxwell’s equations and Fourier’s heat-conduction equations.
under frequency domain-steady state condition. To be specific, the chain-shaped needle was made of stainless steel with an outer diameter of 500 um. The HB, PP, and carbon layers are simplified with toluene, PP, and graphite sheets, respectively. Moreover, the carbon was simulated as a 10-um-thick successive layer. In all simulation plots, color bars represent the normalized electromagnetic field strength. The power lost per unit $<P_{\text{eddy}}>$ mass is described by

$$<P_{\text{eddy}}> = \sqrt{f \mu_r H_0^2},$$  \hspace{1cm} (Equation 6)

where $f$, $\mu_r$, $\rho$, and $H_0$ stand for electrical resistivity, local permeability, electrical conductivity, and applied magnetic field strength, respectively.

The AMF-initiated catalytic method is fundamentally different from conventional heat processes in principle, and the thermal balance equation of AMF-initiated catalytic process is described as

$$\rho c_p \frac{dT}{dt} = \nabla \times \left[ \kappa \nabla T + \frac{L_{qp}}{\chi \varepsilon_0} (P - \chi \varepsilon_0 E) + \frac{L_{qp}}{\zeta T/ (\zeta + 1)} \left( M - \frac{\zeta}{(\zeta + 1)} B \right) \right]$$

$$\quad + \frac{1}{2} \delta E_0^2 + \frac{1}{2} \varepsilon_0 \varepsilon_2 E_0^2 + \frac{1}{2} \varepsilon_0 \mu_0 \mu_2 H_0^2 \right] (w \times m^{-3}),$$  \hspace{1cm} (Equation 7)

where $\kappa$ is thermal conductivity; $T$ is temperature; $L_{qp}$ is the linear phenomenological coefficient of heat flow caused by the electric field; $\zeta$ is susceptibility; $\chi$ is electric polarizability; $\delta$ is electrical conductivity; $E_0$ is applied electric field strength; $w$ is angular frequency; $\varepsilon_0$ is the permittivity of free space; $\varepsilon_2$ is the local imaginary permittivity; $\mu_0$ is the permeability of vacuum; $\mu_2$ is the local permeability; and $H_0$ is applied magnetic field strength.

The thermal balance equation of conventional heat process is conducted in

$$\rho c_p \frac{dT}{dt} = \nabla \times (\kappa \nabla T) (w \times m^{-3}),$$  \hspace{1cm} (Equation 8)

where $\kappa$ and $T$ represent thermal conductivity and temperature, respectively.

The AMF excitation heating rate per unit volume ($P_t$) (in joules per second) is calculated as the following:

$$P_t = \frac{1}{2} \delta E_0^2 + \frac{1}{2} \varepsilon_0 \varepsilon_2 E_0^2 + \frac{1}{2} \varepsilon_0 \mu_0 \mu_2 H_0^2 \right] (w \times m^{-3}),$$  \hspace{1cm} (Equation 9)

where $\delta$, $E_0$, $w$, $\varepsilon_0$, $\varepsilon_2$, $\mu_0$, $\mu_2$, and $H_0$ are as described above for Equation 7.

In addition, the penetration depth $\delta_d$ can be obtained in

$$\delta_d = \sqrt{\frac{\rho}{\mu_2 \pi f}} \right] (mm),$$  \hspace{1cm} (Equation 10)

where $\rho$, $\mu_2$, and $f$ are as described above for Equations 6 and 7.

SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2022.100934.
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